

# Geological model of an alpine lateral valley with implications for the design of a groundwater monitoring network – the example of the Padaster Valley (Eastern Alps, Austria)

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## Abstract

During the construction of the Brenner Base Tunnel (BBT), on the Austrian project side about 12 million m<sup>3</sup> of tunnel excavation material have to be disposed of in landfills, since this material cannot be used as aggregate. Therefore, the Padaster Valley, a side valley of the Wipp Valley, will be filled in with nearly 8 million m<sup>3</sup> excavation material and with a maximum filling height of about 78 meters.

Due to the size of the disposal site and the settlements situated immediately downstream, the geological underground conditions and in particular the hydraulic behaviour of the groundwater body play an important role for the planning and the construction of the disposal site. Based on field data, borehole and pit logging and sampling, geophysical investigations and lab data, a conceptual geological model was established for the complex sediment content of the quaternary infill of the Padaster Valley.

Combining above data and the established conceptual geological model, Multiple Point Geostatistical Simulation (MPS) was used to derive a quantitative and realistic volumetric representation of the sedimentary infill. It is the basis for the conceptual hydrogeological model of the Padaster Valley.

For the design of the groundwater monitoring network of the complex site the elaboration of a hydrogeological conceptual model in the early project phase was essential. We assume several flow systems in the quaternary infill lacking thick or continuous layers in form of aquitards or aquicludes; most of the hydraulic impact is due to fine-grained sediment lenses and layers within the soft rock body. The hydrogeological conceptual model with implications to the groundwater monitoring network in the alpine valley site is discussed.

The results of this study shall contribute to a better comprehension of the complex geological conditions and hydrogeological processes in alpine side valleys.

Im Zuge der Errichtung des Brenner Basistunnels (BBT) müssen auf der österreichischen Projektseite ca. 12 Millionen m<sup>3</sup> an Ausbruchsmaterial deponiert werden, da das Material für die Nutzung als Zuschlagstoff nicht geeignet ist. Diesbezüglich wird ein Seitental des Wipptales, das Padastertal, mit 8 Millionen m<sup>3</sup> Material und einer maximalen Schütthöhe von ca. 78 m aufgefüllt.

Aufgrund der Größe der Deponie, aber auch der unmittelbar talseitig gelegenen Siedlung, spielen sowohl für die Planung als auch für die Ausführung der Deponie der geologische Untergrund und insbesondere das hydraulische Verhalten des Grundwasserkörpers eine wesentliche Rolle. Auf Grundlage von im Feld erhobenen Daten, Bohrungen und Schürfen, sowie geophysikalischen Erkundungen und Laborversuchen wurde ein konzeptionelles geologisches Modell für den komplexen Sedimentkörper der quartern Talfüllung des Padastertals erstellt.

Durch Kombination von Erkundungsergebnissen und geologischem Modell, wurde mittels Multiple Point Geostatistical Simulation (MPS) eine quantitative und realistische Darstellung der sedimentären Talfüllung erstellt. Das MPS Modell stellt dabei die Basis für das konzeptionelle hydrogeologische Modell des Padastertals dar.

Zur Errichtung eines Grundwassermessstellennetzes für die komplexe Baustelle war die Ausarbeitung eines hydrogeologischen Modells in einer frühen Projektphase notwendig. Es zeigt sich, dass sich im Lockergesteinskörper verschiedene Fließsysteme eingestellt haben, obwohl augenscheinliche mächtige oder durchgehende Trennschichten in Form von Aquitards oder Aquicludes fehlen. Diesbezüglich wird auf die hydraulische Wirkung von feinkörnigen Linsen und Lagen im Lockergesteinskörper eingegangen. Weiters wird das hydrogeologische konzeptionelle Modell mit Auswirkungen auf das Grundwassermessstellennetz in dem alpinen Seitental diskutiert.

Die Untersuchungen und Ergebnisse sind ein Beitrag zum Verständnis der komplexen hydrogeologischen Prozesse in alpinen Seitentälern.

## 1. Introduction

The Padaster Valley is used as a disposal site for the 64 km long Brenner Base Tunnel (BBT) that will connect Innsbruck (A) with Fortezza (I) as a deep-lying railway tunnel (Bergmeister,

2011). This alpine side valley will be filled in with nearly 8 million m<sup>3</sup> excavation material, with a maximum filling height of about 78 m.

## Geological model of an alpine lateral valley with implications for the design of a groundwater monitoring network – the example of the Padaster Valley (Eastern Alps, Austria)

In contrast to the quaternary geological studies of the surrounding side valleys (see for example Heissel, 1932; Draxler et al., 2003; Magiera, 2003; Kerschner et al., 2014;), the geological conditions and the composition of the quaternary sediments of the Padaster Vally had never been investigated before.

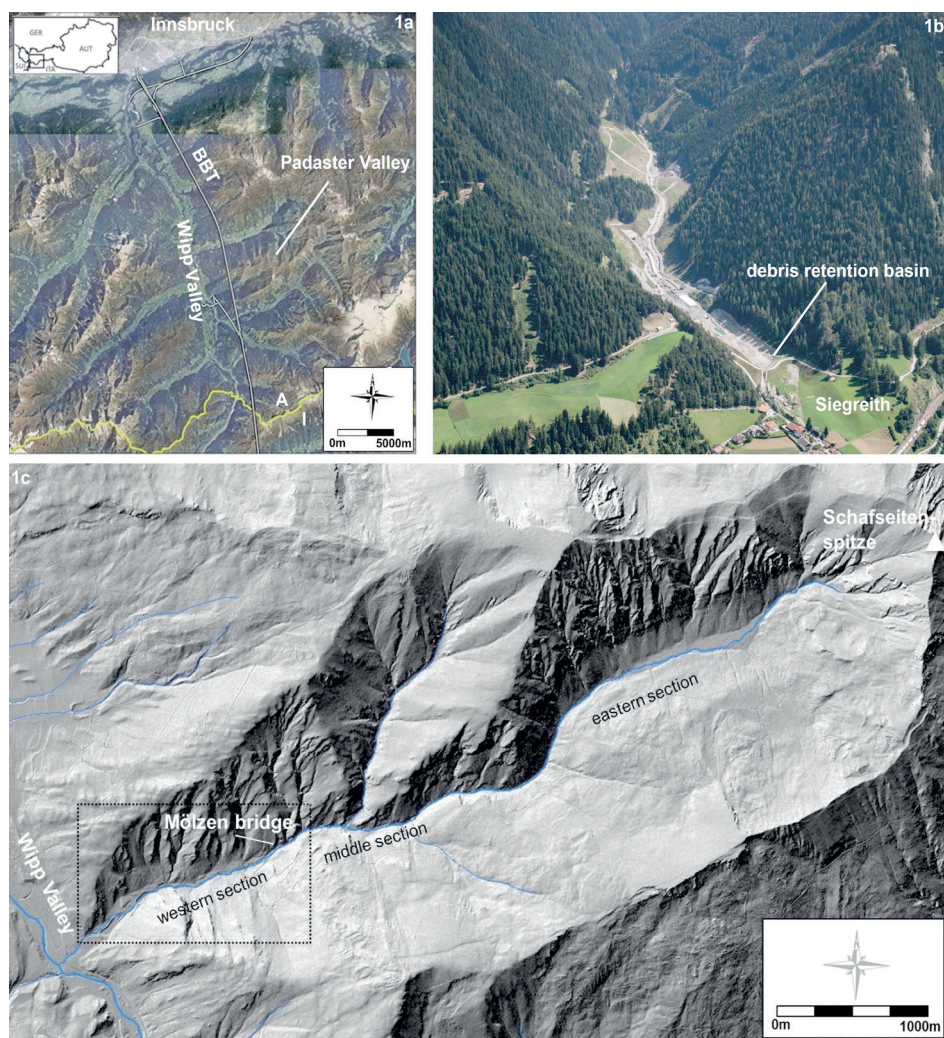
Due to the loading effect, settlements and reductions of the pore volume causing a rising of the water level in the quaternary infill are possible. Their evaluation requires a detail knowledge of the geological and the hydrogeological conditions.

Therefore the structure of the Padaster Valley had to be studied in detail for disposal site planning. It was prospected in various steps, thus allowing the subsequent elaboration of a detailed geological model. Site investigations were mainly aimed at studying the depth of the bedrock surface and the characteristics of the quaternary sediments

through boreholes and seismic investigations. Especially the seismic investigations, validated by several core drillings, gave information about the shape of the bedrock surface and showed that the whole valley is glacially eroded. Samples of the soft rock taken from drilling cores and from pits showed that the heterogeneous quaternary valley infill is composed of different sediment types.

Integrating the conceptual geological model, exploration data and actuogeological analogs, Multiple Point Geostatistical Simulation (MPS) was used to derive a realistic 3D-model of the internal architecture of the quaternary valley infill.

The refined geological model was used to understand the several flow systems and to design the hydrogeological conceptual model of this alpine side valley which is used to set up a monitoring network.



**Figure 1:** Overview of the study area in the Eastern Alps and the Padaster Valley. a) Insert shows location of the study area in the Eastern Alps. The Padaster Valley is an alpine side valley east of the Wipp Valley and south of Innsbruck (Tirol). The white line shows the BBT tunnel route in the northern project area. The yellow line represents the national border between Austria (A) and Italy (I). b) Overview of the Padaster Valley (Status 07/2012) and of the settlement of Siegreith (Steinach am Brenner) further downstream: the new debris retention basin is located at the mouth of the valley, to the east the disposal site (view to the east). c) Digital elevation model of the Padaster Valley with a resolution of 1 m based on ALS-data. (Land Tirol, 2015); from a geomorphological point a section division in a western, middle and an eastern section is possible (see chapter 2); the framed area is shown in detail in Figure 2 with the boundary of the disposal site.

## 2. Study area

The Wipp Valley is a north-south trending alpine valley in the Eastern Alps that connects Austria with Italy through the Brenner Pass, the most important pass in the Eastern Alps (Figure 1a). From this main valley, several lateral valleys branch off to the east and to the west.

The Padaster Valley is an east-west trending side valley of the Wipp Valley on the orographic right hand side (Figure 1b). It is about 6 km long and has a catchment area of about 11.3 km<sup>2</sup> (Figure 1c). From a geomorphological point of view a separation in 3 sections is possible. The western downstream section comprises the valley entrance, which is bounded by medium steep to steep slopes (generally between 25° and 40°) in the northern flank and steep slopes (generally between 35° and 45°) in the southern flank. The valley floor is about 100–150 m wide. Before disposal operations, part of the valley was used agriculturally as grassland. This section continues narrowing to the east, up to the Mölzen bridge where the valley becomes a V-shaped wooded valley. Several channels run from the slopes to the Padaster brook where



they form debris cones. East of the Mölzen bridge a narrow, few decametres broad gorge-like section follows (middle section). There are also some steps in the bed of the brook. Here, the

Inzentral brook flows into the Padaster brook. The valley widens again in the third, the eastern section. In this area, several small brooks flow towards the Padaster brook. The Schafseitenspitze

peak with 2.602 m is the highest point of the range surrounding the valley.

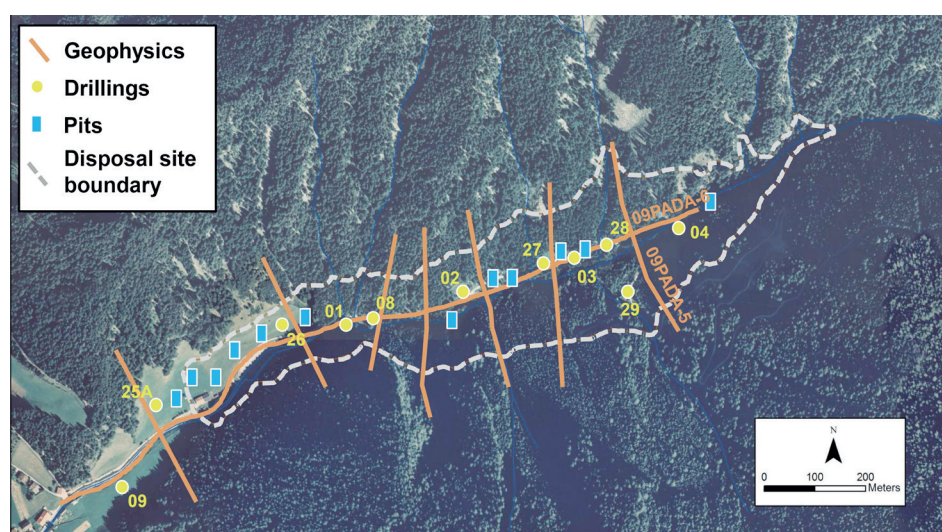
The disposal site and the project area discussed in this article are located in the western and middle section of the Padaster Valley (see framed area in Figure 1c). The disposal site has an overall length of about 1,385 m and a surface area of about 22.5 ha. The extent of the disposal site is shown in Figure 2.

### 3. Geological-hydrogeological exploration Phases of the Padaster valley

For the geological and hydrogeological exploration, the disposal site has been studied during several exploration phases (Table 1, Figure 2). This allowed ongoing refinements of the geological model (BBT-SE, 2010, 2012). For the work presented here the results of the prospection activities of the following table were used.

Project phase	Prospection scope	Prospection activities
Feasibility Study	<ul style="list-style-type: none"> <li>• Geological model</li> <li>• Realisation of groundwater wells</li> <li>• Groundwater conditions</li> <li>• Monitoring Padaster brook</li> </ul>	<ul style="list-style-type: none"> <li>• Geological Mapping 1:2.000 scale</li> <li>• Geomorphological scans considering slope movements</li> <li>• Hydrogeological mapping (springs, channels)</li> <li>• Realization of core and percussion drillings: 18 borehole drillings with a prospection depth between 5 and 70 m in order to investigate the stratigraphic conditions of the soft rock body and the depth of the bedrock surface. 13 boreholes were made as core drillings and a further 5 drillings were made as drillings without core extraction</li> </ul>
Approval planning	<ul style="list-style-type: none"> <li>• Detailed geological model</li> <li>• Soil mechanics</li> <li>• Hydrogeological conditions</li> <li>• Monitoring Padaster brook</li> </ul>	<ul style="list-style-type: none"> <li>• Standard penetration tests (SPT) in order to determine the compaction of the soft rock</li> <li>• Groundwater wells</li> <li>• Laboratory tests in order to determine the geological-geotechnical and hydraulic parameters</li> <li>• Pits</li> <li>• 2D hybrid seismic for an overall length of 3,770 m: here, a longitudinal profile with a length of 1,456 m and 7 cross profiles with a length between 208m and 442 m were measured and calibrated with the core drillings</li> </ul>
Site preparation work	<ul style="list-style-type: none"> <li>• Exploration of technical sites</li> <li>• Georiskanalysis</li> <li>• Compliance of authorization constraints</li> </ul>	<ul style="list-style-type: none"> <li>• Detailed mapping (M 1:100 to M 1:1000)</li> <li>• Pits (disposal site contact surfaces)</li> <li>• Test boreholes for the prospection of the bedrock surface in the foundation area of structures</li> <li>• Monitoring of water resources</li> </ul>

**Table 1:** Geological-hydrogeological exploration in the Padaster Valley



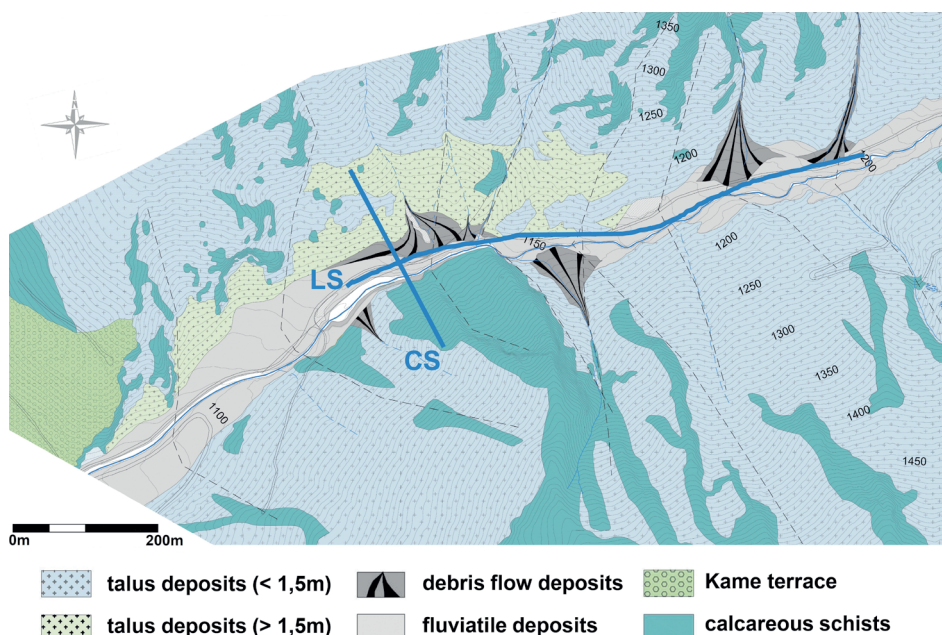
**Figure 2:** The Padaster Valley (western and middle section, see Figure 1c) with investigations (geophysics, drillings, pits) undertaken in the different prospection campaigns. The grey line shows the extent of the disposal site. The two seismic sections 09PADA-6 and 09PADA-5 were discussed in chapter 5. Drillings from west to east: 09=St-B-09/07, 25A=St-B-25A/09, 26=St-B-26/09, 01=St-B-01A/04 and St-B-01B/04, 08=St-B-08/05, 02=St-B-02A/04 and St-B-02B/04, 27=St-B-27/09, 03=St-B-03A/04 and St-B-03B/04, 29=St-B-29/09, 28=St-B-28/09, 04=St-B-04/04.

### 4. Geological setting

The Padaster Valley lies in the Glockner nappe complex, which forms the Obere Schieferhülle at the western edge of the Tauern Window. In this domain calcareous schists and the schistosity is dipping to NW (Figure 3). Due to the dipping the northern flank of the valley is steeper than the southern flank.

Borehole drillings show that the entire valley has been subject to glacial erosion. In the valley, the bedrock surface is approximately 20-60 m below ground surface. The quaternary valley infill of the Padaster Valley consists of Holocene and Pleistocene sediments of different sediment types.

Gravel-dominated fluvatile sediments with low fines content predominate. Near the side channels, these sediments inter-finger with debris flow sediments richer in fines. Intercalated fine-grained layers of sand and silts play an important role for the hydrogeological model. These layers are interbedded in the gravel-dominated fluvatile sediments over the entire width of the valley. Their longitudinal extension ranges from several decimetres up to several hundreds of meters. Figure 3 indicates the position of two geological sections (longitudinal section and cross section) which show the composition of the quaternary valley infill (discussed in detail in chapter 7 and shown in Figure 10 and 11).



**Figure 3:** Detail of the geological map of the Padaster Valley. The 2 geological sections (CS: cross section – see Figure 10, LS: longitudinal section – see Figure 11) form the basis of the geological model.

## 5. Geophysical prospections

Seismic investigations were carried out to study the bedrock surface, to differentiate the soft rock material, with particular attention to the ground compactness, especially concerning layer density, as well as to identify deposition structures within the quaternary loose material infill. Hybrid seismics was applied combining tomographic refraction and reflection seismic procedures (Frei and Keller, 2000). A 1,456 m longitudinal profile was measured along the valley floor, as well as 7 cross profiles ranging from 208 m to 442 m (Figure 2). Geological interpretation is based on the seismic information calibrated on the basis of core drillings.

### 5.1 Hybridseismic profiles

The seismic profiles in Figures 4a to 4c (GeoExpert ag, 2010) show the tomographic refraction-deduced field of the seismic propagation velocities and the seismic reflection deep profile of the longitudinal axis of the Padaster valley (Figure 4a) and the cross profile done in the Mölzen bridge area (Figure 4b and 4c).

The seismic propagation velocities (Figure 5) are an indirect parameter for rock densities. Slow velocities mean soft rocks, high values are an indicator for solid and compact rock. The isoline at 2200 m/s (emphasized in black in Figure 5) reflects the boundary between soft rock and compact soft rock. Velocities above the isoline of 4000 m/s (emphasized in white in Figure 5) reflect undisturbed solid rock. The area between these two velocity limits comprises highly solidified and/or hypersolidified soft rock (e.g. ground moraine) or loosened rock. Since the ranges of the seismic velocities of different rock types overlap, geological layer boundaries usually cannot be clearly defined. Therefore, borehole calibration is

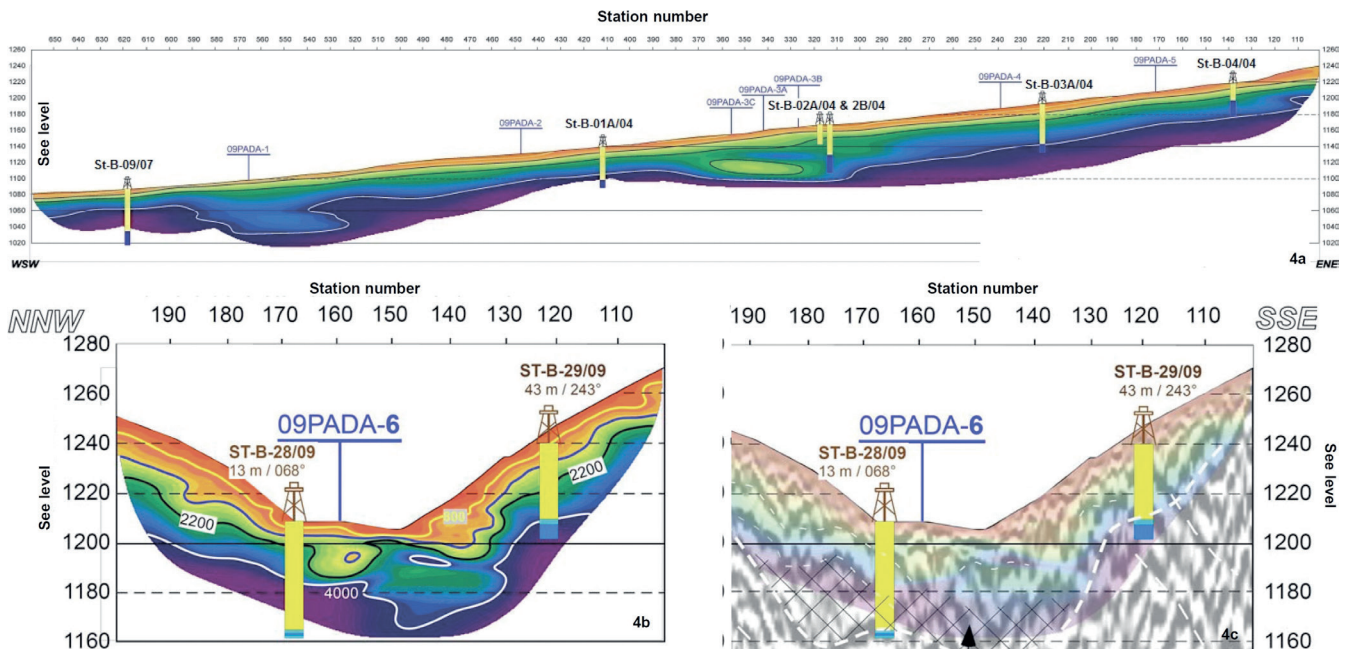
very important for the interpretation of seismic velocities, in order to define the bedrock surface as exactly as possible by means of the velocity field.

### 5.2 Interpretation of the seismic prospection

The following conclusions can be drawn from the interpretation of seismic studies:

- In a velocity range below 3000 m/s nearly homogeneous conditions prevail in the longitudinal extension. As a consequence, there is a homogeneous picture in lateral direction along the entire stretch (see Figure 4a). Wave velocities increased evenly over almost the entire stretch with increasing depth. This is because with increasing depth, overburden thickness and therefore compaction profile increases.
- In the case of fractured or fragmented shallow rock there is no measureable velocity contrast to the densely bedded soft rock.
- The marked course of the bedrock in the cross profile (white dotted line in Figure 4c) shows a nearly U-shaped valley. In the borehole St-B-28/09, rock is encountered about 20 m deeper than assumed on the basis of the Iso-velocity curve of 4000 m/s within the velocity field (white line in Figure 4b). Apparently, there must be highly compact debris material and/or moraine material above the bedrock.
- According to the cross profile (see Figure 4b and 4c), the soft rock is in certain parts characterized by complex structures due to the different soft rock types.
- Very high velocities in the valley infill are understood as densely bedded moraine material (over-consolidated ground moraine) and debris material in the lower part of the valley infill.





**Figure 4:** Seismic profiles of the longitudinal axis of the Padaster valley and the cross profile done in the Mölzen bridge area (locations in Figure 2, legend in Figure 5). a) Tomographic refraction-deduced velocity field along the longitudinal axis of the Padaster valley (profil 09PADA-6, GeoExpert ag, 2010). b) Tomographic refraction-deduced velocity field of the seismic cross profile done in the Mölzen bridge area (profil 09PADA-05, GeoExpert ag, 2010). c) Interpreted hybrid-seismic cross profile done in the Mölzen bridge area (profil 09PADA-05, GeoExpert ag, 2010).

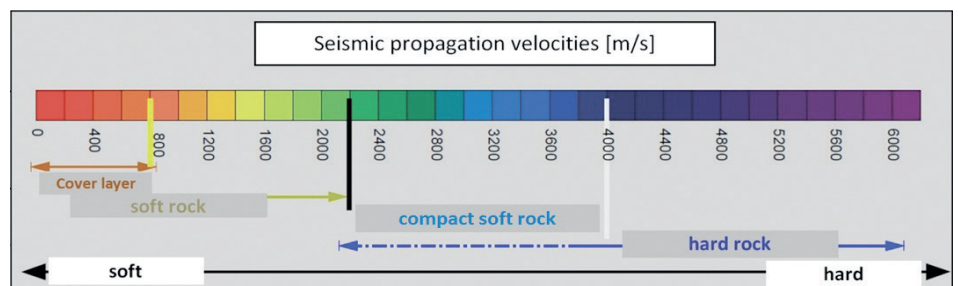
## 6. Quaternary sediment infill

From drilling cores and from pits (see Figure 2) 66 samples of the soft rock were taken and subjected to sieve analysis and sedimentation tests. Figure 6 illustrates four main groups:

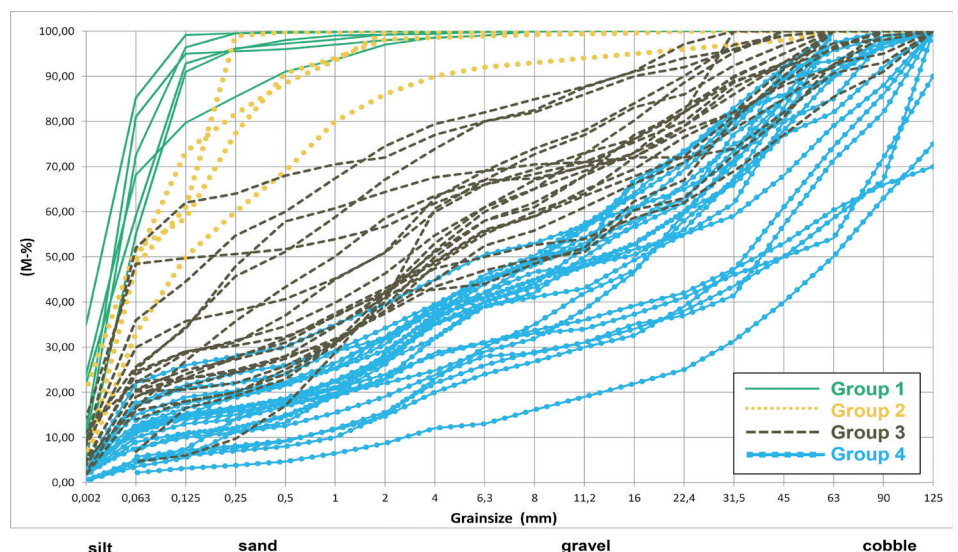
- Group 1: Fine-grained sediments (silt and clay)
- Group 2: Sand and silt
- Group 3: Gravels with a wide grain size distribution and a high proportion of fines
- Group 4: Gravels with a wide grain size distribution, cobbles and a low proportion of fines

### 6.1 Group 1: Fine-grained sediments (silt and clay)

Group 1 consists of silt and clay dominated sediments. The samples show a 55–85% content in fines <0.063 mm, the percentage of clay ( $\phi < 0.002$  mm) is generally between 8–35% (Figure 7a). The layers with these fine-grained sediments are generally several decimetres thick (Figure 7b-c). The bore-



**Figure 5:** Legend of the colour-coded velocity field with the defined borders for rock boundaries of seismic propagation velocities (GeoExpert ag, 2010).

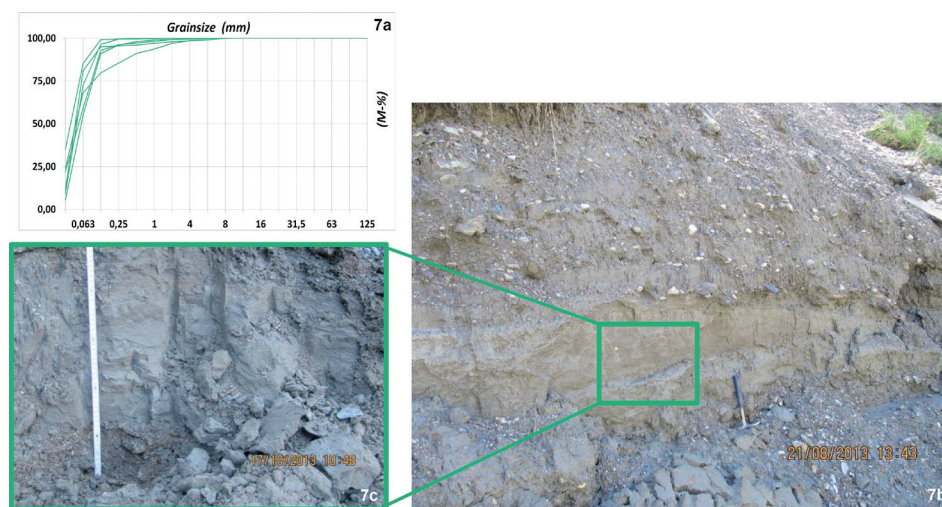


**Figure 6:** Grain size distribution of the various sediment groups belonging to the quaternary Padaster Valley infill. Group 1: Fine-grained sediments (silt and clay), Group 2: Sand and silt, Group 3: Gravels with a wide grain size distribution and a high proportion of fines, Group 4: Gravels with a wide grain size distribution, cobbles and a low proportion of fines.

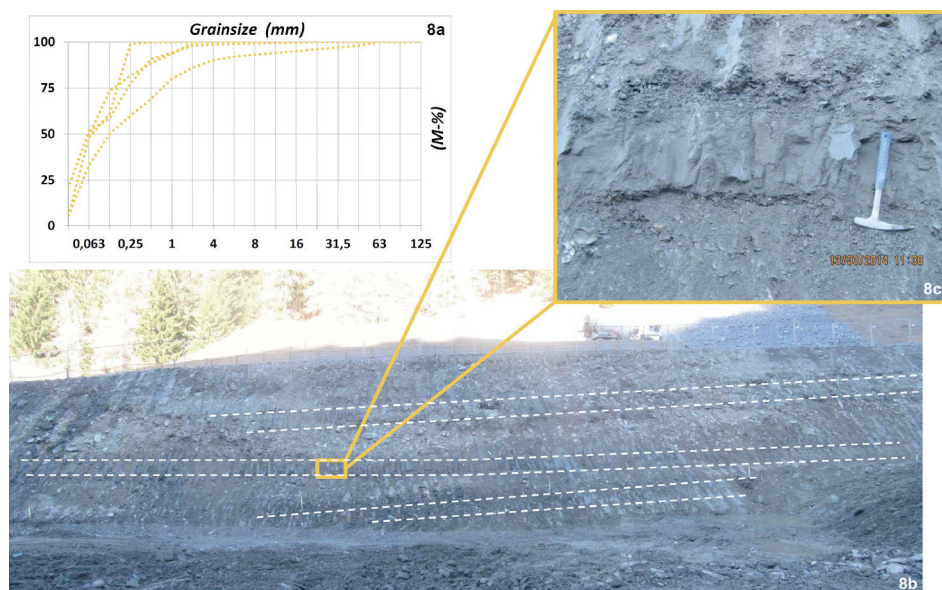
hole St-B-25A/09 (location in Figure 2), drilled at the western end of the valley, also showed metre-thick silt layers. In general, the silt-clay sequences show a fine layering. Locally there are intercladed fine sand and individual gravel layers with a thickness of several mm to cm.

This type of sediment is concentrated mostly on the western side of the Padaster Valley; the drillings St-B-09/07 and St-B-25A/09 showed numerous layers up to a metre thick.

The sediments of group 1 are interpreted as localized standing water sediment with a lateral extension generally in metre scale. Water discharge was widely observed at outcroppings, whereas the fine grained sediments act as flow barriers.



**Figure 7:** Group 1: Fine-grained sediments (silt and clay). a) Grain size distribution. b) Outcrop at eastern part of the valley, <1 m thickness, lateral extension approximately 5 m. c) Detailed view of the fine-grained layer.



**Figure 8:** Group 2: Sand and silt. a) Grain size distribution. b) Cut-and-cover trench (approximatel 5 m deep) for the diversion tunnel for the Padaster brook: fine-grained, sand and silt-rich layers (dark colour) several decimetres thick lie horizontally between the coarser sediment layers with cobbles, gravel and sand, about a metre thick (fluvial deposits from the Padaster brook). c) Detailed view of a layer consisting of sand and silt, between layers of well-rounded gravel.

## 6.2 Group 2: Sand and silt

Group 2 consists of sandy and silty sediment types. The samples show a 35-50 % content in fines <0.063 mm, whereas the percentage of clay ( $\phi < 0.002$  mm) in the samples analysed is about 5 %, with a maximum of 20 % (Figure 8a). The thickness of the sand and silt layers encountered varies between a decimetric and metric scale (Figure 8b-c). Besides fine layering, caused by mica-rich layers and variations in grain size in a millimetric scale, these sediments usually show sedimentary structures caused by flowing water. Also, in the usually medium-dense layered sediments, individual polymict gravel debris (in part, strongly fractured) can be observed. These sediments extend all over the Padaster Valley, and the frequency of occurrence increases from the western end of the valley to the east.

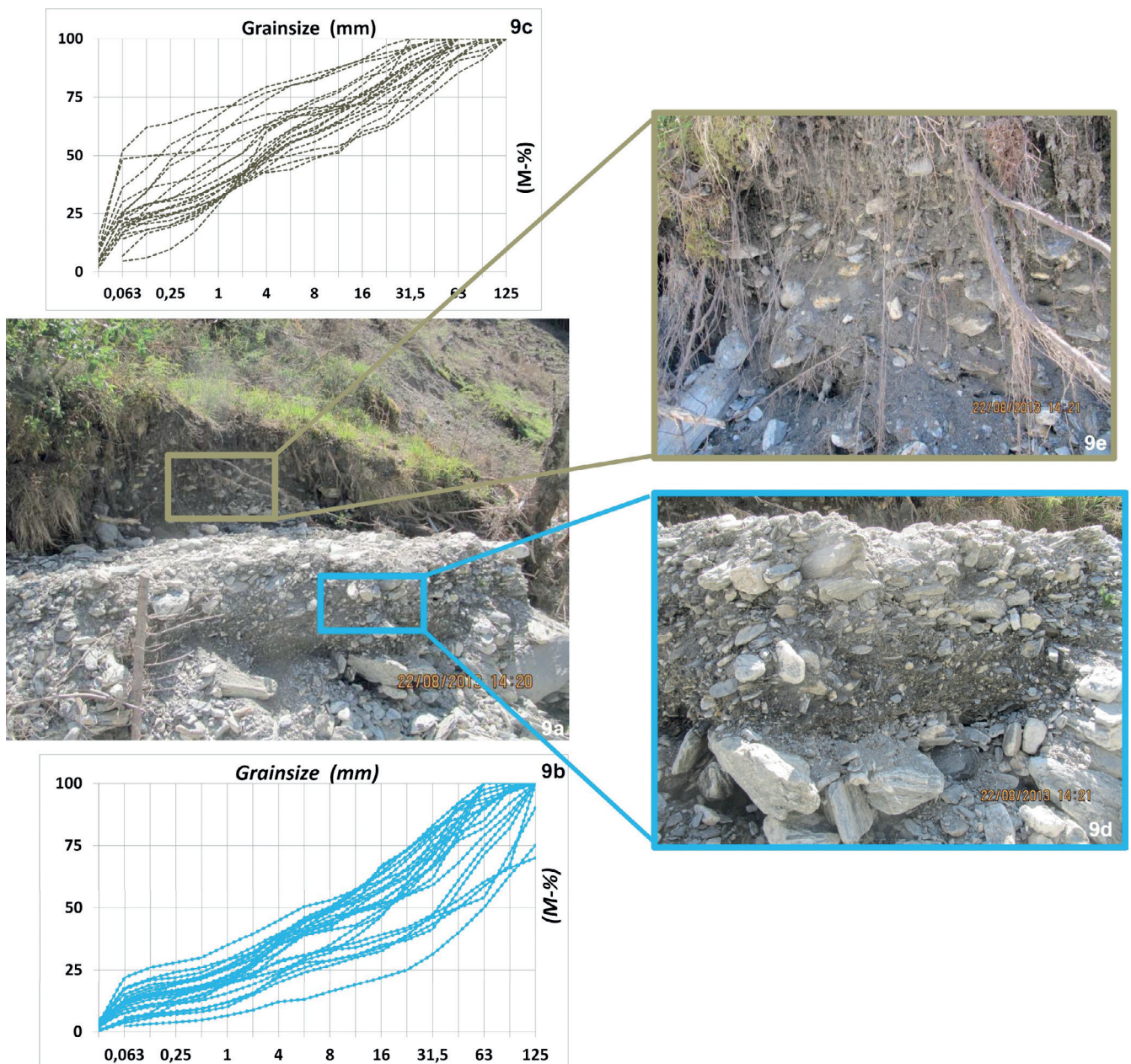
The sediments are interpreted as fluvial deposits in areas with very low flow velocities, which however, as opposed to the sediments in group 1, show significant lateral and spatial extension. Water discharges were widely observed at the top of these fine grained layers.

## 6.3 Group 3: Gravels with a wide grain size distribution and a high proportion of fines

Group 3 consists of gravels with a wide grain size distribution with a high proportion of fines (Figure 9a). The samples are characterized by 15-30 % of fines <0.063 mm, rarely the fine content exceeds a maximum of 50 % (Figure 9c). The samples were taken from debris flow sediments. The extension of this group is also linked to the trenches on both sides of the Padaster Valley; however, as far as volume is concerned, sediments make up a significant part of the quaternary valley infill.

The sediments have a wide range of particle sizes and the grain size distribution is never uniform, poorly sorted and chaotically structured, with cobbles in dm size and large boulders with several cubic metres in volume in a silt-sand-gravel matrix (Figure 9e). Typi-





**Figure 9:** Overview of Group 3 and Group 4. a) Area where the alluvial sediments (light-colored sediments in the foreground) interfinger with the debris flow layers (dark-colored sediments in the background; compared to the layered gravel-dominated alluvial sediments, the debris flow layers consist of very poorly sorted sediments, with a wide grain size distribution and a high amount of fines. b) Grain size distribution of group 4. c) Grain size distribution of group 3. d) Detailed view of the layered, well sorted gravels in the alluvial layers from the Padaster brook. e) Detailed view of the very poorly sorted sediments of the debris flow, with wide grain size distribution and layers with a high amount of fines.

cally, we find immature debris flow sediments consisting of massive layers of immature sediments and alternating layers of poorly differentiated gravel. The side channels carry water only periodically. During high-water events they can transport large amounts of debris down to the valley floor which will then interfinger with the sediments carried by the Padaster brook.

Beside the debris flow sediments, there is a second type of sediment with a comparable grain size distribution. The drilling results show on the bedrock surface a sediment with a monomictic component composition (phyllitic rock types) and with a high compactation. For this reason this sediment type is supposed to be moraine material (ground moraine). There is no grain

size analysis available, but in the drillingcore the sediment is described as gravel and cobbles with a high amount of fines. Therefore this sediment type is also assigned to group 3.

#### 6.4 Group 4: Gravels with a wide grain size distribution, cobbles and a low proportion of fines

Group 4 consists of cobbly, sandy gravels with a wide grain size distribution and a low fine content (Figure 9a). These sediments are dominant in the alluvial Padaster Valley itself, fluvial sediments from the Padaster brook that make up a significant part of the quaternary valley infill. The percentage of fines <0.063 mm is, on average, 8-12 % with a maximum of 20 %

(Figure 9b). This group includes gravel-dominated sediments from the Padaster brook, a mixture of gravel and sand with cobbles and boulders and a low amount of silt (Figure 9d). The gravel, cobbles and boulders are subrounded to rounded, rarely angular or well rounded. The shape of the grains is generally plate-like or elongated. The debris includes local rock types such as phyllite (carbonate phyllite, sericite phyllite) and schists, secondarily vein quartz and foreign debris such as gneiss and individual amphibolites. Gneiss and amphibolite are more rounded than phyllites. The fluvial sediments are well assorted, with regulated clasts and sedimentary layering.

## 7. Quaternary geological model

Due to the glacial erosion the bedrock surface covered by the quaternary infill forms an irregularly edged trench shape dipping to the West. At borehole St-B-09/07, located at the western end of the valley (Figure 2), the bedrock surface is 53 m deep; at the easternmost borehole, St-B-04/04, the bedrock surface is at 21 m depth. Locally, the bedrock surface is covered by ground moraine.

The fluvial sediments from the Padaster brook (group 4: gravels with a wide grain size distribution, cobbles and a low proportion of fines) consist of gravel dominated layers with varying grain sizes and are, in general, layered horizontally with localized sandy intercalations.

Close to the side channels, the fluvial sediments interfinger with the debris flow sediments of group 3 (Gravels with a wide grain size distribution and a high proportion of fines). These debris flow layers from the side channels and the fluvial layers from the Padaster brook (group 4) are very similar in structure. The difference consists mainly in the geological origins and in the level of maturity. In contrast to the debris flow sediments the fluvial sediments show a lack of larger boulders and a smaller amount of fines. The manually constructed geological cross-section in Figure 10 shows the interfingering of the fluvial sediments of the Padaster brook with the debris flow sediments from the side channels.

The large lateral extension of the sand and silt layers (group 2) ranging from several dozen metres to one hundred metres can be clearly seen in the manually derived longitudinal section along the valley in Figure 11. The almost horizontal sand layers are clearly outlined, lying between the gravel-dominated sediment from the Padaster brook (group 4). Subsequent erosion of the fine-grained layers by debris flow events was also observed at several outcroppings.

The alluvial conoid at the western end of the Padaster Valley consists of cobbly gravel with localized sand and silt. The rounded components consist mainly of phyllite material from the Padaster brook drainage basin, but a significant amount of exotic rocks such as gneiss and amphibolites can also be observed. The fact that allogenic material can be found at least in the western part of the Padaster Valley indicates that the Wipp Valley glacier penetrated into the valley.

The most recent debris can be found close to the actual bed of the brook. This sediment consists of slightly rounded

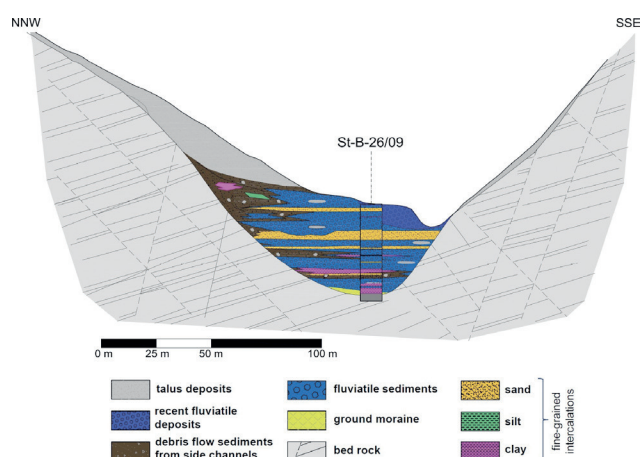
and rounded gravel with sand and silt, localized fine-grained sediments and individual large boulders that are several cubic metres in volume. Lateral along the valley talus debris dominate. These are composed mainly by local Bündner schists and secondarily by relocated moraine material.

To find out the area of origin of the extensive sandy-silty layers (group 2), samples were taken from various outcroppings at different depths and in various locations. Petrographic thin-sections of these samples were analyzed and were compared with those from the most recent bed sediments of the Padaster brook and the river Sill (analysis: K. Krainer-University of Innsbruck, BBT-SE, 2014). This analysis shows that only the sample from the river Sill also includes components from the Central Gneiss formation (orthogneiss from the Brenner region) and the Altkristallin (garnet, hornblende, compositions of quartz, epidote/zoisite, hornblende; area west of the Wipp Valley/Brenner fault) besides products from the Obere Schieferhülle (Bündner schists, marble). All other samples, meaning the samples from the individual sandy layers of the Padaster Valley and those from the recent bed of the Padaster brook, contain components (quartz, calcite, muscovite/sericite, chlorite and rarely feldspar) that come from the rocks in the Obere Schieferhülle (mica schists, phyllites, marble). These show no indication of an origin in the Central Gneiss or Altkristallin formations. We can therefore conclude that the sandy-silty layers are of local origin.

Figure 8 shows alternating layers of gravel dominated fluvial deposits (group 4) and sand and silt layers (group 2) with a sharply defined boundary. The missing of a gradual passage in sedimentation shows that there was an abrupt change in the flow velocity of the water.

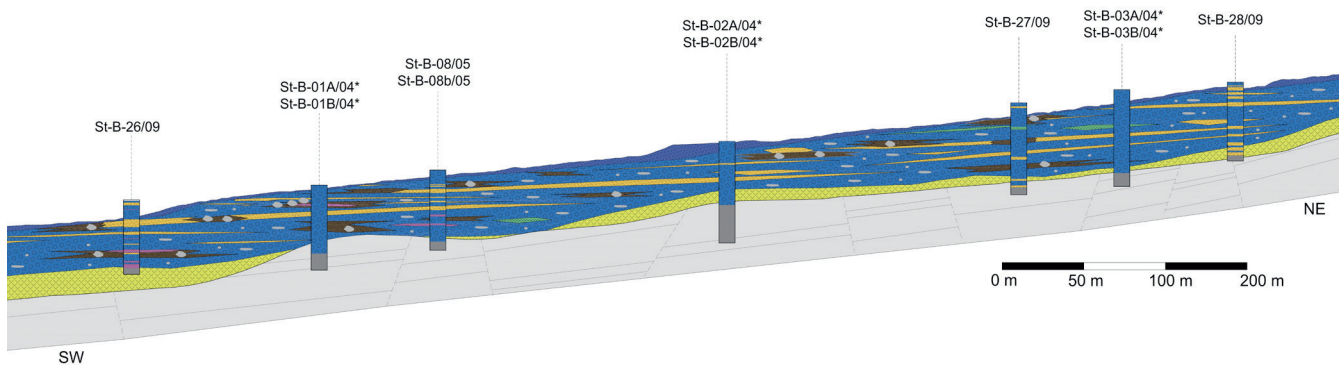
Concerning sedimentation dynamics, the following assumptions were made for modelling:

- The gravel dominated fluvial sediments of group 4 were deposited under a high flow velocity (higher flow regime).
- In contrast to the gravel dominated sediments, the sand and



**Figure 10:** Manually constructed cross-section in the western part of the Padaster Valley (section not exaggerated, the location of this section is shown in Figure 3), illustrating the interfingering of fluvial sediments with the debris flow sediments from side channels and fine-grained intercalations).





**Figure 11:** Detail of the manually constructed longitudinal section of the Padaster Valley (section not exaggerated, the location of this section is shown in Figure 3, legend same as Fig 10) and illustration of exploration boreholes (core drillings and drillings without core extraction like St-B-01A/04, 02A/04, 03A/04): in some areas, the bedrock surface is covered by ground moraine. The main part of the quaternary valley infill is composed of gravel-dominated fluvial sediments, debris flow sediments and fine-grained intercalations.

silt sediments of group 2 were deposited under a lower flow velocity (lower flow regimes).

Based on these assumptions, the following geological model was derived and abstracted into the training image for Multiple Point Geostatistical Simulation (see chapter 8):

The Padaster brook was a braided river. In the channels of this flow system, the gravel dominated fluvial sediments (group 4) were deposited. During particular high-water events, the Padaster brook flooded sporadically the entire valley and due to the low slope and the subsequent reduced flow regime, the extended sand and silt layers (group 2) were deposited. Due to debris flows from the side channels (group 3) the fine layers were subsequently partly eroded. Shallow water may have stood for longer periods in side bays and isolated depressions, allowing particles in suspension to deposit as layered, fine-grained sediments (silt and clay, group 1) that reach several decimetres to meters thickness with low lateral extension. After the flood events and the shifting of the channels, the brook deposited fluvial gravel again, creating the interfingering that can be seen in the cross-section (Figure 10).

To deposit such a sediment sequence, a distal barrier at the mouth of the valley or in the Wipp Valley is required to lift the erosion level of the Padaster Valley and to form an accumulation area. The sedimentation in the accumulation area was therefore linked with a distal barrier, meaning that the sedimentation in the Padaster Valley increased with the build up of the barrier.

Two scenarios can be considered that have led to the formation of possible barriers:

- Debris from large mass movements such as, for example, debris flows or rock falls
- A glacier in the main valley (Wipp Valley)

An argument against the first scenario could be that there is a lack of large debris masses at the mouth of the valley that could have acted as barriers. With regard to rock fall masses, the digital elevation model (Figure 1c) shows several scarps on the slopes. However, no signs of rock fall masses can be seen in the boreholes. Furthermore, mass movements generating rock fall

material would have to build up constantly in order to create the necessary accumulation space in the Padaster Valley.

With the second scenario, that of a build-up of a glacier in the main valley, this continuous creation of accumulation space can be explained more easily. Similar developments of quaternary valley infills are described by de Graaff (1997) for alpine valleys in Vorarlberg as well.

## 8. Multiple-point geostatistical simulation of the quaternary valley infill

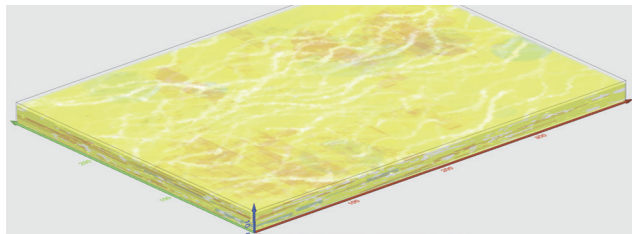
Based on the conceptual geological model discussed above, a three-dimensional geological model of the quaternary infill of the Padaster Valley was established. The aim of the model is to serve as an extensible volumetric basis for hydrogeological and geotechnical considerations in connection with the planned deposit (Marschallinger et al., 2015). It was limited to the soft rock due to the complexity of the sedimentary infill

	Model Volume	Training Image
Xmin	16300	0
Xmax	17450	398
Ymin	111200	0
Ymax	111800	298
Zmin	1030	0
Zmax	1300	19,5
dX	2	2
dY	2	2
dZ	0.5	0.5
nX	576	200
nY	301	150
nZ	541	40
<b>total voxels</b>	<b>93796416</b>	<b>1200000</b>

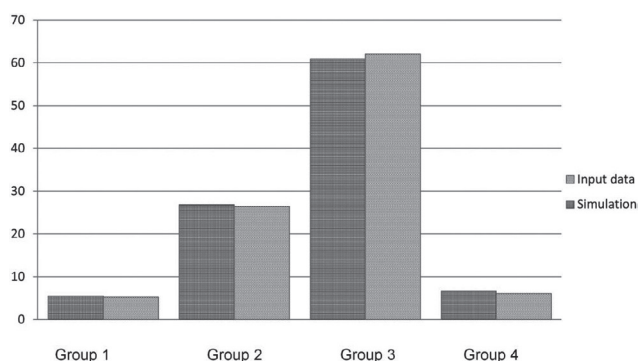
**Table 2:** Model volume and training image parameters (X= Easting, Y=Northing, Z=elevation (meters, project coordinate system); min, max= minimum and maximum in relevant direction (statistical range). dX, dY, dZ=voxel size (meters) in X, Y, Z directions; nX, nY, nZ=number of voxels in X, Y, Z directions).

and the minor importance of the hard rock for the groundwater flow systems.

Multiple Point Geostatistics (MPS) is a modern approach to three-dimensional modeling of complex geological structures (Strebelle, 2000) such as expected in postglacial sediment series of alpine valleys. In contrast to traditional, variogram-based modeling and simulation (Deutsch and Journel, 1998), MPS incorporates geological expert knowledge via a so-called Training Image (TI). The TI is a two- or three-dimensional conceptual representation of the geological context that permits geologists an intuitive formulation of geometrically complex geological structures plus their genetic relationships like erosion of pre-existing sediments (compare Figure 12). The MPS algorithm lifts patterns and associated statistical parameters from the TI, replacing the 2-point structure provided by the variogram in classical geostatistics. During simulation, patterns are conditioned to primary hard and soft data from outcrops, drillings or geophysics. MPS simulation yields statistically fluctuating, but equally probable realizations that can be post-processed to enable scenario modeling. Generally, the results of geostatistical simulations are coded in grid data format: a MPS 3D-simulation is represented by a so-called voxel array that is made up of contiguous, prismatic cells ("Voxel" is an acronym for "volume element", e.g. Hughes et al. (2013); see Marschallinger et al. (2014) for further explanation). Since



**Figure 12:** 3D Training Image (TI) for the Padaster Valley quaternary sediment sequence (geometry parameters in Table 2). Semi-transparent rendering to portray internal structure. Colors: green – group 1; orange – group 2; yellow – group 3; white – group 4. Layer structure is clearly visible on confining vertical planes. Top surface shows that finer-grained sediments are eroded by meandering group 4 channels (fluvial gravel). Directions: North = green axis, East = red axis, Up = blue axis. Units = meters.



**Figure 13:** Comparing distributions of sediment groups 1-4 in input data and a representative MPS realization (number 31).

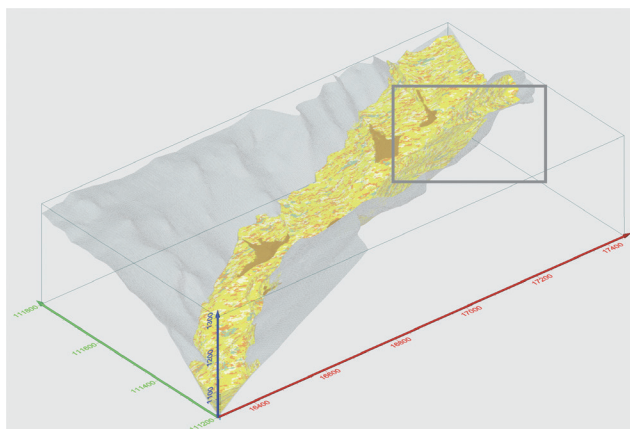
the general project focus was on the sedimentary part of the Padaster Valley aquifer, core drilling data are dominantly available for that part and MPS simulation was confined to a sub-volume bounded by terrain surface at the top and bed rock surface at the bottom. Table 2 gives the geometric properties of the Padaster Valley voxel model: the prismatic model volume has dimensions of 1150m\*660m\*270m (XYZ axes), with the long axis running in E-W direction. A trade-off between realistic reproduction of sediment structures and MPS memory consumption yielded a voxel size of 2m\*2m\*0.5m. This enabled MPS to reproduce minor sediment structures while maintaining a reasonable total voxel number.

- The MPS training image for the Padaster Valley quaternary sediment sequence (Figure 12) is based on high resolution satellite imagery from actuo-geological analogs (Google Earth®: Himalayan periglacials, Pasterze front end) and on available borehole and outcrop data. From the satellite images, spatial statistics on the shape and lateral extents of typical periglacial gravel, sand and silt formations were extracted (Jandrisevits et al., 2014). Furthermore, lateral extents were confined by deriving horizontal directional variograms for each of the four sediment groups. Statistics on bed thickness was obtained from available borehole data. From these informations, a 3D-TI was assembled with an object-based training image generator (Caers, 2011).

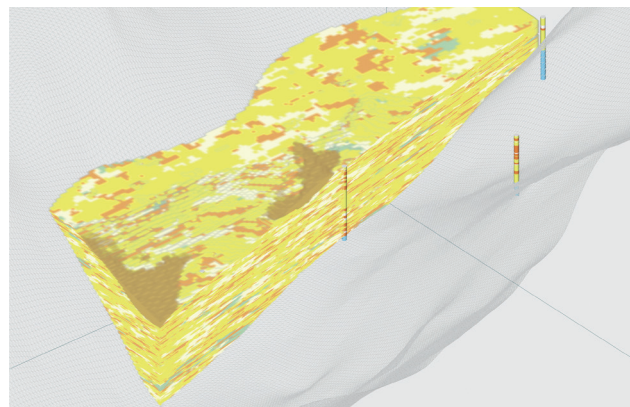
The TI includes, based on above statistics, group 1-4 sediment geometries and also portrays erosion relations. The TI size is 200m\*150m\*40m (X\*Y\*Z) with a spatial resolution of 2m\*2m\*0.5m (Table 2). Figure 12 is an oblique, semi-transparent view of the TI, exposing its internal structure: a matrix of a gravel-dominated sediment with a high portion of fines (group 3) holds intercalated sand beds (group 2) and silt-clay ponds (group 1), all cut by gravel channels (group 4).

MPS was performed with SGeMS v2.5 (Stanford Geostatistical Modeling Software, Remy et al., 2009). Simulation input comprised 4298 data points resampled from borehole and pit logs as well as from geological surface mapping. All input data were assigned to the four sediment groups 1-4 considered above. MPS was run in conditional mode, meaning input data were exactly reproduced at original locations in all simulations. A vertical trend with a decreasing probability of fine-grained sediments with increasing Z coordinate was applied to account for the decrease of silt and clay from bottom to top of the investigation volume, as observed in the boreholes (compare Figure 15). Figure 13 gives the histograms of sediment groups 1-4 in input data and one representative simulation (number 31), showing the almost perfect input data reproduction by MPS. While a single conditional MPS realization can be considered equivalent to an expert's guess of the involved geological geometries, a larger number of MPS realizations also depicts the statistically permissible geometrical fluctuations as derived from the input data and the TI (Caers, 2011). Like in classical geostatistical simulation, this approach allows deriving local probabilities via post-processing – in our case the probability to





**Figure 14:** Simulation volume outlines and voxel model of the Padaster Valley quaternary infill, MPS realization number 31. The simulation volume extends from drilling St-B-09/07 (west) to St-B-04/04 (east). Color coding: white – group 4; yellow: group 3; orange: group 2; green: group 1; brown: alluvial fans. Oblique view from SW, north direction is given by green (Y) axis, axis units are meters. Box refers to position of Figure 15.

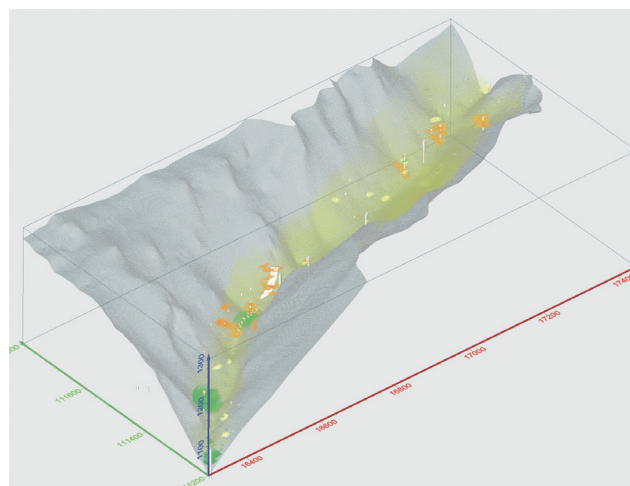


**Figure 15:** Enlarged view of MPS realization number 31 (position see box in Figure 14 same viewing direction). The voxel model was clipped at E-W, N-S and horizontal profile planes to disclose the internal structure. Dimension of visible part of voxel model in E-W direction is 320m. Borehole St-B-28/09 is in the plane of the E-W profile. In Figure 15, next borehole to the right is St-B-29/09, rightmost borehole is St-B-04/04. Color coding same as in Figure 14, blue in boreholes is undifferentiated bed rock. See chapter 8 for details.

meet, in each voxel, a specific sediment group (compare Figure 16). To provide a sound basis for later postprocessing, fifty MPS realizations were computed.

Figures 14 and 15 are oblique views of MPS-realization number 31 that was randomly chosen from the stack of fifty statistically fluctuating realizations. Figure 14 shows the whole simulation volume and the geometry of sediment groups 1-4. The box in Figure 14 gives the location of Figure 15, an enlarged detail in which the voxel model has been clipped along E-W, N-S and horizontal planes. The horizontal section indicates some of the meandering fluvial gravels that cut pre-existing finer-grained material. The vertical E-W and N-S sections expose the extended, horizontal-planar structures of sand benches and the pond-like shapes of fine-grained sediments that decrease in number with increasing Z coordinate. The E-W section cuts core drilling St-B-28/09 to demonstrate the conditioning of the MPS realization: simulated sediment groups and structures adapt to sediment groups 1, 2, 3 as observed in the borehole. 3D models of recent alluvial fans (brown) were derived by geometrical modeling and later incorporated into the MPS model by Boolean operations.

Since the characteristics described above hold for each MPS realization and all realizations are equally probable, statistics at the voxel level can be derived from the MPS data stack via postprocessing. As a basis for stable postprocessing, fifty MPS realizations were computed (computing time about 20 hours/PC with I7 processor, 4GHz clock rate, 64 GB memory, win7). Figure 16 shows the simulation volume and the bedrock surface (grey), the locations of drillings and pits (white) and the postprocessing result. In the matrix of group 3 (transparent yellow), subvolumes of the following sediment types are shown: green – group 1; orange – group 2; light yellow: group 4. In these sub-volumes, postprocessing all 50 realizations yielded convergence towards a specific group



**Figure 16:** Results of postprocessing 50 MPS realizations. Subvolumes with strong convergence ( $p \geq 50\%$ ) of realizations: green – group 1; orange – group 2; light yellow – group 4. Grey: bed rock surface. Oblique view from SW, north direction is given by green (Y) axis, axis units are meters.

with a probability of more than 50%. This is considered a stable prediction of the relevant sediment group.

## 9. Hydrogeological conceptual model for the design of the groundwater monitoring network

Based on the above-mentioned geological model and the MPS results, the following points can be outlined as hydrogeologically relevant issues:

- The western section of the Padaster Valley shows a heterogeneous quaternary fill with thickness increasing from east (20 m) to west (60 m) covering hard rock dominated by calcareous schists.
- The calcareous schists dip medium steep to the NW. Different discontinuities like the schistosity, fractures and faults are present. From packer tests performed in similar

# Geological model of an alpine lateral valley with implications for the design of a groundwater monitoring network – the example of the Padaster Valley (Eastern Alps, Austria)

rocks in boreholes situated close to the Padaster Valley is known that the hydraulic permeabilities of these rocks are generally low, less than

- $1 \times 10^{-8}$  m/s) (Burger et al., 2014). Single discontinuities are responsible for local higher hydraulic conductivities and therefore hydraulic active discrete flow systems.
- This fill consists predominantly of gravel-dominated fluvial sediments and debris flow sediments (group 3 and 4).
- Locally fine-grained layers and lenses of silt and clay (max. thickness of around 1 m, group 1) are intercalated.
- The gravel-dominated sediments include intercalated fine-grained layers of sand and silts (group 2), which cover the gravel over the entire width of the valley, with a longitudinal extension ranging from several decimetres up to several hundreds of meters.

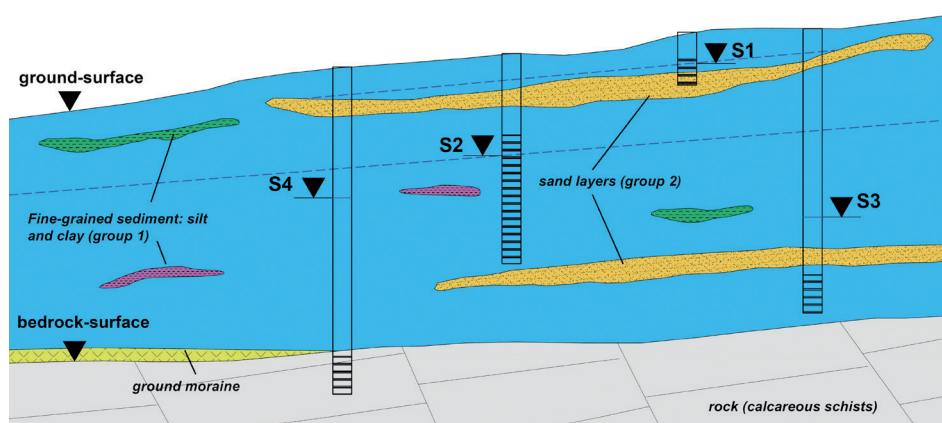
The soft rock infill of the valley is dominated by group 3 and 4. From a hydrogeological point of view, groups 3 and 4 do not appear to be different enough to form separate aquifers, in spite of the varying amount of fines. Thus, it looks like that the sediment of group 3 and 4 form one aquifer with different hydraulic conductivities due to the varying fine content. The

localized fine-grained layers (group 1 and 2) are the determining factor, to form different ground water flow systems. This is underlined by experiences during drilling the boreholes: When drilling the boreholes, varying water levels inside the borehole were measured in the soft rock, even if the core drilling showed a quite uniform sediment.

The following hydrogeological conceptual model based on the geological observations was used to design the groundwater monitoring network (Figure 17):

- System 1: Perched system above lenses and layers of sediment groups 1 and 2
- System 2: Unconfined aquifer in sediments groups 3 and 4
- System 3: Local confined conditions
- System 4: Hard rock with saturated discontinuities

System 2 represents the unconfined (main) aquifer of the valley, including most of the the entire heterogeneous valley infill. Perched systems (system 1) form locally over sand and silt layers that act as a barrier with limited extent. System 3 reflects local confined conditions that are caused by the sand and silt layers acting as hydrogeological aquitards. These confined conditions caused sudden water level rises during drilling.



**Figure 17:** Image showing the hydrogeological conceptual model (any relation of scale) as a basis for the design of the groundwater monitoring. Due to the complex geology groundwater monitoring wells with different depths and various filtering stretches are necessary. The image shows that the fine-grained layers (group 2) have an influence on groundwater behaviour. Significant, large-scale barrier layers dividing the valley groundwater into varying levels are missing here.

System	Groundwater well	Screen section from – to [m b.g.s.]	Water level [m b.g.s.]	Monitoring depth for T and e.c. [m b.g.s.]	T [°C]	e.c. [μS/cm]
1	St-B-02B/04	3-11	4	9	8,7	381
2	St-B-27/09	11-49	10	20	6,5	350
	St-B-28/09	11-44	5,2	20	6,4	335
3	St-B-03B/04	18-30	17	21	6,5	335
	St-B-08/05	27,6-42,6	25,6	35	6,4	348
4	St-B-09/07	54-68	10,5	60	8,6	424

**Table 3:** Selected groundwater wells situated along the axis of the valley at different sea levels: depth of the water table, temperature (T), electrical conductivity (e.c) at specified monitoring depth by the date of 30.08.2010 (b.g.s.=below ground surface)

The hard rock is formed by schists. Discontinuities like the schistosity, fractures and fault zones are saturated in shallow depths and form the system 4. From the water levels (see Table 3) it can be derived, that the flow system 4 drains water into the quaternary infill. Due to the generally low hydraulic conductivities of the hard rock, the amount of water flowing from the hard rock into the quaternary infill is assumed to be low and occur at single local hydraulic active discontinuities.

Monitoring wells with different designs related to the depth and length of the filter sections were set up based on the hydrogeological conceptual model groundwater. The positions of the wells determined by the topographic conditions are shown in Figure 2. The water levels and physical conditions (temperature and electrical conductivity) for representing groundwater wells are shown in Table 3.

The shallow, perched system 1 is monitored by two



groundwater wells. The depth of the monitoring wells ranges from 10 to 11 m with a screen length ranging from 3 to 8 m. The system 1 is characterised by shallow water tables and high temperature and electrical conductivity values (see Tabel 3). The groundwater table of the unconfined (main) aquifer (system 2) is monitored by 7 groundwater wells with depths ranging from 10 to 49 m and is lower than that of system 1. To characterize the physical behaviour (water temperature and electrical conductivity) of the total groundwater body, groundwater wells with long filter section were chosen. The temperature and the electrical conductivity values of system 2 are the lowest of the monitored systems (see Table 3). Locally, due to the extension of fine grained layers in the quaternary infill, confined conditions exist (system 3). The water temperature and the electrical conductivity values of system 3 are similar to system 2. This deep system 3 is monitored by 6 groundwater wells with depths ranging from 30 to 60 m. The lengths of the screen sections vary from 12 to 30 m. The deepest ground water flow system (system 4) is located in the shallow part of the hard rock and is characterized by high piezometric levels and shows the highest temperature and electrical conductivity values (see Tabel 3). For monitoring the deepest groundwater flow system, one 68 m deep groundwater monitoring well with a screen length of 14 m is available.

## 10. Conclusion

The Padaster Valley, an Alpine side valley, has been subject to detailed geological and hydrogeological investigations. Parameters like the depth of the quaternary infill, thickness and extension of the different sediment types are well known from surface outcrops, pits and seismic investigations which are validated by several core drillings. From these data, a multiple-point geostatistics 3D model of the quaternary infill was set up to serve as the quantitative basis for a hydrogeological model.

The geological model for this alpine side valley based on the investigations for planning the disposal site shows the following results:

- Due to the glacial erosion the bedrock surface covered by the quaternary infill is nearly U-shaped and approximately 20-60 m below ground surface, dipping to the West.
- The quaternary valley infill can be divided in 4 different sediment groups:
- Group 1: Fine-grained sediments (silt and clay);
- Group 2: Sand and silt;
- Group 3: Gravels with a wide grain size distribution and a high proportion of fines;
- Group 4: Gravels with a wide grain size distribution, cobbles and a low proportion of fines.
- The three-dimensional model shows an extension of the sand and silt layers (group 2) ranging from 48-80 m to 160-200 m.

The derived hydrogeological conceptual model shows several

groundwater flow systems mainly situated in the sedimentary infill of the Padaster Valley. In the hard rock, discontinuities within the schists of the Glockner nappe define the flow paths. The main aquifer is unconfined and located in the quaternary soft rock sequence where mixed to coarse grained alluvial sediments and debris flows with varying amounts of fine-grained material are intercalated. Layers and lenses of fine grained sediments (silt and clay) are embedded within alluvial sediments and debris flows. Due to both limited thickness and limited lateral extent of the fine grained sediments, separated aquifers with a large extent are not established in the quaternary infill. The fine grained sediments have an impact on the local hydrogeological conditions. However, local perched groundwater systems and local confined conditions in the regional unconfined aquifer are referable to local fine grained sediments with limited extension.

For the groundwater monitoring of the alpine side valley several groundwater wells with different lengths and depths of screen sections are necessary. For the definition of the groundwater monitoring network the conceptual hydrogeological model was essential.

Finally due to the dominance of sediment types group 3 and 4 the alpine side valley is suitable as a disposal site for the projected size. Sediments of groups 1 and 2 at, or close to the valley floor are not appropriate as a foundation surface. Therefore soil replacement is locally necessary before starting the deposition of excavation material. The influence of the disposal on the groundwater body is systematically monitored. Due to the design of the groundwater wells possible influences affecting the groundwater flow systems can be detected. The groundwater monitoring network enables the evaluation of eventual impacts on shallow, perched groundwater bodies to deeper flow systems.

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