Hybrid seismic surveying for detailed characterization of the shallow and intermediate depths subsurface

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Summary

Conventional reflection seismic velocity analysis tools invariably provide unsatisfactory results when applied to seismic data acquired for mapping complex subsurface structures in the near surface depth range until 300 to 500 m.

The method of hybrid seismic surveying, a combination of high-resolution reflection seismic profiling with seismic refraction tomography inversion, overcomes this drawback by extracting more accurate information from the refraction seismic velocity field to be used for the derivation of stacking velocities and of time-to-depth conversion velocities in reflection seismic data processing.

Reciprocal calibration of the seismic reflection and refraction tomography results is instrumental for obtaining spatial imaging congruency resulting in the spin-off product of the best fitting velocity information possible.

In opposition to the conventional "deep target" reflection seismic data processing sequences, the application of weathering and elevation field static corrections is integrated in the steps of NMO correction and final post stack time-to-depth conversion.

Hybrid seismic sections jointly image the subsurface structures and also characterize the stiffness of soil and rock layers. The method can be extended by complementary seismic shear wave refraction tomography data acquisition and inversion for the non-invasive and in-situ derivation of spatially continuous dynamic elasticity parameters such as E-modulus 2D sections.

Guidelines are specified as to the choice of the data acquisition parameters for optimal reflection seismic imaging resolution and for attaining maximum seismic refraction tomography investigation depth.

1. Generic description of hybrid seismic data processing

In Figure 1 to the right, the seismic velocity field is derived by seismic refraction tomography inversion (**1**) from a data set acquired in a single field operation using recording parameters for high reflection seismic resolution, such as small geophone station spacings, and an adequately long active spread lay-out designed for maximum refraction depth penetration.

The velocity information thus obtained is used for NMO correction, common depth point (CDP) stacking and time-to-depth conversion in the reflection seismic data processing flow (**2**).

The refraction tomography velocity field (**1**) is transparently overlain onto the reflection seismic depth section (**2**) for visual correlation purposes, resulting in a hybrid seismic section (**3**), which is then subjected to geological-geotechnical interpretation (**4**).

With hybrid seismic surveying, structural details such as tectonic faulting and depositional layering are portrayed simultaneously with geomechanical rock properties.

The results of (**1**) and (**2**) are completely independent of each other, which reduces the danger of interpretational uncertainties and ambiguities.

2. Prerequisite of spatial congruency

In authentic hybrid seismic data processing, the imaging results of refraction tomography (**1**) and of seismic reflection profiling (**2**) are reconciled by reciprocal calibration for obtaining spatial congruency.
The latter is a measure of accuracy of the derived velocity field (see Fig. 2 on next page).

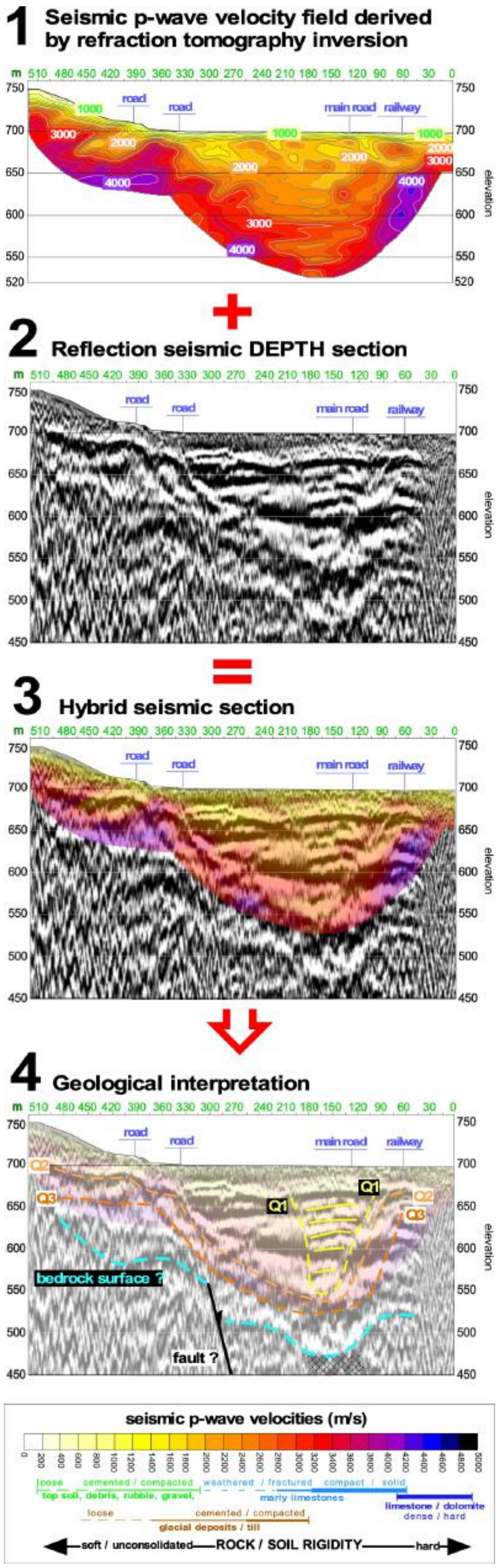

Figure 1: Hybrid seismic data evaluation flow

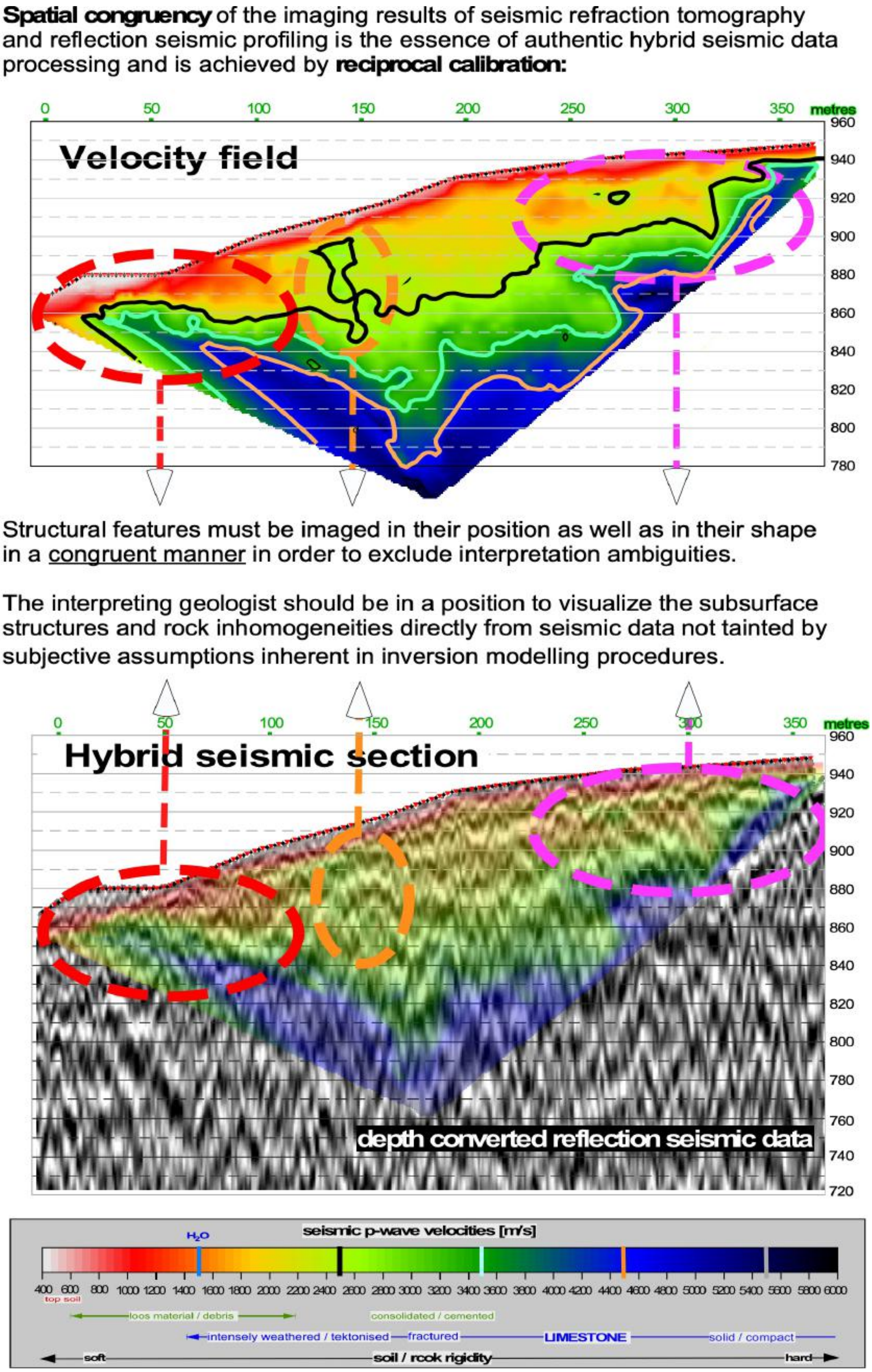

Figure 2: The principle of spatial congruency of the refraction and reflection imaging results

3. The application of static corrections in the reflection seismic data processing flow

In conventional standard reflection seismic data processing, field and residual static correction techniques are used routinely for processing deeper data and are based on the assumption that two-way-time (TWT) anomalies for reflection events below the surface layers are to be attributed to irregularities of the surface topography and/or to strong lateral and vertical velocity variations near the surface. These TWT static-correction values applied to each individual trace within a common-depth-point (CDP) gather are instrumental in obtaining the sharpest possible reflection event on the stacked CDP traces – alas at the expense of the imaging resolution at shallower depths. The collateral damage thus caused by applying these TWT corrections to the entire individual seismogram is that all relevant information in the near surface depth range – which is of interest to the engineering geologist or geotechnical engineer – is corrupted.

In hybrid seismic surveying, no static corrections of any type are applied before CDP stacking. The zero time line refers to the surface relief, no matter how irregular the terrain elevations may be. The field weathering static corrections compensating for near surface velocity anomalies are integrated in the NMO correction by taking into account the velocity function as extracted from the refraction tomography velocity field at each CDP position. Surface elevation statics are applied after time-to-depth conversion of the TWT stacked section. The result is a seismic reflection depth section with structural information from the very surface, which is to be jointly presented with the refraction tomography velocity field as a hybrid seismic section (see Figures 1 and 2 above).

4. Spatially continuous dynamic elasticity parameters derived by hybrid seismic surveying

Quantitative determinations of geotechnical elasticity parameters of Young's **E**-modulus, shear modulus **G** and Poisson's ratio ν are usually carried out either by laboratory analysis of rock samples from boreholes or obtained from the results of bore hole geophysical wire line logging surveys. The measured parameters needed are the propagation velocities both for P-and S-waves (V_p & V_s) and the rock/soil density ρ.

Complementary S-wave refraction tomography inversion to P-wave hybrid seismic surveying is highly beneficial for geotechnical construction site characterizations for the following reasons:

- The P- and S-wave velocity parameters (V_p & V_s) are of the in-situ type since they have been recorded in an undisturbed environment;
- V_p & V_s velocity fields are recorded along seismic transects, dynamic rock elasticity parameters (for example Youngs' E-modulus) derived are spatially continuous and portrayed as 2D depth sections;
- Surface based non-invasive seismic probing methods are considerably less costly than wire line logging surveys and rock samples collected at discrete bore hole locations.

See Figure 3 on the next page.

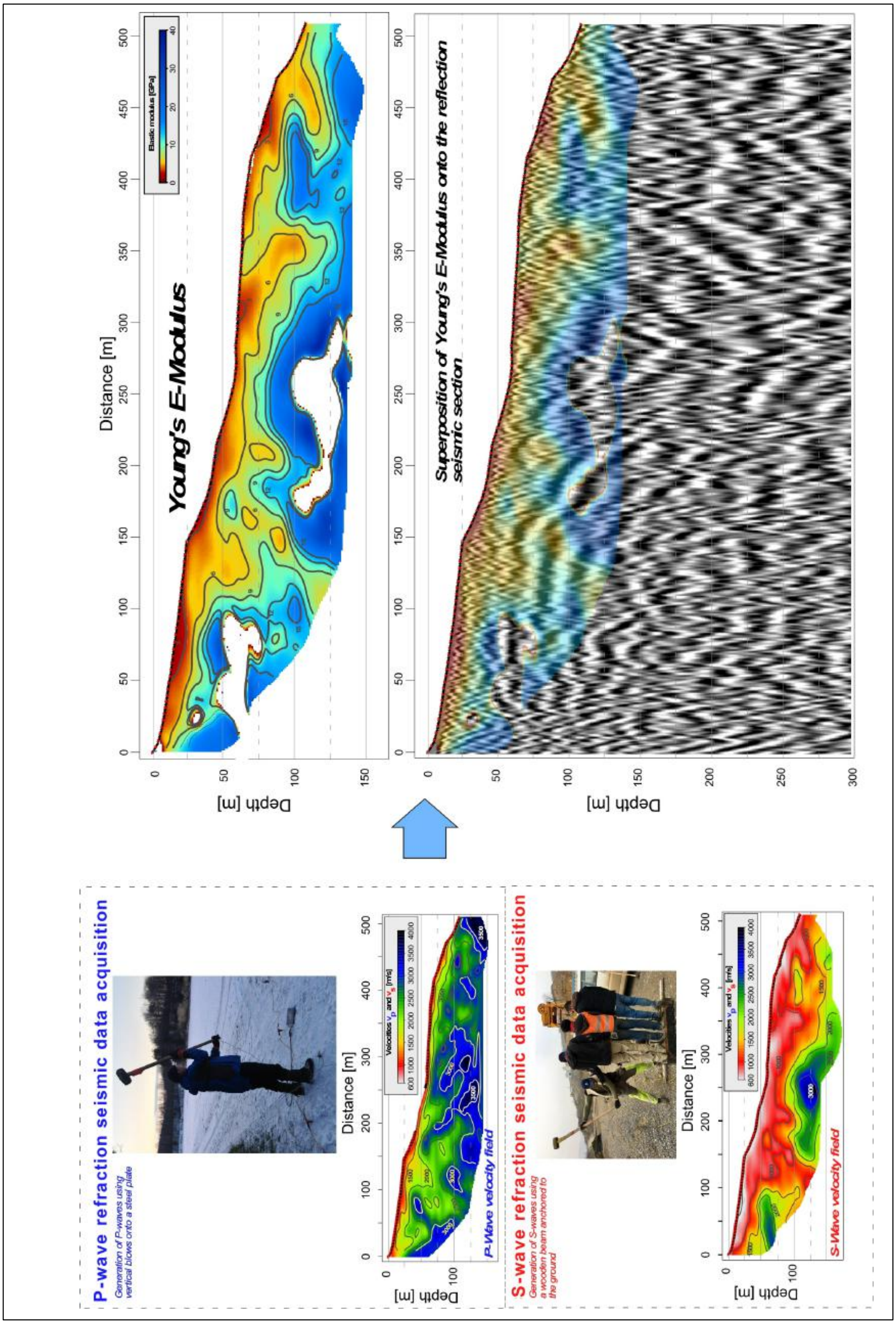

Figure 3: Hybrid seismic non-invasive and spatially continuous geotechnical ground stability assessment by derivation of a 2D E-modulus section.

5. Data acquisition parameters for optimizing imaging resolution and depth of investigation

The resolving power of reflection seismic data is proportional to the spatial data density, defined by the spacing between the receiver stations and the separation between the source points. The smaller the separation between the geophone stations, the higher is the imaging resolution of the seismic data.

The attainable depth of seismic refraction tomography, on the other hand, is a function of the length of the active spread lay-out.

Therefore, even with small receiver spacings, it has to be ascertained that a long enough active spread is to be laid out for attaining the desired investigation depth. For this reason an adequate number of data channels and geophones are mandatory.

Based on the desired depth of investigation, the following basic rules apply for acquiring hybrid seismic data for ensuring an adequate reflection seismic data density and an optimal refraction tomography investigation depth:

1. The receiver station spacing should not exceed 1/50 to 1/30 of the required depth of investigation (depending on the locally attainable data quality and the complexity of the subsurface structures).

2. The length of the active spread should be at least 3 - 4 times larger than the desired depth of investigation.

3. The source point distance is to be chosen not larger than 1 – 3 times the receiver station spacing (depending on the locally attainable data quality and on the complexity of the subsurface structures).

Working example based on the above given rules for a desired investigation depth of 100 m:
- A receiver station spacing of 2 m is appropriate (see rule 1. above).
- The spread length must be 300-400 m, which means that with a geophone spacing of 2 m, the active lay-out is to consist of 150-200 geophones, which means that a recording seismograph should feature this number of data channels (see rule 2. above).
- The source point distance should not exceed 6 m. Under very difficult conditions 2 m – 4 m is preferrable (see rule 3. above).

The use of staggered successive roll-along recording cycles with a move-up distance of half a spread length is recommended, as pictured in Figure 4 below:

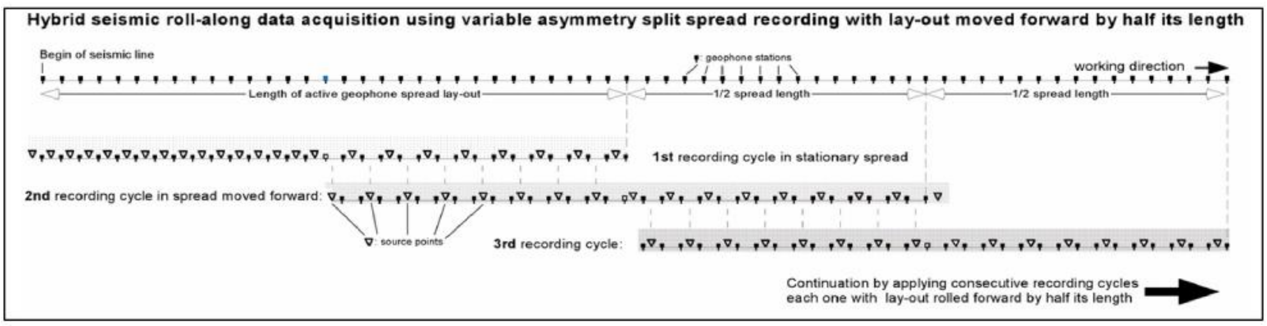

Fig. 4: Schematic roll-along recording procedure for full coverage of maximum source – receiver offset data along seismic transects being several times longer than the active spread lay-out.

Recording cycle 1: Start recording in the first spread position with regular source point distances until the center of the spread. Then continue recording with twice the source point distance until the far end of the spread.

Recording cycle 2: Move the entire active spread forward by half its length and relocate the source (hammer or weight dropper) back to the rear end of the spread now in its new, second position. Continue recording at the source points at twice the source point separation distance and between the source point positions activated in cycle 1.

Recording cycle 3: As in cycle 2, move the spread forward by half its length and relocate the source back to the rear end of the spread now in its new, third position. Continue recording as in cycle 2 at every second source point.

Subsequent recording cycles are identical to cycle 3. Make sure that in the last recording cycle of the line regular source point distances are observed over the entire length of the geophone spread.

This staggered roll-along scheme of semi-stationary spreads (Fig. 4) has the advantage that in each cycle maximum offset data both in the forward and reverse directions are obtained for continuous maximum refraction tomography investigation depths.

6. Conclusion

High resolution reflection seismic profiling combined with refraction tomography inversion is a universally applicable tool for mapping shallow subsurface structures down to depths in the order of 500 m.
Detailed velocity information obtained from the refraction tomography velocity field is indispensable for processing reflection seismic depth sections. In hybrid seismic surveying the disadvantanges of one method are compensated for by the benefits of the other.

Apart from the substantially lower costs by reducing the data recording work to one single field operation, the major advantage is to be seen in the enhanced interpretation reliability gained by the joint presentation of the results of the two methods, which are completely independent of each other.

Hybrid seismic surveying maps in great detail structural features in a joint image with the rock/soil rigidity parameters.

The hybrid seismic method can be extended to include shear wave refraction tomography for generating spatially contiuous dynamic elasticity E-modulus 2D sections for geotechnical site characterizations.

Time lapse application of hybrid seismic surveying is an appropriate technique for monitoring alterations of rock mechanical properties around repositories.

References

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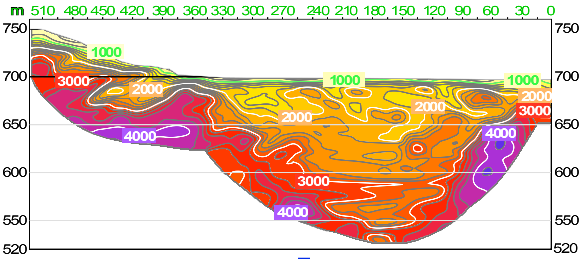
Hybrid Seismic Characterization of Shallow and Intermediate Depth Surbsurfaces

A) Hybrid Seismic Data Processing and Evaluation Flow

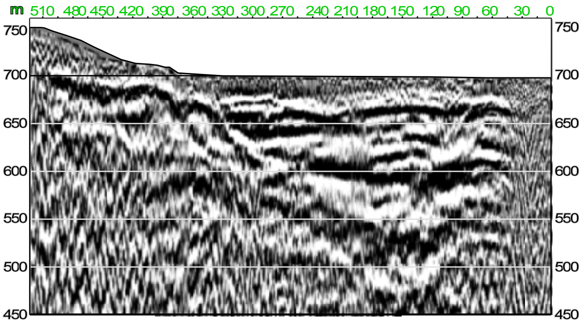
Seismic refraction tomography inversion is combined with high resolution reflection seismic profiling by extracting accurate seismic velocity information for the derivation of reflection seismic stacking and time-to-depth conversion velocities.

The joint representation of the reciprocally calibrated refraction and reflection imaging results enables the geologist to better steer clear of interpretation pitfalls and to exclude ambiguities.

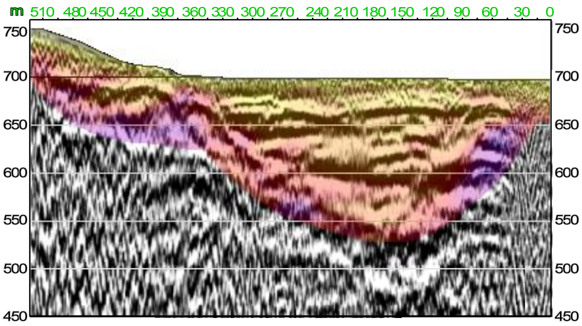
1 Seismic p-wave velocity field derived by refraction tomography inversion



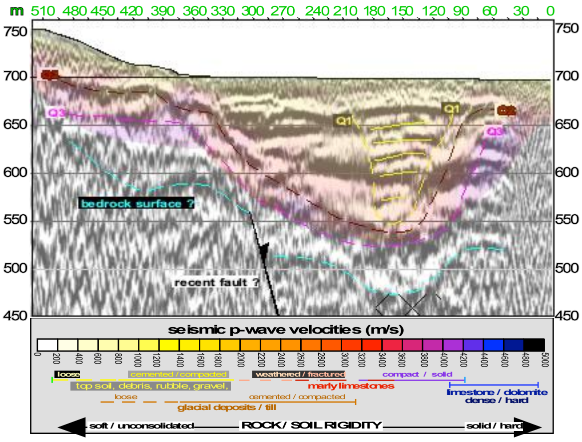
2 Reflection seismic DEPTH section



3 Hybrid seismic section

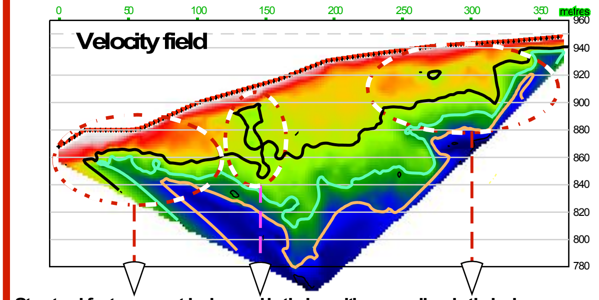


4 Geological interpretation



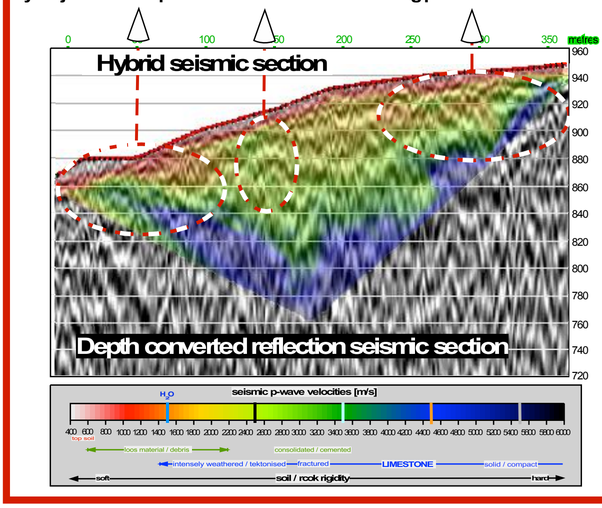
B) Key Issue is Spatial Congruency of Reflection & Refraction Imaging Results

Spatial congruency of the imaging results of seismic refraction tomography and reflection seismic profiling is the essence of authentic hybrid seismic data processing and is achieved by reciprocal calibration.



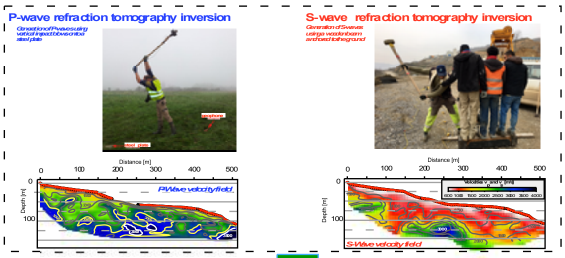
Structural features must be imaged in their position as well as in their shape in a congruent manner in order to exclude interpretation ambiguities.

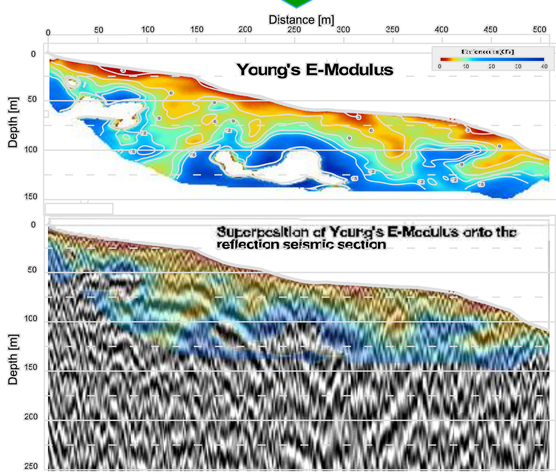
The interpreting geologist should be in a position to visualize the subsurface structures and rock inhomogeneities directly from seismic data not tainted by subjective assumptions inherent in inversion modelling procedures.



C) Derivation of Dynamic Elasticity Moduli

Hybrid seismic surveying complemented by shear wave refraction tomography inversion is instrumental for the in-situ and non-invasive derivation of spatially continuous 2D elasticity moduli sections.





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