GeoExpert ag

GAMANJUNNI ROCK MASS MOVEMENT SITE / KÅFJORD, NORWAY

HYBRID SEISMIC MAPPING OF THE SUBSURFACE STRUCTURES

Data acquisition field work from 6. until 9. October 2016

Report

Client / Project Management

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LIST OF ENCLOSURES

Enclosure N°

A **Gamanjunni situation map** of the seismic lines (not yet available)

In Enclosures 1a, 1b, 2a & 2b the evaluation results are presented as follows:

Fig. 1 p-wave velocity field derived by refraction tomography inversion using the analytical dT-V velocity field as intial model for iterative inversion.

Fig. 2 Hybrid seismic section with analytical dT-V velocity superimposed unto the reflection seismic TWT-depth converted section.

Fig. 3 Tentative (geophysical) interpretation of the hybrid seismic section in Fig. 2

Gamanjunni line 16GAMA-1 (cross line)

1a Fig. 1 & Fig. 2

1b Fig. 3

Gamanjunni line 16GAMA-2 (longitudinal line)

2a Fig. 1 & Fig. 2

2b Fig. 3

APPENDIX Seismic velocities and density of rock types & various types of material

PREAMBLE

List of terms and abbreviations in seismic surveying

Seismic p-wave velocity (v_p)	Propagation velocity of sound in rock material; v_p is directly proportional to the rock/soil strength/rigidity
Seismic velocity field	Distribution of the intrinsic seismic p-wave velocities in the subsurface. The seismic velocity field is derived by the method of seismic refraction diving wave tomography.
Acoustic impedance (Z)	Product of seismic p-wave propagation velocity (v_p) and rock/soil density (ρ); $Z = v_p \times \rho$
WET	Wave path Eikonal Traveltime tomography; iterative modeling algorithm for deriving the continuous seismic velocity field for refraction seismic tomography inversion
Geophone	Device which converts ground movement (displacement) into voltage, which may be recorded at a recording station. The deviation of this measured voltage from the base line is called the seismic response and is analysed for structure of the earth.
x – t domain	2-dimensional plane in which seismic data are presented; the horizontal x - axis represents the profile distance along the surface, the vertical t – axis denotes the traveltime of seismic signals.
Offset	Distance between the seismic source point and a particular receiver station in the active spread
TWT	Two Way Time; time it takes for a seismic (source) signal generated at the surface to travel to the depth of a reflecting interface and back to the surface
CDP / CMP	Common Depth Point / Common Mid Point (for horizontally layered formations CDP ≡ CMP)
NMO	Normal Move Out correction: travel time correction for the horizontal alignment of reflection events situated on a reflection hyperbola in the x-t domain of a field file.
Hybrid seismic section	Joint representation of the seismic p-wave velocity field and the high resolution reflection seismic section.

1. INTRODUCTION

1.1 Survey objectives

A seismic survey is to be carried out for mapping the internal structures of the Gamanjunni rockslide mass in Kåfjord community. The volume of the unstable rock mass is approx. 26 million m^3 with an annual sliding displacement rate of up to 6 cm.

The Gamanjunni's rock slide is classified as a high risk object.

Survey objectives

- the determination of the lateral extension of the deposit
- the determination of the depth of the bottom layer of the rockslide.
- The acquisition and processsing of seismic data according to the hybrid seismic method along one cross line and one longitudinal line.
- Provision of a tentative (geophysical) Interpretation of the processing results

Laying out the seismic recording equipment (geophones, service cables & electronic devices) on the rock slide endangered Gamanjunni slope.

1.2 Method statement of hybrid seismic surveying

The method of **hybrid seismic surveying** is a combination of high resolution ref***lec***tion seismic profiling with the technique of ref***rac***tion seismic tomography inversion, the two most common modern surface geophysical surveying disciplines in civil engineering.

An impact, or controlled vibrations, generated at the earth's surface, produce a seismic source signal, which penetrates the sub-surface as a semi-spherical wave front. At the boundaries between layers, physically defined by acoustic impedance contrasts, the seismic waves are reflected and refracted in analogy with the laws of physical optics. The reflected and refracted signals find their way back to the surface where they are recorded by acoustic sensors (geophones). The lay-out of the geophone receiver units for 2-dimensional surveys commonly is linear at equidistant positions

1.2.1 Refraction seismic surveying / refraction diving wave tomography

Fig. 1 portrays the trajectory of the wave paths of the seismic source signal in the sub-surface. Depending on the ray's angle of incidence with the interface, part of the acoustic energy travels as a totally refracted wave along the interface boundary and continuously emits energy back to the surface.

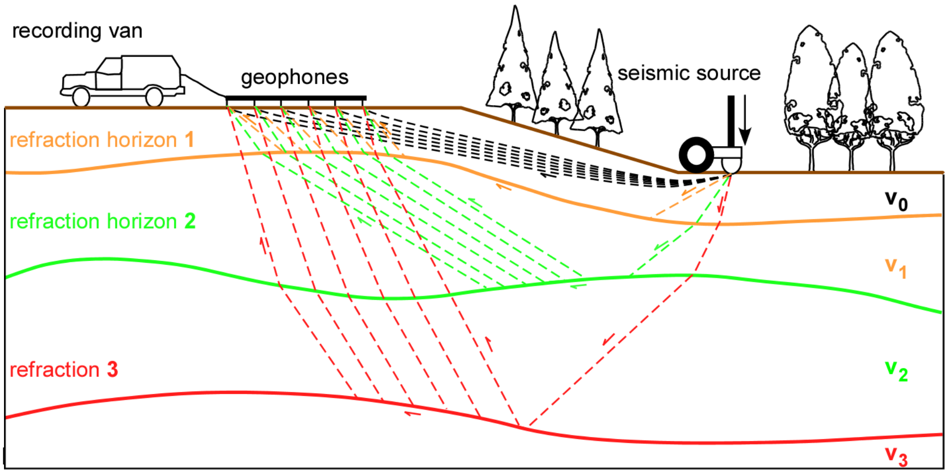


Fig. 1: Seismic refraction ray-path trajectories for a situation with three layer boundaries

On a distance – time diagram, the seismic propagation velocities along the different refraction horizons 1 – 3 are determined (see **Fig. 2** below):

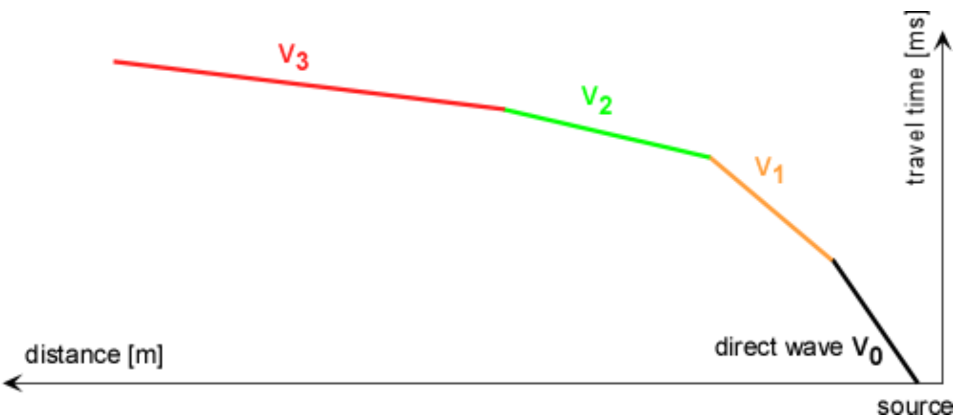


Fig. 2: The 2-dimensional distance – time diagram for deriving the propagation velocities of the seismic signal along the different interfaces of acoustic impedance contrasts.

The method of **refraction seismic tomography inversion**, or **curved ray path tomography** is appropriate for deriving the velocity gradient field under complex geological conditions.

In areas with no sharp velocity contrasts in the subsurface, (i.e. at gradually weathered rock surfaces) or with highly complex sedimentary layer structures, the seismic imaging of velocity horizons with the use of the traditional refraction seismic surveying method is highly inaccurate. Contrary to the derived depth models based on traditional refraction seismic surveys, the results of refraction tomography profiling are not influenced by subjective judgement and are therefore more accurate. The seismic velocity field is a direct representation of the rock rigidity distribution in the subsurface. The velocity gradient field facilitates the identification of lithological layers and the detection of decompaction (i.e. weathered) zones.

The data inversion in a first step is done by the analytical derivation of an initial velocity gradient field using the Delta-t-V **C**ommon **M**id**P**oint (CMP) technique in a 3-dimensional coordinate system (see **Fig. 3**), followed by WET (**W**ave path **E**ikonal travel time **T**omography) iterative finite-element modelling resulting in the final continuous velocity field as portrayed in **Fig. 4**.

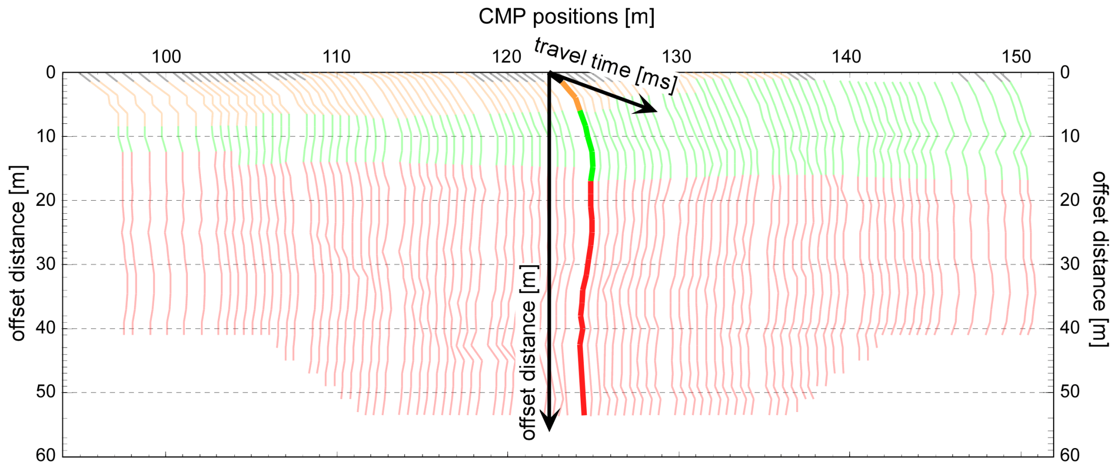


Fig. 3: 3-dimensional Distance-Travel Time diagram at the mid-points between source points and receiver stations are instrumental when using the analytical CMP derivation of the initial velocity field. The horizontal axes are the CMP positions on the surface and the travel time respectively, the vertical axis denotes the offset distance between source and receiver positions.

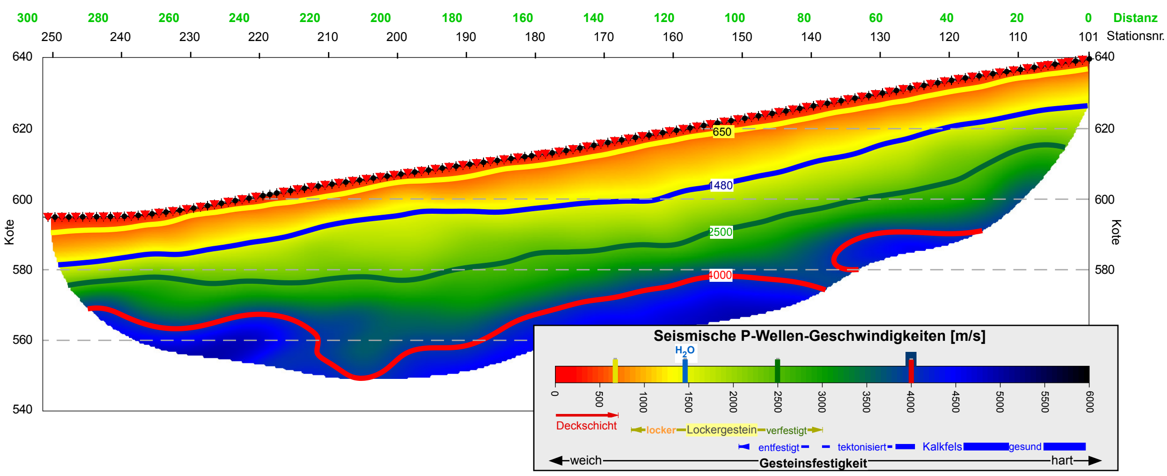
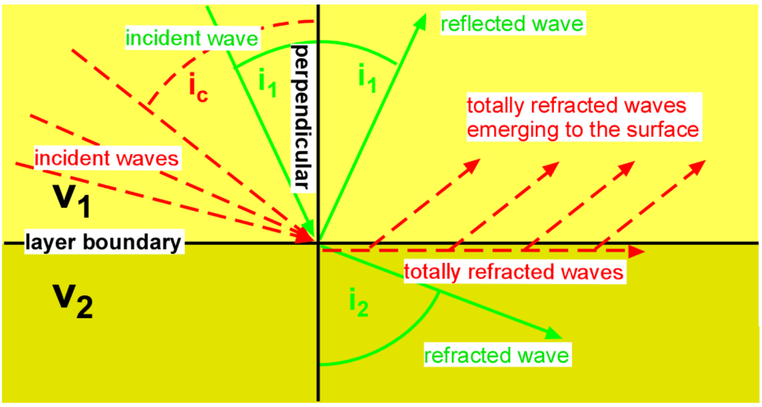


Fig. 4: Distribution of the p-wave velocities as derived by the diving wave tomography technique along a 300m long seismic profile. Since the rock / soil rigidity is directly proportional to the p-wave propagation velocity, the base of the sedimentary overburden as well as decompaction zones in the bedrock are identified.

In analogy with the laws in optics that cause the refraction of rays of light at the boundaries between two layers with differing propagation velocities of light (**Snell's Law** s. **Fig. 5**), seismic rays with an angle of incidence greater than the critical angle from the vertical cannot penetrate the layer below, resulting in the total refraction of the ray at the layer boundary. The totally refracted seismic wave then travels along the surface of the hard layer and continuously emits part of is signal energy back to the earth's surface.

Snell's law of refraction for seismic waves at a layer interface:



$$\frac{\sin i_1}{\sin i_2} = \frac{v_1}{v_2}$$

as a rule: $v_2 > v_1$

Fig. 5: Refraction of seismic raypath at the interface between a soft layer above a hard layer below. The raypath with the angle of incidence i_1 at the interface is deflected from the vertical at a larger angle i_2 from the vertical when it enters the hard layer below with the higher velocity v_2. As the angle of incidence i_1 approaches the critical angle i_c the angle of emergence i_2 becomes 90° with the result that the seismic wave is totally refracted and cannot penetrate the layer below.

1.2.2 Reflection seismic surveying

The underlying principle in reflection seismic profiling is identical with the echo sounder on a ship: A source signal generated at the surface penetrates the ground in a vertical or near vertical direction. At layer boundaries, i.e. at interfaces of velocity contrasts, the signal is reflected back to the surface – as is the case with the signal of the echo sounding device at the sea bottom. Unlike the echo sounding technique, where the transmitter and the receiver are assembled into one unit at the ship's bottom, in seismic reflection surveys there is an arrangement of a large number of receivers (geophones) which record the signal emitted from a single source position (see **Fig. 6**).

The reflection seismic data acquisition procedure is the classical **roll-along** technique: The recording arrangement consists of a number of geophone stations laid out at a regular, equidistant spacing. As with refraction seismic tomography, the seismic source may be of an impact type (hammer, weight dropper) or explosives fired in shallow boreholes. As the source moves up in the working direction of the seismic profile, a number of geophone stations, corresponding to the move-up distance of the source, at the rear end of the spread are disconnected and new stations are activated at the front end. The roll-along technique of recording seismic data may be likened to the locomotion of a caterpillar.

In this manner, reflection points on layer boundaries at various depths in the subsurface are sampled by a multitude of transmitter-receiver configurations resulting in a so-called **multiple coverage** of seismograms at each common midpoint point position.

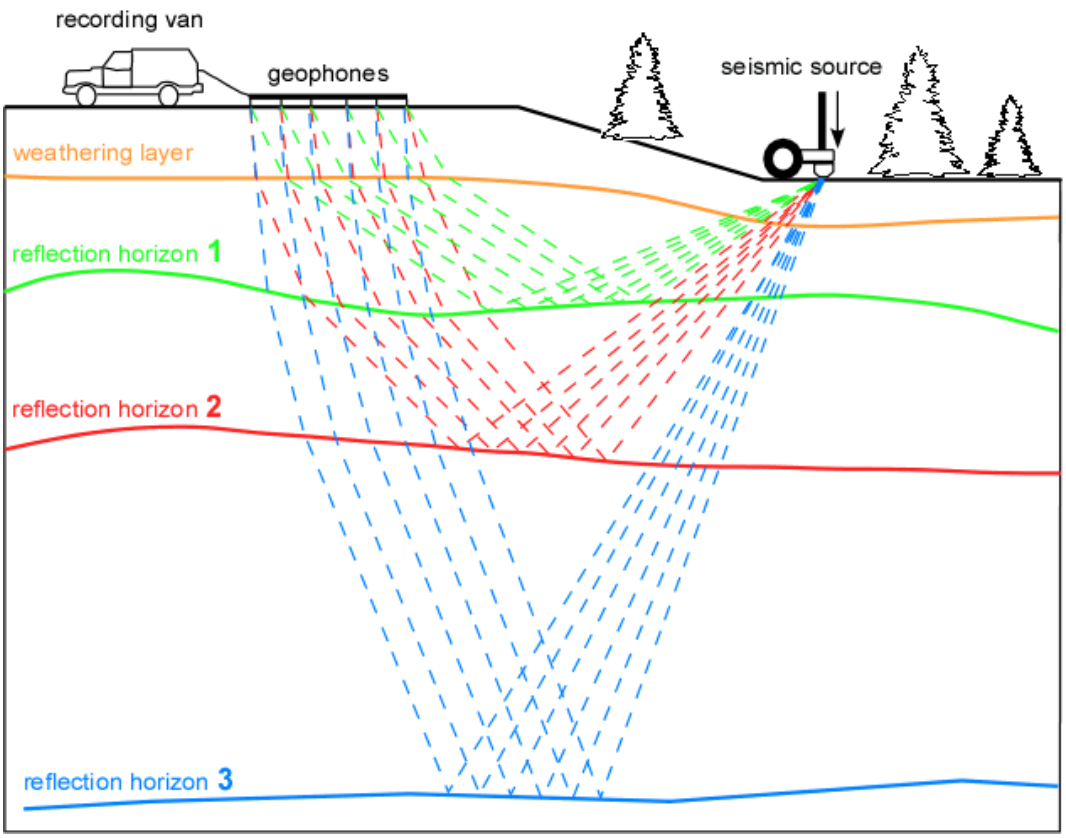


Fig. 6: Schematic presentation of the seismic reflection geometry of ray paths

The data redundancy resulting from multiple coverage seismogram data is instrumental in assembling them into a reflection seismic section which images the subsurface structures as depicted in **Fig. 7** below.

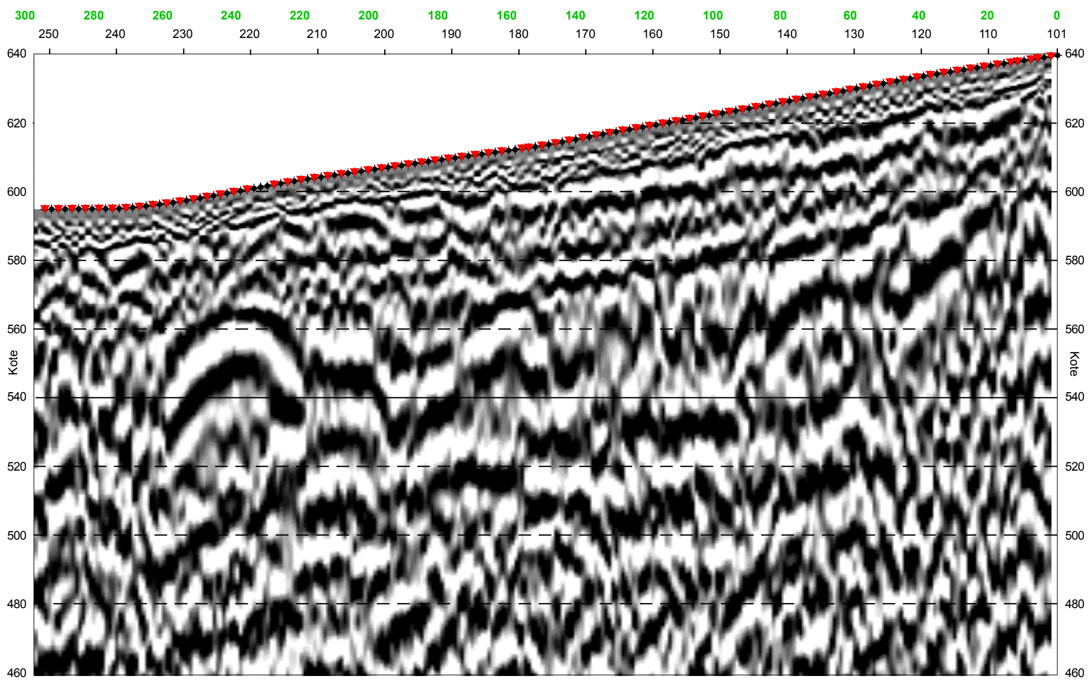


Fig. 7: Reflection seismic depth section as processed from the same data set as the velocty field in Fig. 4.

1.2.3 Hybrid seismic sections

Reflection seismic profiling as well as refraction diving wave tomography inversion, when applied as the sole prospection methods have their undisputed merits, but unfortunately also some short-comings:

Comparative performance summary of refraction tomography surveying and high resolution reflection seismic profiling:

	Reflection seismic profiling	*Refraction seismic tomography inversion*
High resolution at shallow depths (< 10 m)	LIMITED	GOOD
High resolution at greater depths (> 20 m)	GOOD	LIMITED
Depth of investigation	HIGH	LIMITED
Rock / soil quality indicator & rippability	POOR	GOOD
Detection of velocity inversions	POOR	GOOD
Fault zone indicator	GOOD	LIMITED

As an obious conclusion from the above comparison of the capabilities of the two methods, it is desirable to combine their data acquisition and evaluation procedures.

Thanks to the recent technical advances implemented in modern seismic recording instrumentation, the data acquisition for both methods can be combined into one single field operation, which results in a substantial reduction of the costs. By an appropriate joint data processing procedure the full potential of the information contained in the data is being extracted from the data.

Although the results of the reflection seismic data processing and the refraction tomography evaluation are based on the same data set, they are completely independent from each other. By comparing the two evaluation results, they can be used for reciprocal calibration of the two methods, which enhances the reliability of the joint interpretation. As a consequence, the short-comings of one method are compensated by benefits of the other.

An effective direct and comparative correlation is obtained by transparently overlaying the seismic velocity gradient field derived from refraction tomography inversion onto the reflection seismic depth section in **Fig. 8.**

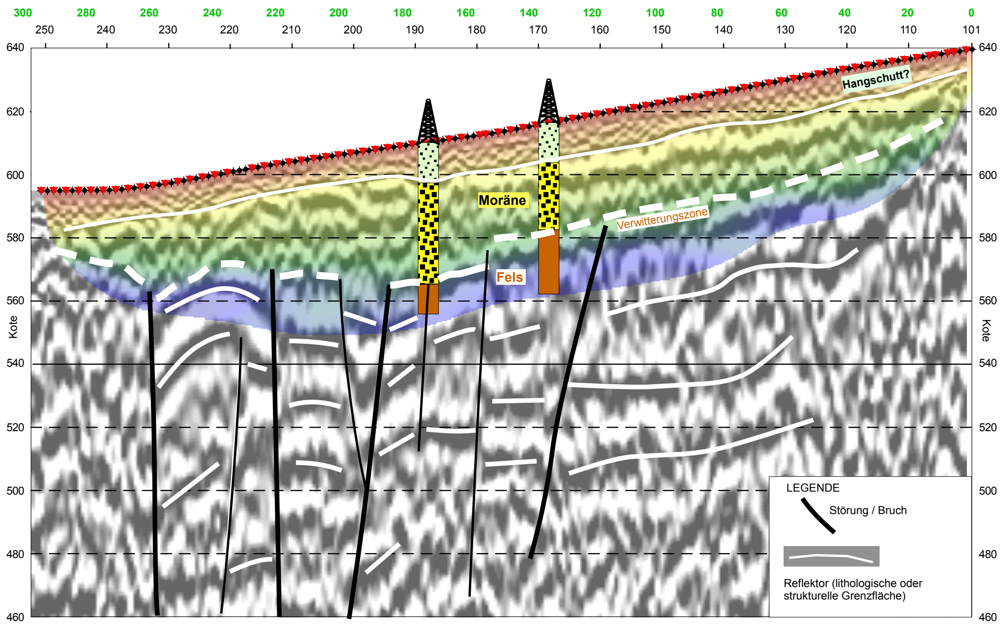


Fig. 8: Interpretation of the hybrid seismic section, the joint presentation of the velocity field in **Fig. 4** and the reflection seismic section in **Fig. 7**

1.2.4 The parameters for optimizing imaging resolution and investigation depth

The resolving power of hybrid seismic sections is directly proportional to the spatial data density defined by the spacing between the receiver stations, and to a lesser extent, by the distance between the source points. The attainable depth of investigation is determined by the length of the active geophone spread.

The smaller the spacing between the receiver stations the higher is the imaging resolution, and the longer the length of the active spread the greater is the attainable depth of investigation.

Therefore, it is mandatory that the data acquisition is carried out with the maximum number of available data channels in order to be able to work with a sufficiently long active spread for the depth range to be investigated.

The following basic rules of thumb apply for high resolution hybrid seismic surveying

1) The receiver station spacing should not exceed 1/60 to 1/20 of the desired depth of investigation (depending on the local conditions, i.e. attainable data quality).
2) The source point distance is to be chosen not larger than 2 – 4 times the receiver station spacing (depending on the local conditions, i.e. attainable data quality).
3) The length of the active spread should be at least three times the desired depth of investigation.

Central recording unit and laptop computer for data acquisition control, data storage and QC.

2 DATA ACQUISITION PARTICULARS / FIELD WORK

2.1 Time schedule

Date	Time / Period	Activities / remarks
29.09.2016	afternoon	Seismic recording equipment handed over to freight forwarder at Zurich Airport
04.10.2016	afternoon	Mobilization of the seismic crew (Zurich Airport - Tromsø)
05.10.2016	morning	Mobilization of the seismic crew (Tromsø - Samuelsberg)
	1215 - 1500	Unpacking of the equipment
	1530 - 1700	Stand-by (the helicopter is not available because of wind)
06.10.2016	0800 - 1200	Stand-by (the helicopter is not available because of wind)
	1215 - 1245	Helicopter transfer to survey site
	1245 - 1600	Seismic spread lay-out on line 16Gama-1
	1600 - 1630	Helicopter transfer to the NVE-base
	1630 - 1700	Briefing and planing for the next day
07.10.2016	0800 - 0845	Helicopter transfer to survey site
	0845 - 1015	Seismic spread lay-out on line 16Gama-1
	1015 - 1045	Instrumentation check
	1045 - 1515	Seismic data recording work on line 16Gama-1
	1515 - 1645	Picking up spread / site clearance
	1645 - 1715	Helicopter transfer to NVE-base
08.10.2016	0800 - 1500	Helicopter transfer to survey site ; transfer of equipment to 16Gama-2 ; lay-out of spread
	1500 - 1530	Instrumentation check
	1530 - 1630	Seismic data recording work
	1630 - 1700	Picking up and charging batteries
	1700 - 1715	Helicopter transfer to NVE-base
09.10.2016	0800 - 0830	Helicopter transfer to survey site
	0830 - 0930	Instrumentation check ; Source crew moves to the line
	0930 - 1100	Seismic data recording work
	1100 - 1430	Picking up spread and site clearance
	1430 - 1515	Helicopter transfer of crew and equipment to NVE-base
	1515 - 1600	Debriefing and organization for travel
10.10.2016	0830 - 1130	Packing of seismic equipment and despatch
	1130 - 2300	Demobilization of the seismic crew (Samuelsberg- Zurich)

2.2 Summary of the seismic data acquisition parameters

Lay-out type	split spread of variable asymmetry
Number of channels	max. 240
Receiver station spacing	2.0 m
Geophone pattern	single geophones
Geophone type	4.5 and 10 Hz
Source point spacing	4.0 – 6.0 m
Source type(s)	8 kg hammer & plate
Vertical stack (8 kg hammer)	2 - 3
Recording Instrumentation	SmartSystem (**www.seismicinstruments.com**)
Sampling rate	0.5 ms
Recording time	1024 ms
Field filters	LC 4 Hz; HC anti-alias

2.3 Composition of the seismic crew

GeoExpert personnel

Romain Bauer	Party chief, seismic observer, spread lay-out
Fabian Isler	Line check, spread lay-out, source activation

NVE personnel

3 - 4 assistants	Spread lay-out, geodetic surveying, source activation, logistic support

Fig. 2.1 Hammer-and-plate seismic source on line 16GAMA-2

2.4 The seismic recording equipment and logistics

1	Seismic data acquisition system SmartSystem; 240 channels, 24 bit A/D-conversion by Seismic Instruments Inc., Austin TX (www.seismicinstruments.com)
1	Laptop computer for data recording, quality control and data storage
12	Seismic geophone strings each with 20 integrated 10 Hz geophones at 2.75 m intervals
10	Line cables (45 - 83 m)
8	Hybrid Smart Line Interface Modules (HSLIM)
4	Battery Boosters
1	Sledge hammer of 8 kg & 1 steel base plate (seismic source set-up)

2.5 The recording conditions for the seismic survey

The weather conditions were favourable during the recording period. Rain and fog occured mainly during the lay-out and the pick-up of the seismic spread.

Due to the irregular and heterogeneous terrain conditions, with boulders of various sizes and loose material, the planting of geophones proved to be not a straightfoward affair, as either small holes had to be drilled for them, or they had to be wedged between boulders with no direct contact with the firm ground (see F**ig. 2.2** below).

Despite of this, the data quality obtained is to be rated – surprisingly - as good to very good and meets the requirements for subsequent data processing.

Fig. 2.2 Typical terrain conditions on the Gamanjunni survey site

3 SEISMIC DATA PROCESSING

3.1 General remarks

- The system **SPW** (Seismic Processing Workshop) of Parallel Geoscience Corporation, Austin TX, was used for processing the reflection seismic data (www.parallelgeo.com).
- The refraction diving wave tomography data processing was carried out using the system **RAYFRACT** of Intelligent Resources Inc., Vancouver Canada (www.rayfract.com).

The most recent versions of both systems have been used for the data processing.

3.2 Seismic reflection and refraction diving wave tomography data processing

Reflection seismic data processing steps

A Data preparation
A1 Reformatting and data verification
A2 Geodetic survey data and recording geometry assignment
A3 Data editing (suppression of dead and noisy traces / pre-trigger delay correction)
A4 Preliminary analysis of refraction velocities

B Signal enhancement
B1 Analytical muting of refraction arrivals
B2 Spherical spreading amplitude correction and amplitude equalisation
B3 Spectral amplitude balancing
B4 Optional predictive or spiking deconvolution
B5 Band pass filtering
B6 Sliding variable window AGC

C Velocity analysis and stack
C1 Common mid-point sort
C2 Semblance velocity analysis
C3 Optional dip-move out correction
C4 Normal Move Out correction
C5 Optional surface consistent residual static corrections
C6 Subsurface consistent CMP trim static corrections
C7 CMP stack
C8 Band-pass filter
C9 Sliding window AGC
C10 Coherency filtering

D Time-depth conversion for final display
D1 Dix conversion of NMO velocities to interval velocities
D2 Optional time migration
D3 Direct time to depth conversion
D4 Topographic static corrections
D4 Final display

Parameter tests are being carried out for each processing step.

Derivation of the seismic velocity field by iterative refraction diving wave tomography

The processing technique of diving wave (or curved ray-path) tomographic inversion is applied to the data. Hidden layers caused by velocity inversion and decompaction zones are detected by using the common midpoint approach developed by Gebrande (Gebrande, H., 1986. CMP-Refraktionsseismik. In: L. Dreses et al.; Symposium "Seismik auf neuen Wegen" sponsored by Dt. Vereinigung d. Erdölgeol. u. Erdöling., Celle, 191-205).

The technique is based on the analysis of the CMP-sorted first arrival time picks in a 3-dimensional coordinate system defined by the x-axis (CMP-positions), the travel time axis and the offset axis (see **Fig. 3.1** below).

The results of the analysis provide a good estimate of the initial model of the velocity gradient field which is then subjected to the iterative tomographic inversion procedure. Usually up to 10 iteration steps are needed for this velocity field smoothing procedure.

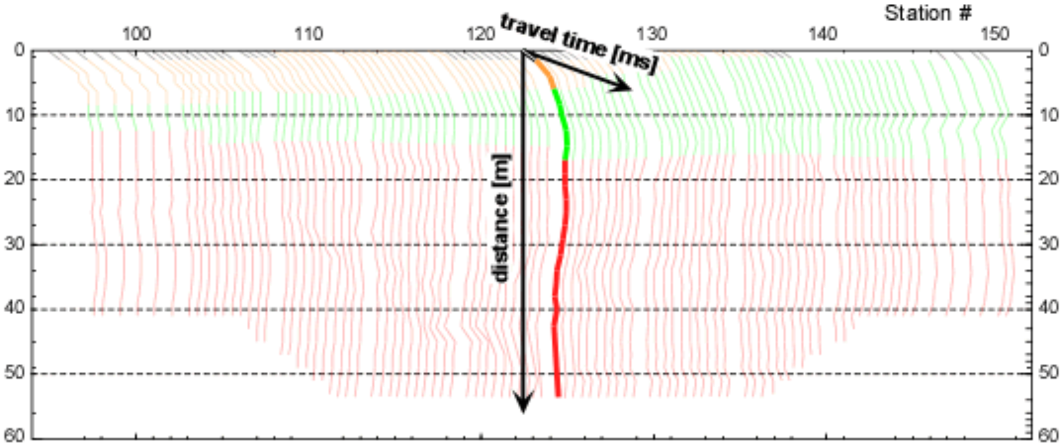


Fig. 3.1 Common MidPoint (CMP) sorted seismic refraction data set arranged in the 3-D coordinate system of a) source – receiver distance (vertical axis), b) CMP station position (horizontal axis), and c) travel time axis.

Sequence of refraction tomography processing steps

<u>A Data preparation</u>

A1 Reformatting and data verification
A2 Geodetic survey data and recording geometry assignment
A3 Data editing (suppression of bad / dead traces, etc.)

<u>B Determination of refraction arrival times and calculation of velocity field</u>

B1 First break picking in the shot domain and optionally in the CMP-domain
B2 Common midpoint sort of time picks
B3 Analytical determination of refraction velocities in the 3-dimensional Time-Offset-CMP domain (dT-V method by Gebrande)
B4 Tomographic inversion of the velocity gradient field by iterative modelling by using the dT-V velocity field as the initial model

3.3 Convention for presenting reflection seismic data

The data in a reflection seismic section are presented as an assembly of individual seismic signals at regular intervals along a seismic profile. The simplest way of representing the signals are single wiggle lines (first to the left in **Fig. 3.2** below). A more capturing presentation is the variable area form (second to the left). Combining these two modes results in the var-wiggle mode. Another method of data visualisation is the variable density mode (second from the right).

The compressional phase of seismic signals is defined in this report as the onset of the positive amplitude excursion in black. Since the source signal is produced by an explosion or by an impact at the surface, the signal starts off with a compression of the ground particles. Thus the arrivals of reflection events are defined by the compressional phase.

In rare situations of velocity inversions, cases in which formation velocities are lower than in the layers above, polarity reversals of the reflected signals occur. The beginning of the reflection event would then be characterized by a dilatational phase, represented in this report as a negative amplitude excursion, i.e. in white.

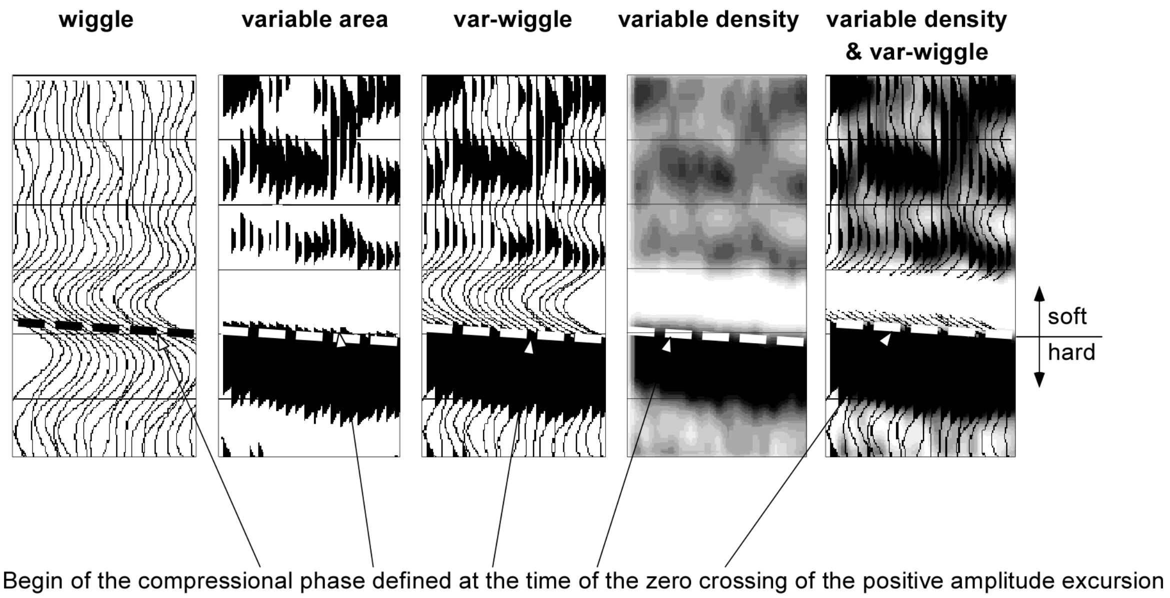


Fig. 3.2 Representation of reflection seismic data and the definition of a reflection event.

3.4 The presentation of the results

The processing results for each seismic line are presented in 3 figures:

Figures 1 *in Enclosures 1a & 2a: "p-wave velocity field derived by refraction diving wave tomography"*

Seismic propagation velocities are directly proportional to the rock strength or the rigidity of soil and rock material. The seismic velocity field enables the geologist or the geotechnical engineer to locate and validate decompacted zones indicating faults or unconsolidated soil conditions. With the help of the colour encoded calibration scale the type of rock and its mechanical properties, such as the degree of weathering or of compaction, can be roughly deduced.

Note: The investigation depth of the refraction tomography method is limited by inherent constraints of method. As a rule of thumb the attainable investigation depth is between one fourth and one third of the length of the active geophone spread lay-out. Thus with a 900 m long geophone spread the attainable investigation depth is between 220 m to 300 m provided the seismic velocities in the subsurface increase with increasing depth.

Figures 1 portray the velocity field after 5 tomography inversion iterations applied on the starting model of the velocity field derived by the analytical dT-V method.

Figures 2 *in Enclosures 1a & 2a:* "Hybrid seismic section with p-wave velocity field dT-V velocity analysis (CMP refraction evaluation)"

This combined representation of the velocity field as derived by the velocity field derived by refraction tomography and superimposed onto the reflection seismic depth section facilitates the comparison and correlation of the results of the two methods.

Figures 3 *in Enclosures 1b & 2b*

A tentative geophysical interpretation by GeoExpert's processing geophysicists has been applied to the hybrid seismic sections of **Figs. 2**. It is is to be regarded as a contribution to a more comprehensive assessment of the situation by a geologist being familiar with the local geological setting.

4 DATA INTERPRETATION AND EVALUATION

4.1 Interpreting seismic data

For the detection of faults and rock discontinuities, being one objective of the survey, a preliminary interpretation based on a visual inspection of the hybrid seismic sections using the CANVAS graphic software package is carried out. The interpretation being of a tentative geophysical nature, no a priori knowledge of the local geology or information from external sources such as borehole logs and core analysis data is taken into account.

For a more comprehensive evaluation the co-operation of a geologist being familiar with the local geological setting is recommended.

4.2 Data quality aspects, pitfalls in seismic interpretation

The factors which degrade the quality of seismic data are the following:

a) Ground unrest from external sources such as civilization noise (traffic, industry, agricultural activities) and unfavourable weather conditions.

b) Unavoidable self generated noise such as ground roll.

c) Contamination by ray path geometry artefacts due to complex subsurface structures

In a complex geological setting as is the case at the Gamanjunni site, and due to the inhomogeneous subsurface structures, the interpreter is confronted with a variety of dipping reflection events, from which he has to discern ray path geometrical artefacts and true events pointing to fault planes.

The illustrations on the next two pages portray interpretational difficulties attributable to ray path geometry aspects. Two pictorial examples of diffraction hyperbolae and horizontal reflection events caused by complex subsurface structures and their contamination effects are presented.

EXAMPLE 1

Diffraction hyperbolae occur at any material and structural discontinuity such as at sharp ledges and at fault outcrops.

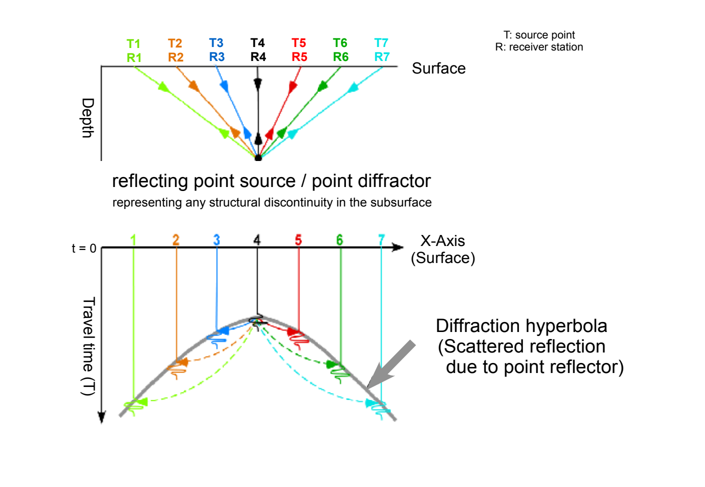


Fig. A Seismic waves originating from points T1 - T7 are scattered at the point reflector in all all directions (according to the Huygens' prinicple) and recorded at the receiver stations R1 - R7 (upper diagram).

The arrival times of the reflected signals vary due to the variable distances from points 1 - 7 to the point diffractor.

In the X-T plane (lower diagram) the scattered signal arrival times lie on a hyperbola shaped graph.

This **diffraction hyperbola** is a geometrical artefact, and is regarded as undesirable noise, which most often masks useful reflection events at greater depths.

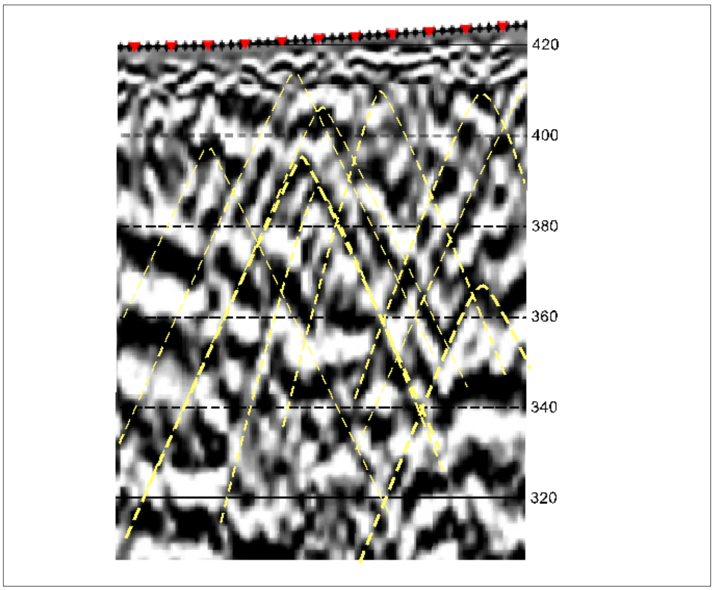


Fig. B Example of an 80 long segment of a seismic section being severely contaminated by numerous diffraction events due to the intensely karstified subsurface.

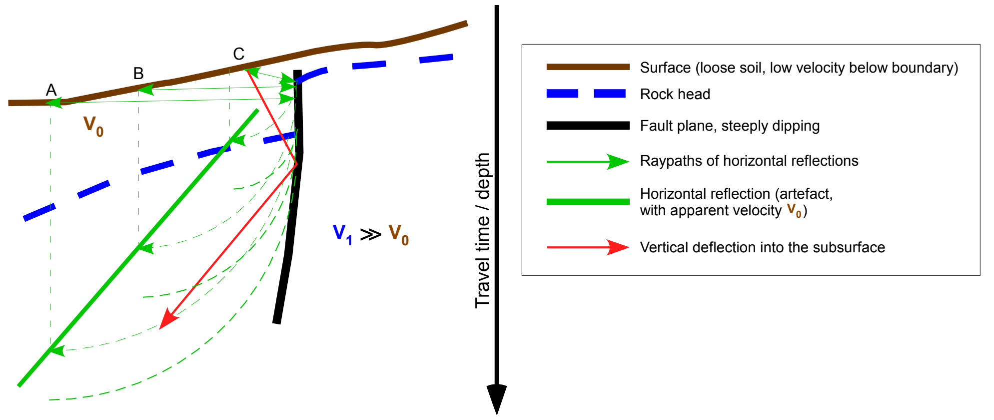
The amplitudes of the steeply dipping legs of the diffraction hyperbolae often are very prominent. They sometimes completely mask useful reflection signal events.

The degree of contamination caused by diffraction hyperbolae is directly proportional to the complexity of the subsurface structures.

One of the most difficult tasks for the seismic interpreter is not to confound diffractions with actual fault planes.

EXAMPLE 2

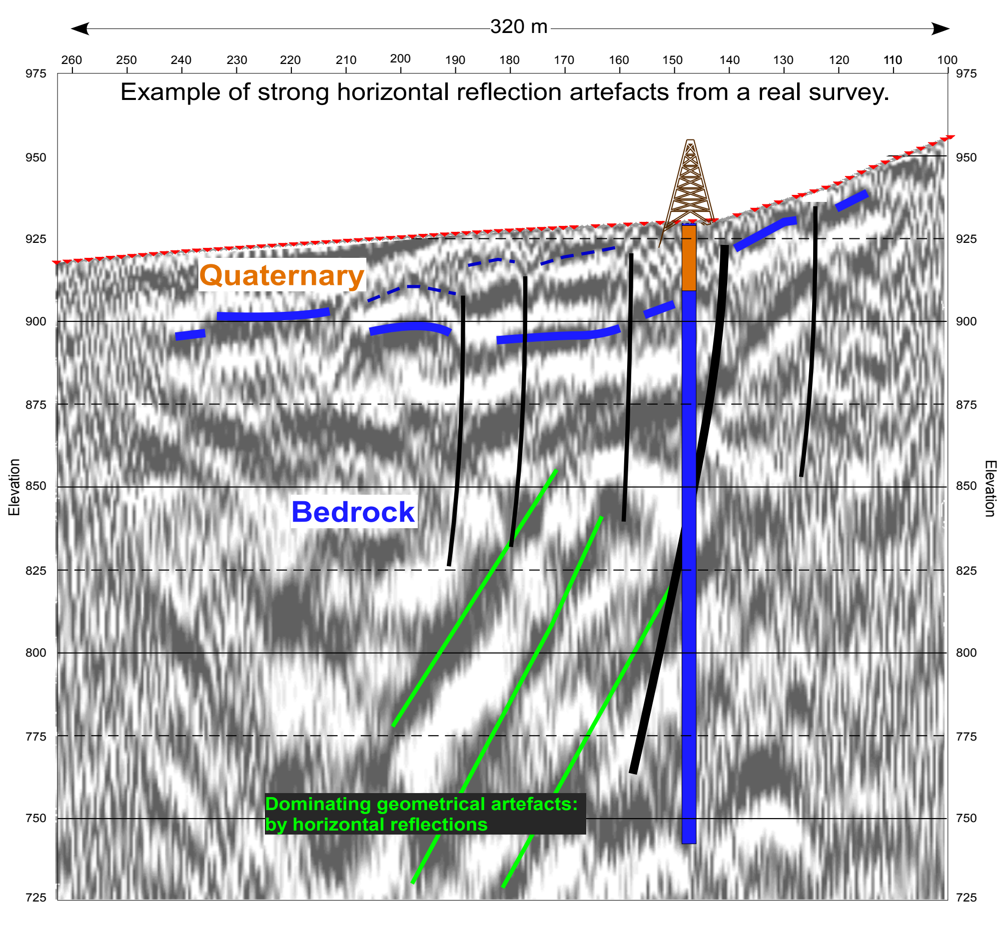
Geometrical ray path artefacts caused by ***horizontal reflections*** at vertical faults:



Horizontal reflections from steeply dipping faults may cause undesired geometrical artefacts.

Signals emitted from positions A - C bounce back at the fault plane within the overburden low velocity layer.

The horizontal reflection from the vertical fault is represented on the seismic section as a dipping reflector artefact with an apparent velocity corresponding to the seismic velocity of the overburden layer (continous green line).



4.3 Brief discussion of the results

The subsurface of the investigated area is characterized by intense tectonic activity with numerous faults and fold structures on a small scale.

Due to the irregular topography of the bedrock surface and the heterogenous composition of the unstable rock mass, the latter being made up of boulders of variable sizes, an assessment of its volume is doomed to be inaccurate. This holds particularily for profile 1, on which the boundary between the bedrock in place and the overburden of debris and loose boulders is be suspected to be situated along the 2500 m/s iso-velocity contour line as shown in Enclosure 1b (dashed red line).

This method of identifying the bedrock surface is also applicable for profile 2 for the line segment above the intersection with profile 1 at geophone station 203 (see Enclosure 2b).

On profile 2 the prominent, decompaction zone between geophone stations 160 and 220, which extends to a depth of > 100 m below the surface, is to be attributed to a major fault system of the cauliflower type as depicted in Enclosure 2b.

5 CONCLUSIONS AND RECOMMENDATIONS

- On the Gamanjunni mass movement endangered slope, the data of two seismic profiles, intersecting perpendicularily at their midpoints, and with a total length of about 900 m, were recorded, processed and interpreted.

- The purpose of the survey is to map the internal structures of the unstable rock mass, particularily its thickness. In addition, information about the degree of tectonisation of the bedrock sub-surface is to be provided.

- It is assumed that the bedrock surface is to be situated along the 2'500 m/s iso-velocity contour lines on the interpreted seismic sections in Figs. 1b and 2b.

- The bedrock in the area investigated is to be characterized as intensely tectonized with small scale fold structures and numerous faults.

- A prominent tectonic fault system oriented in North-South direction is to be associated with a decompaction zone extending to depths of more than 100 m below the surface (see interpretation in Enclosure 2b). .

- For additional investigation of the subsurface by using surface geophysical methods we recommend the hybrid seismic technique as described in this report.

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