Geophysical methods for rock engineering – an overview

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1 Introduction

Geophysical methods are used in rock engineering for two major purposes:

- Determination of physical rock or rockmass properties
- Exploration of underground structure incl. prospection of deposits

Geophysical methods can be applied at different scale:

- Small scale: lab samples (typically: cm- to dm-range)
- Medium scale (typically dm- to decameter-range)
- Large scale (decameter- to km-range)

Small-scale lab tests are used to determine physical rock properties. They are typically performed on rock samples obtained from boreholes, mines, tunnels, outcrops etc. The samples have to be prepared (shape-designed, dried or saturated etc.) to perform the measurements.

Medium-scale field testing comprises borehole logging as well as specific local land geophysical testing like near-field investigations at excavation surfaces. The aim is the determination of rockmass properties as well as a detailed analysis of the local geological structure (stratigraphy).

Large-scale field measurements are used to investigate the geological structure (faults, geological layering etc.) as well as overall rockmass properties.

Takahashi et al. (2004, 2006) have published ISRM suggested geophysical methods for land and borehole geophysics in rock engineering. They explain typical measuring layouts incl. data handling and interpretation.

Please note the following: geophysical methods determine quantities of different physical fields and – in most cases – do not deliver the required geotechnical or geological parameters directly. That means: the geophysical measured quantities have to be interpreted, which can make the result questionable. Often a correlation with results from boreholes is necessary. Also, according to the scale and parameter of measurements the resolution and corresponding scatter has to be considered carefully. Nevertheless, geophysical methods are a very valuable tool in rock engineering.

The topic ‘seismic / seismoacoustic monitoring’ is described in the ebook entitled “Dynamic events in rocks / rock masses”.

2 Classification

There are different possibilities to classify geophysical measurements. One possibility is to distinguish between:

- Active measurements (physical fields are produced artificially)
- Passive measurements (existing physical fields are used)

Another possibility if to distinguish between the different physical fields under investigation:

- Seismic methods (wave velocity)
- Gravimetry (density)
- Electro-magnetic methods (electrical resistivity / magnetic susceptibility / dielectric constant)
- Radiometric methods (neutron- and γ-radiation)

Also common is to distinguish between the places of installation:

- Ground-based measuring (at the surface)
- Borehole logging
- Combination of ground-based measurements with borehole tools

Tab. 2.1 provides a general overview about the basic geophysical properties for different geomaterials.

Tab. 2.1: Average values of geophysical properties (Erkan, 2008)

	Material[#]	Density (g/cm^3)	Magnetic Susceptibility ($\mu / \mu_0 - 1$)	Log Resistivity (Ohm-m)	Dielectric constant ($\varepsilon / \varepsilon_0$)	Seismic velocity (km/sec)
Various	Air	0.001	0	15	1	0.3
	Water	1.0	$-7x10^{-10}$	0-2	80	1.4-1.5
	Ice	0.9	$-7x10^{-10}$	6	3-4	3.4
	Oil	0.6-0.9	$2x10^{-5}$	14	2	1.3
	Salt	2.2	$-1x10^{-6}$	15	6	4.5-5
Unconsolidated Sediments	Soil	1.5	$7x10^{-4*}$	3	4	0.1-0.2
	Clastics	1.9	$5x10^{-4*}$	3-4	4	1-2
	Sand	1.6	$5x10^{-4*}$	4	4	3
Metal Ores	Oxides	3.8-9.1	$3x10^{-3}$	(-1)-2	10-25	5.8
	Sulfides	3.8-8.1	$3x10^{-3}$	(-6)-(-3)	8-31	5.5
Sedimentary rocks	Sandstone	2.2	$4x10^{-4*}$	2-3	5	2-6
	Shale	2.1	$6x10^{-4*}$	0-1	6-8	2.3
	Limestone	2.7	$3x10^{-4*}$	2-3	8-9	3-6
Igneous Rocks	Granites	2.6	$2x10^{-3*}$	4-6	5	5-6
	Basalt	3.0	$7x10^{-2*}$	7	12	5-6
Metamorphics	All	2.6-2.7	$5x10^{-3*}$	3-5	8-10	5.5-6

Anderson (2006), Coe (2018) as well as Adewuyi & Ahmed (2019) provide an overview about the different geophysical methods used in geotechnical engineering.

Tab. 2.2: Application of different geophysical methods to solve geoengineering tasks: M = major application, X = minor application (Anderson, 2006)

Application	Seismic Refraction	Seismic Reflect.	Seismic Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.
Locating buried drums, pipelines and other ferromagnetic objects			M	M				M		
Locating buried non-magnetic utilities			M							
Locating buried non-magnetic utilities				M						
Mapping archeological sites (buried ferro-magnetic objects, fire beds, burials, etc)				M	M				M	
Mapping archeological sites (non magnetic - excavations, burials, etc)				M						
Concrete integrity studies and inspection				M						
Detection of delamination and incipient concrete spallage on bridge decks				M						
Locating rebar in concrete				M	M				M	
Detection of corrosion of rebar embedded in concrete				M						
Evaluation of presence, pattern and density of rebar embedded in concrete destined for demolition				M	x				x	
Pavement integrity studies				M						
Detection of voids beneath pavement				M						
Detection and delimitation of zones of relatively thin sub-grade or base course material				M						
Detection and monitoring of areas of insufficiently dense sub-base				M						
Large-area differentiation and monitoring of insufficient thickness of pavement as a quality assurance measure during construction				M						
Large-area differentiation and monitoring of insufficient pavement thickness as post-construction monitoring technique				M						
Detection of bodies of sub-grade in which moisture content is anomalously high, as a precursor to development of pitting and potholes				M						
Mapping/locating landfills	x			x	M	x			M	
Determining in-situ rock properties (bulk, shear and Young's moduli)	M		M							
Estimating in situ rock properties (saturation, porosity, permeability)					M	M				
Determining in situ rock densities										M
Determining in situ rock properties (dielectric constant)				x						
Mapping abandoned, in-filled open-pit mines and quarries	M	M		x	x	x			x	x
Mapping abandoned underground mines		M	x			x				
Detecting abandoned Mine shafts		x	x	M	M	x			x	

Tab. 2.3: Application of different geophysical methods to solve geoengineering tasks: M = major application, X = minor application (Anderson, 2006)

Application	Seismic Refraction	Seismic Reflect.	Seismic Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.
Mapping lithology (<10m depth)	M	X		M	x	x				
Mapping lithology (>10m depth)	x	M	X		x	x				
Estimating clay/mineral content					M	x	x			
Locating shallow sand and gravel deposits				M	M					
Locating sand and gravel deposits (that contain heavy minerals)									M	
Determining volume of organic material in filled-in lakes or karsted features	M	M			M					M
Mapping top of ground water surface	M (*P-wave*)	M (*P-wave*)		M	M	M				
Determining water depths (including bridge scour)				M						
Mapping groundwater cones of depression	x	x		M	x	x				
Subsurface fluid flow								M		
Mapping contaminant plumes				M	M	x		x		
Mapping crop land salination and desalination over time					M	M				
Locating underwater ferromagnetic objects				M					M	
Mapping bedrock topography (<10m depth)	M			M	x	x				x
Mapping bedrock topography (>10m depth)	x	M			x	x				x
Mapping sub-bedrock structure	x	M		x	x	x				
Delineating steeply dipping geologic contacts (<10m depth)	M			M	M	M				
Delineating steeply dipping geologic contacts (>10m depth)	x	M	x		x	x			x	
Mapping fracture orientation (near-surface bedrock)	M			M						
Mapping fracture orientation	M		M							
Identifying regions of potential weakness (e.g., shear zones & faults; <10m depth)	M		x	M	x	x			x	
Identifying regions of potential weakness (e.g., shear zones & faults; >10m depth)	x	x	M		x	x			x	
Identifying near-surface karstic sinkholes and the lateral extent of their chaotic, brecciated, and otherwise disrupted ground	M	M		M	x	x				x
Mapping air-filled cavities, tunnels, (<10m depth)	x	x	x	M	x	M				x
Mapping air-filled cavities, tunnels, (>10m depth)	x	M	M		x	x				x
Mapping water-filled cavities, tunnels	X (*P-wave*)	M (*P-wave*)	M	x						
Mapping clay-filled cavities, tunnels	x	M	M		x	x				
Estimating rippability	M		x							
Foundation integrity studies	M		x	M						
Dam-site integrity studies	M	M	M	M	x	x		M		
Landslide site evaluation	M		M	x	M	M				
Locating buried well casings (metal)				M	M				M	

3 Popular methods in rock engineering

Within this chapter popular methods applied in rock engineering are shortly characterized. Some selected individual examples are shown in chapters 4 to 7. This chapter does not consider lab-scale methods (see our e-book "Overview about rockmechanical lab testing"), but only in-situ measurements.

3.1 Seismic methods

3.1.1 Active seismic methods

The active seismic methods respond to variations in acoustic velocity and density of the rock material. This methods needs senders (vibrators, explosives etc.) and receivers (seismometers, geophones etc.). Measured parameters are travel times and amplitudes of waves. Most typical constellations used to investigate the geological structure (faults, layering, caves etc.) as well as rockmass parameters (e.g. dynamic elastic moduli) are illustrated in Fig. 3.1.1 and 3.1.2. Seismic tomography allows to reconstruct the underground structure three-dimensional. The basic phenomena are reflection and refraction. Amplitudes and travel times are evaluated as well as the complete signal.

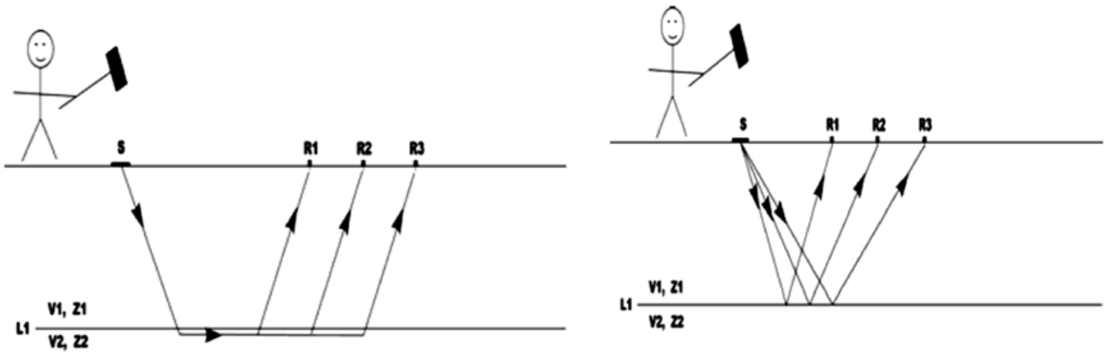


Fig. 3.1.1: Seismic refraction (left) and reflection (right) method

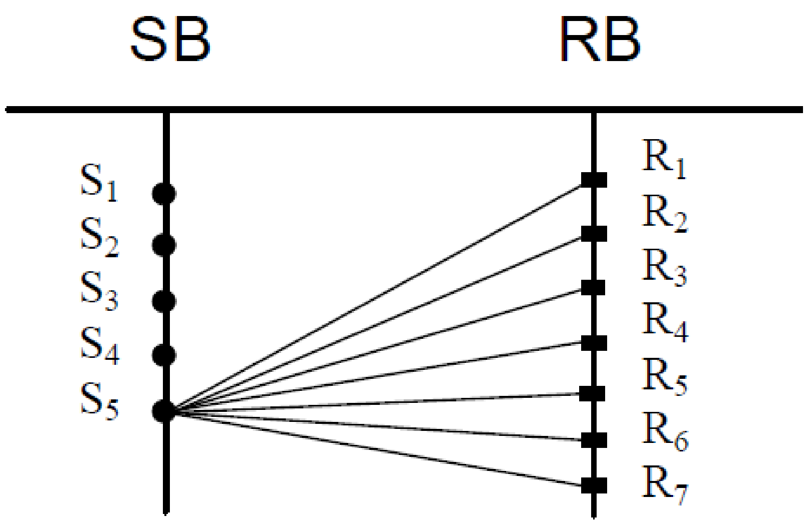


Fig. 3.1.2: Cross-hole tomography

3.1.2 Passive seismic methods

Passive seismic methods are based on observations of seismic waves originated by natural (e.g. earthquakes) or man-made (e.g. rockbursts, blasting, explosions) events. For more details see our e-book “Dynamic events in rocks / rock masses”.

3.2 Gravimetry

In rock engineering gravimetric measurements are mainly used to detect cavities. This is important in mining (especially for abandoned mines) and for activities (surface constructions or tunneling) in karst regions. At larger scale it can also be used to discover mineral deposits with ore of high density.

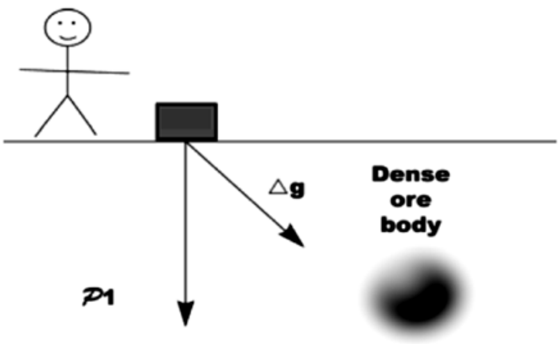


Fig. 3.2.1: Principle of gravimetry

3.3 Electric and electromagnetic methods

Electric and electromagnetic methods comprise a set of different methods like:

- Induced polarization
- Ground penetration radar (GPR)
- Electrical resistivity
- Self-potential
- Electromagnetic

They all measure the electrical conductivity or the magnetic field of the rockmass, which is influenced by porosity, water saturation and structure of the contained minerals.

Especially GPR has seen growing interest and application within the last years in geoengineering.

4 Examples: cavity / karst detection

Geophysical methods are successfully applied for detection of cavities. Typical examples are: detection of karst cavities in respect to tunneling or road/railway construction.

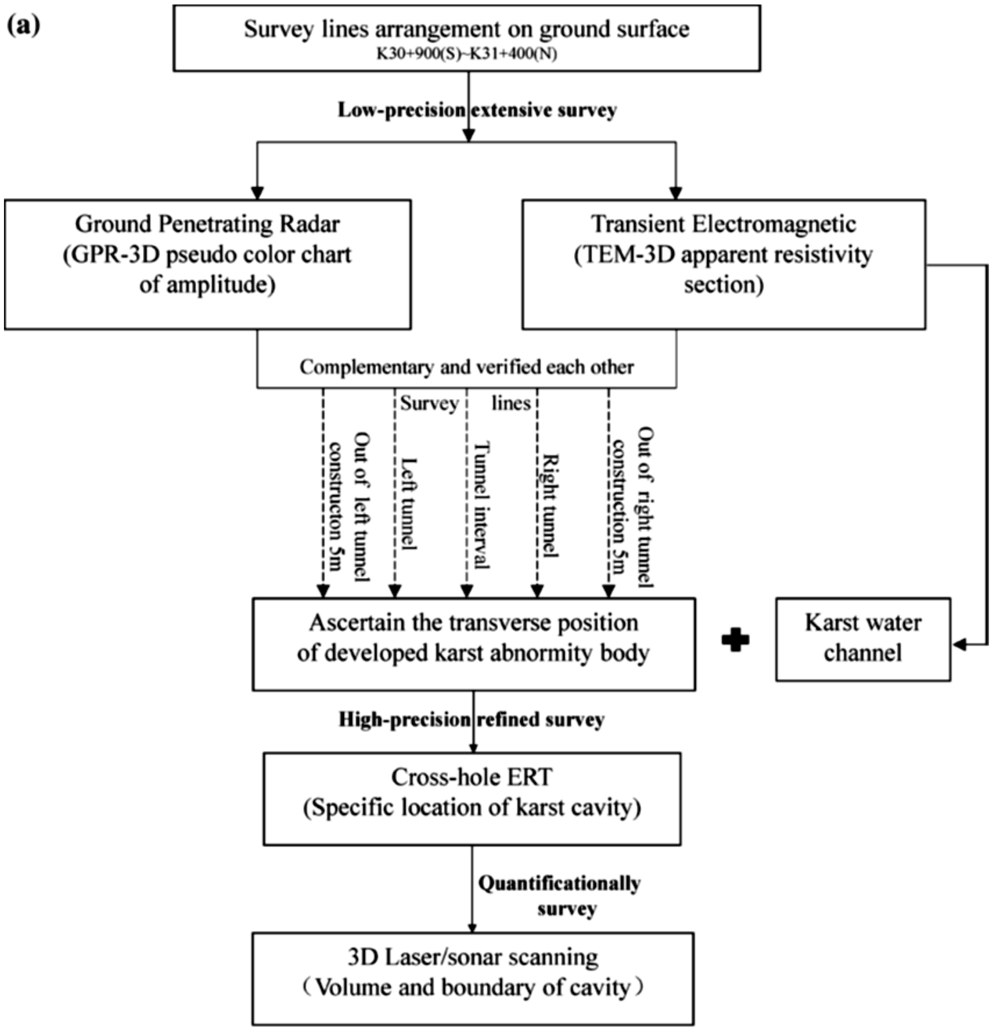
Su et al. (2021) present an integrated geophysical approach comprising ground penetration radar (GPR), transient electromagnetics (TEM), cross-hole electrical resistivity tomography (ERT) and 3D laser scanning to detect karst cavities for a subway project (see Fig. 4.1). Figures 4.2 to 4.5 illustrate the principles of the different methods, which were step-by-step applied, beginning with large scale screening via GPR and TEM followed by cross-hole ERT and ending with precise cavity measurement via 3D laser scanning. Fig. 4.6 shows the final result.

Baradello et al. (2001) also presented an interdisciplinary approach applying gravity method, resistivity method and GPR. Exemplary, Fig. 4.7 shows the result of micro-gravity measurements. The negative anomaly at the left corner indicates a cavity, which was later confirmed by other measuring techniques.

Raithel et al. (2016) show, how geophysical measuring techniques (here: gravimetry and seismic methods) are used to detect large karst cavities along the tunnel route Ulm-Wendlingen (Germany).

Lehmann et al. (2018) describe the application of borehole radar in two different modes: as reflection (RX) mode and cross-hole (CH) mode.

Bacic et al. (2020) documents some examples for karst exploration using seismic methods.



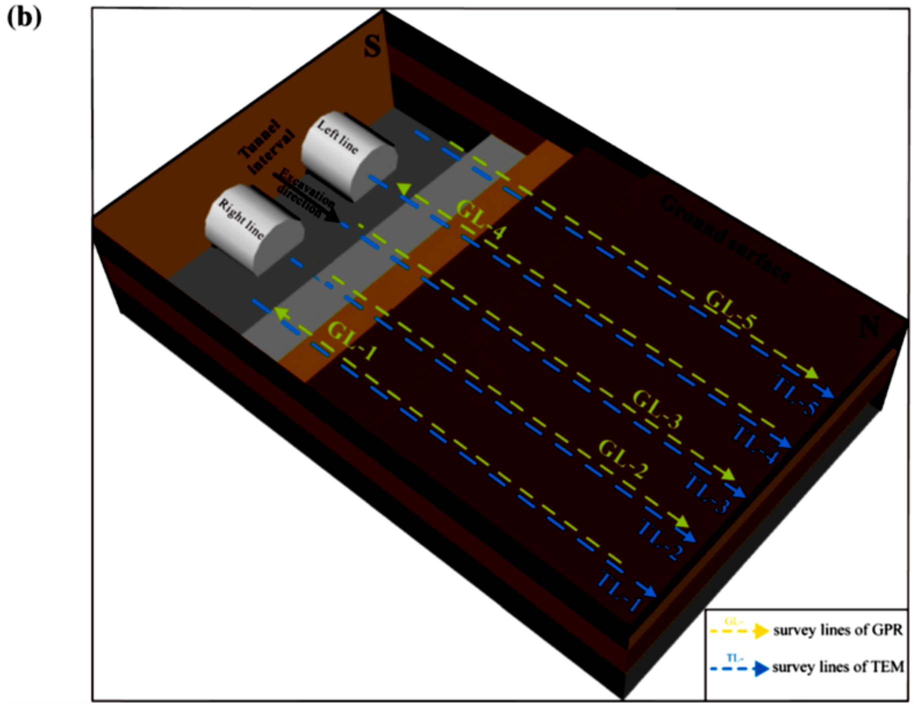


Fig. 4.1: Overview about integrated geophysical approach to detect cavities applied by Su et al. (2021)

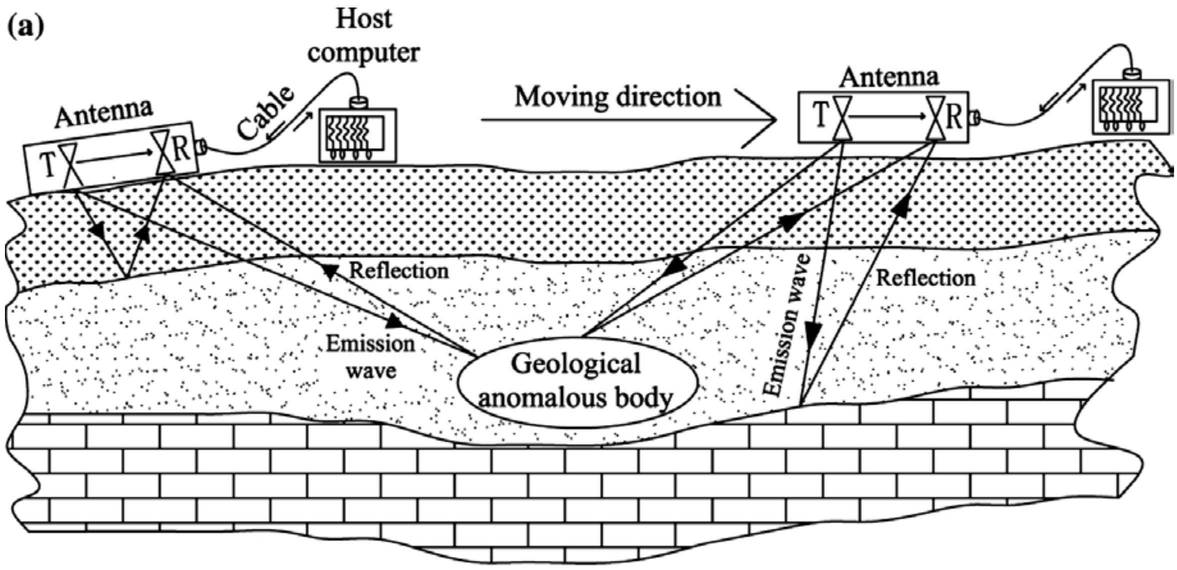


Fig. 4.2: Principle of GPR (Su et al., 2021)

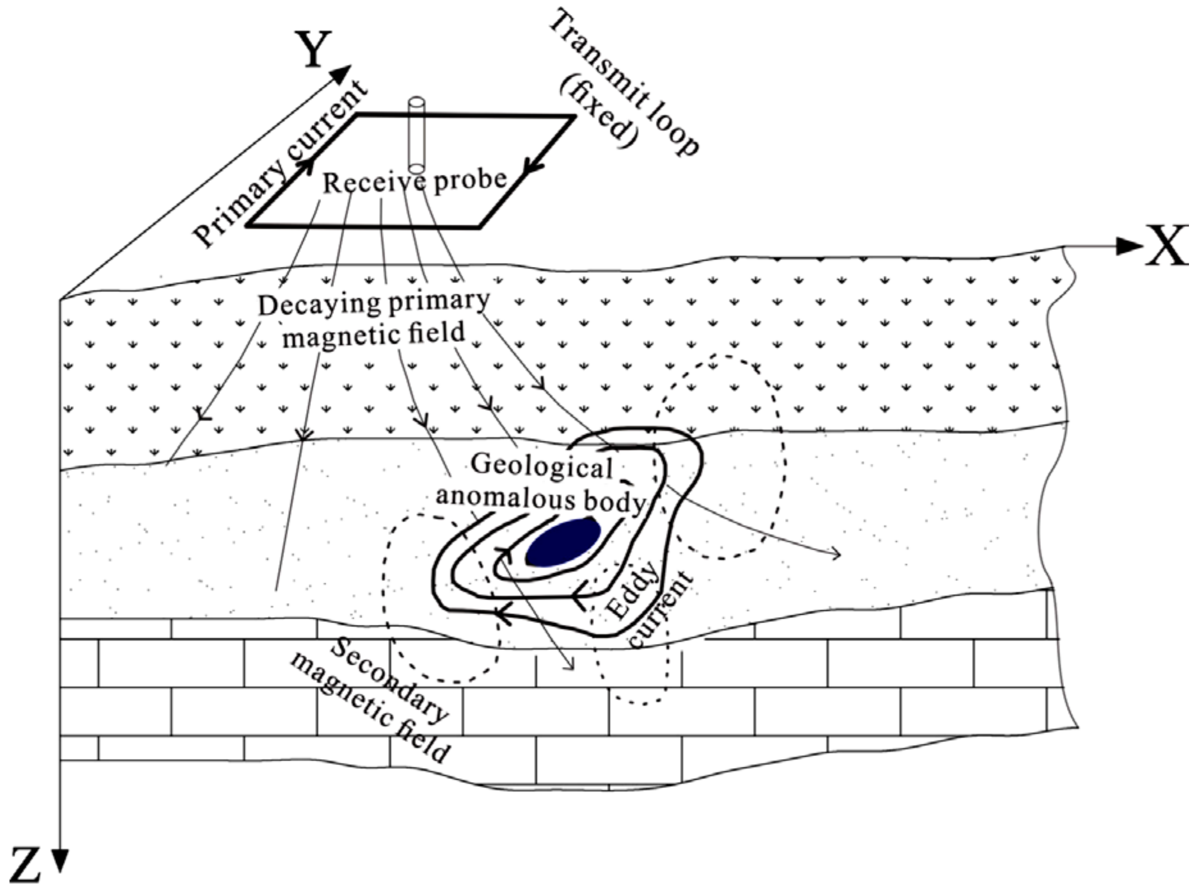


Fig. 4.3: Principle of TEM (Su et al.,2021)

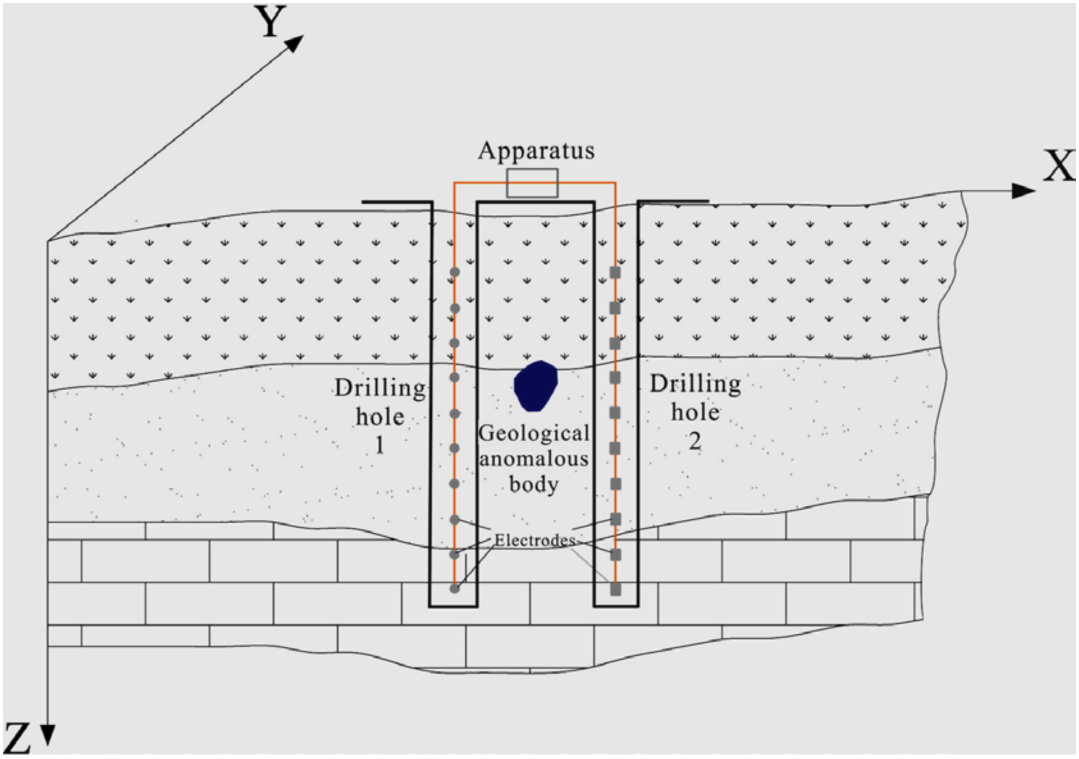


Fig. 4.4: Principle of cross-hole ERT (Su et al., 2021)

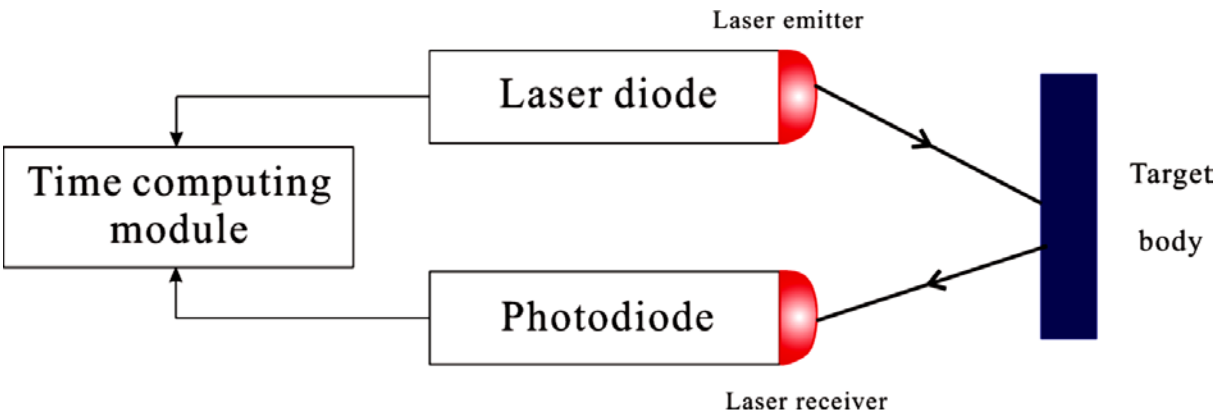
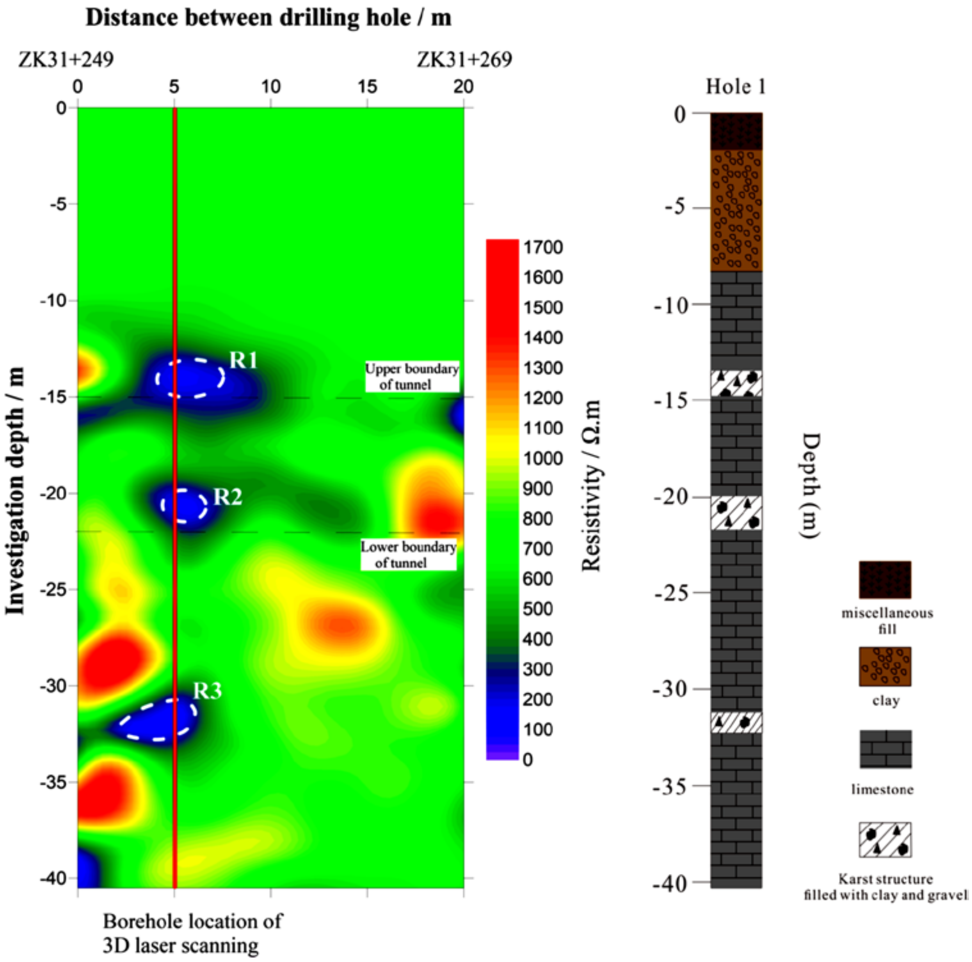
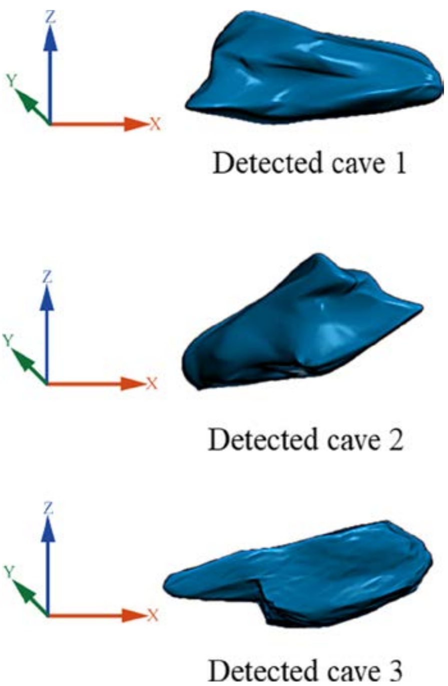


Fig. 4.5: Principle of 3D laser scan (Su et al., 2021)





Name	Surface area (m^2)	Volume (m^3)	Size		
			X (m)	*Y* (m)	*Z* (m)
Cave 5-1	12.50	2.70	3.384	1.85	1.491
Cave 5-2	11.35	2.29	2.9	2.441	1.852
Cave 5-3	10.88	2.15	3.539	1.249	1.392

Fig. 4.6: Detected cavities (Su et al., 2021)

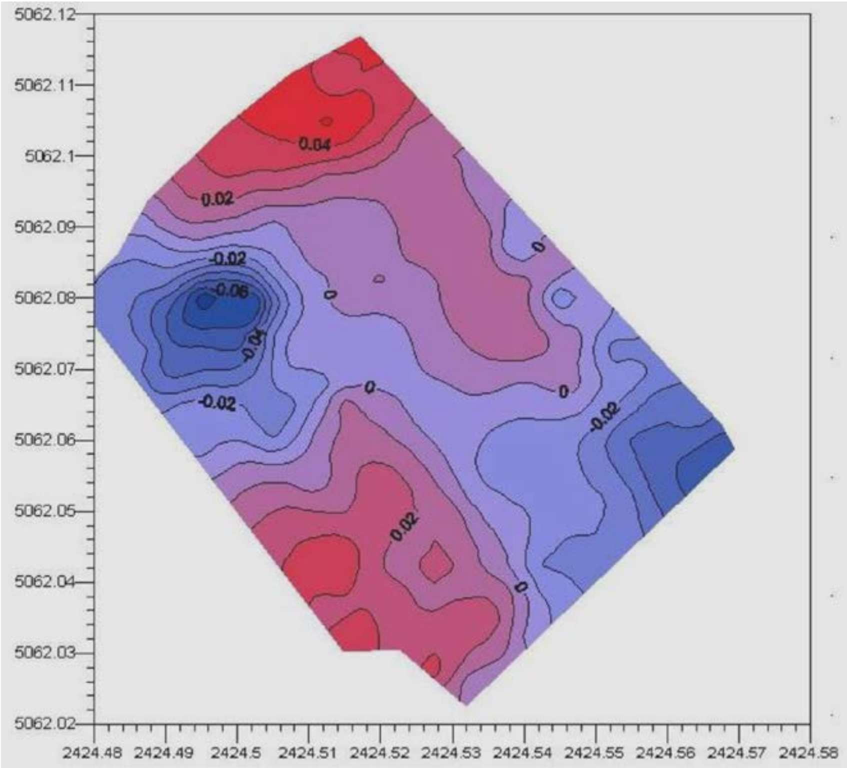


Fig. 4.7: Micro-gravity plot (Baradello et al., 2001)

Fig. 4.8: Large karst cavities along the railway tunnel route Ulm-Wendlingen (Raithel et al., 2016)

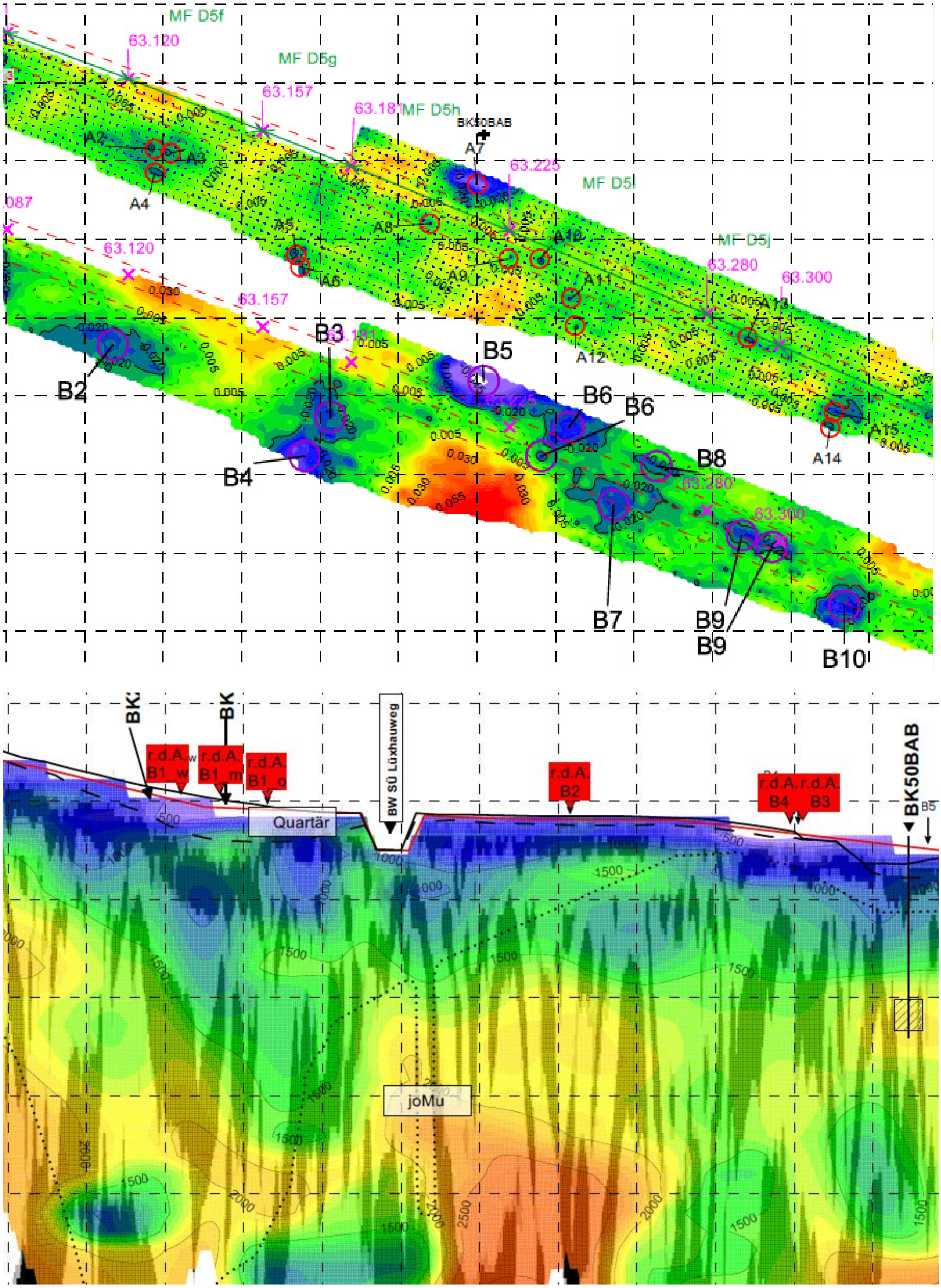


Fig. 4.9: Gravimetric and seismic survey results along the railway route Ulm-Wendlingen indicating karst cavities (Raithel et al., 2016)

5 Examples: exploration while drilling and tunneling

AFTES (2014) and Lechner (2015) provide a detailed overview about the common techniques for exploration while tunneling and drilling, respectively. They also provide information about application areas, accuracy and operating ranges. Some proven geophysical exploration techniques while tunnelling (see Fig. 5.1) are presented by Edelmann (2013).

Fig. 5.2 to 5.4 illustrate the principles of applying seismic, radar based and electrical resistivity based methods in TBM tunnelling.

Comparison of geophysical prediction systems	Geophysical System				
	TSP	ISIS	SSP	BORATEC	MWD
	Tunnel Seismic Prediction	Integrated Seismic Imaging System	Sonic Softground Probing	Borehole Radar Technology	Measurement While Drilling
Manufacturer	Amberg Messtechnik	Herrenknecht AG	Herrenknecht AG	Bo-Ra-tec GmbH	HK Drilling Systems
Method	*Reflection seismics*	*Reflection seismics*	*Reflection seismics*	*Borehole Geo Radar*	*Drilling*
Geology	Hardrock	Hardrock	Softground	does not work in clay and salty water	Any geology
Detection of	faults, voids	faults, voids	heterogeneities, boulders, voids, anthropogenic installations	heterogeneities, boulders, voids, anthropogenic installations	voids, changes of torque, penetration and rotation speed
Resolution / Range	≥ 5m / 150m	≥ 5m / 150m	≥ 0,5m / 40m	0,1m / 10m	0,1 / 30m
Advantage	no downtime, measurement during standstill	no downtime, measurement during standstill	no downtime, measurement during advance	additional information in plane	direct detection, cheap
Disadvantage	blastings required	forerun of 50m for first reliable detection, low resolution	components installed in cutting wheel	preventer necessary on high water pressure	downtime, punctual result, indistinct result

Fig. 5.1: Proven geophysical exploration techniques while tunneling (Edelmann, 2013)

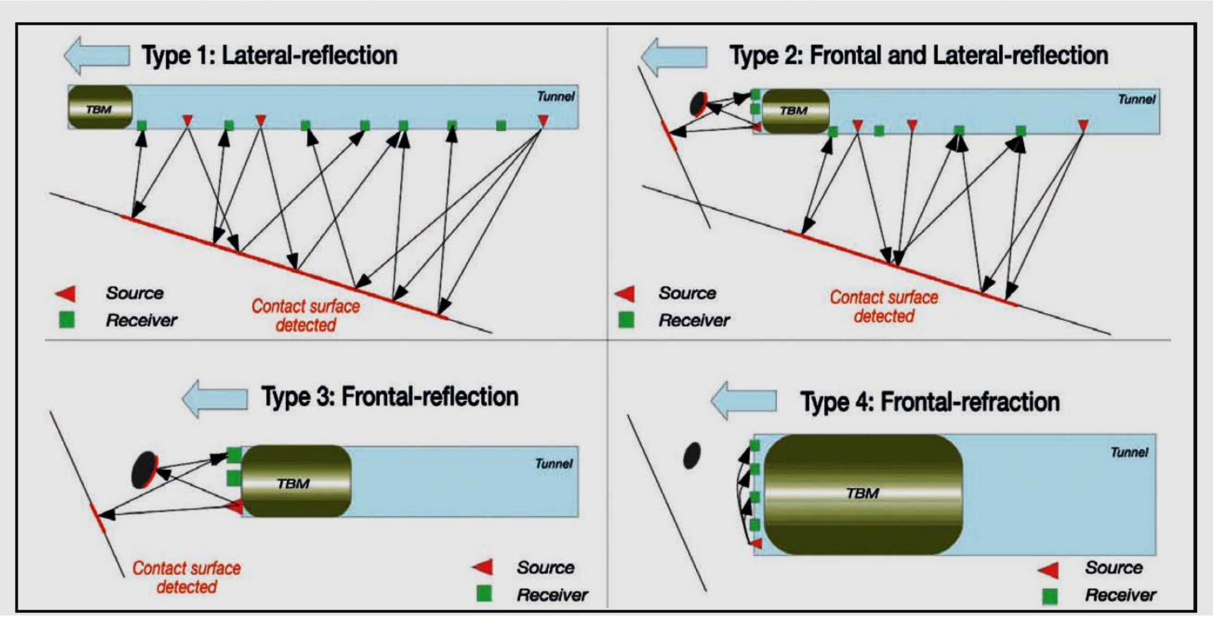


Fig. 5.2: Principles of seismic techniques while TBM tunneling (AFTES, 2014)

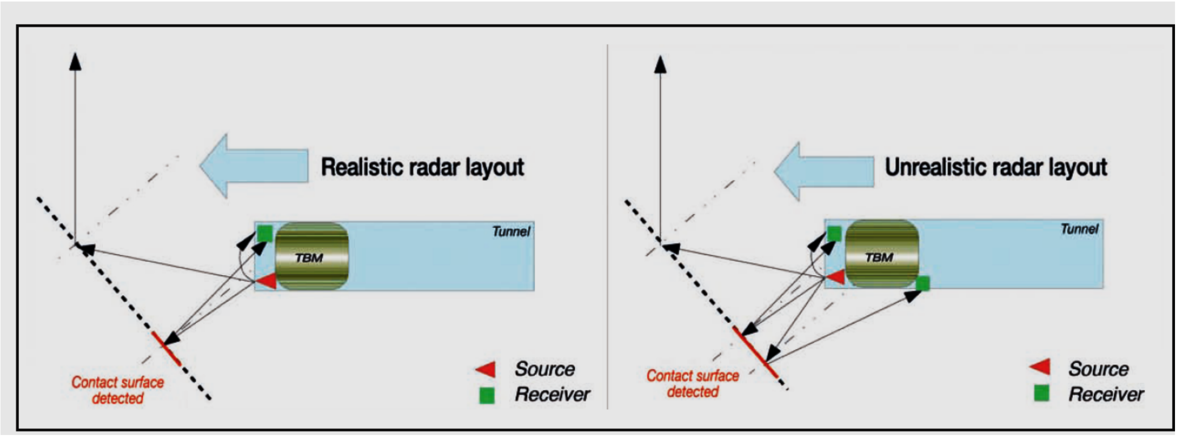


Fig. 5.3: Principles of radar based exploration while TBM tunneling (AFTES, 2014)

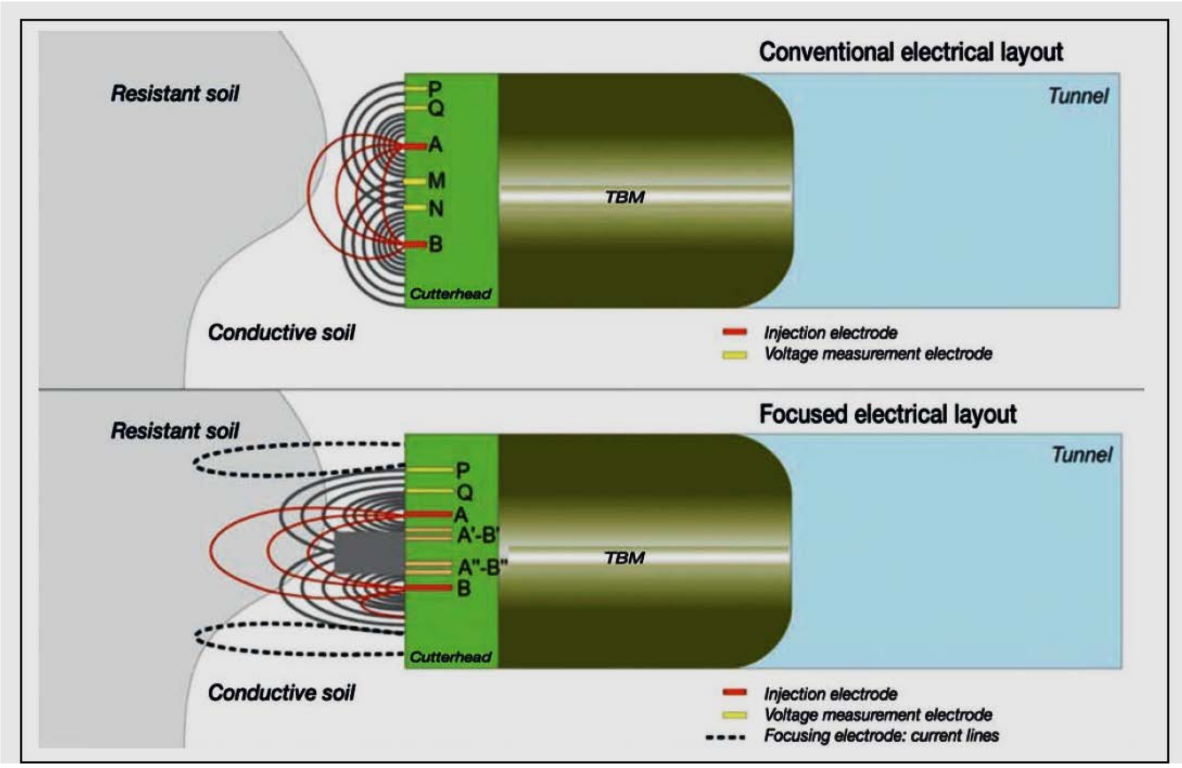


Fig. 5.4: Principles of electrical resistivity based exploration methods while TBM tunneling (AFTES, 2014)

Fig. 5.5 illustrates the application of borehole radar approaches, which can either work in reflection mode or cross-hole mode. Aim is to detect structural inhomogeneities like faults or hard rock blocks in advance, which could potentially create problems for the TBM.

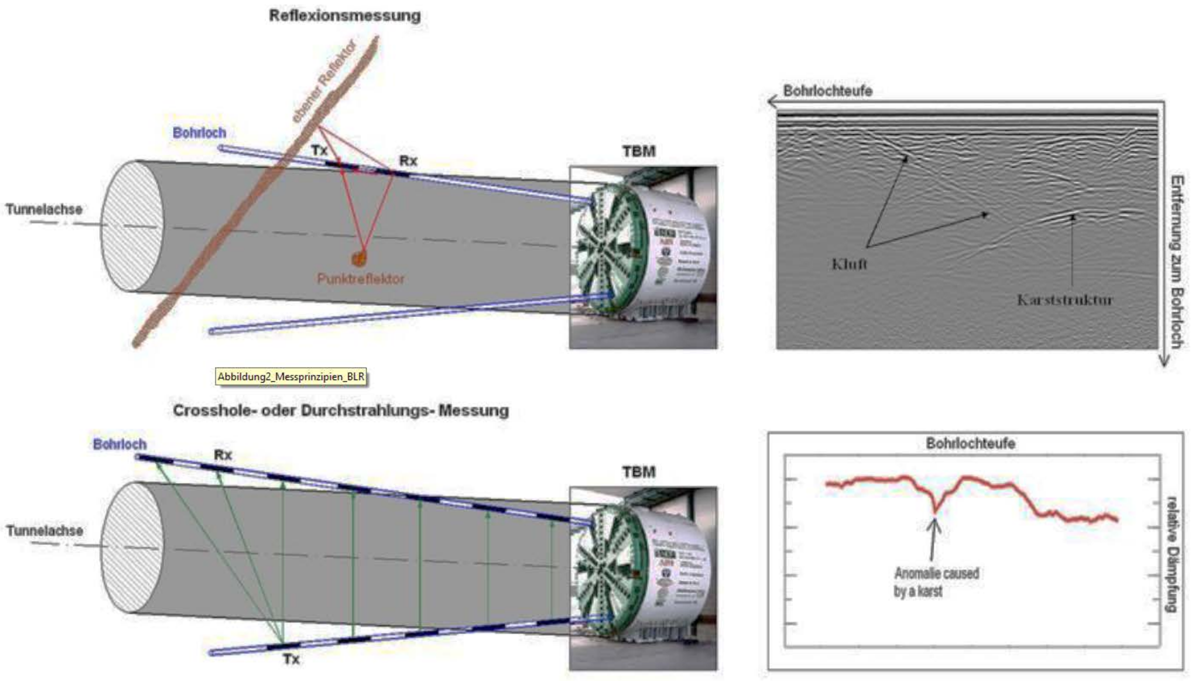


Fig. 5.5: Principle of borehole radar approach in reflection (RX) and cross-hole (CH) mode (Lehmann et al., 2018)

6 Examples: landslides / rockfall

Konietzky et al. (2004a,b) and TFV (2007) document how geotechnical (extensometer, inclinometer, geodetic), geophysical (AE monitoring, seismic, geoelectric resistivity) and hydraulic field measurements as well as several lab tests using rock samples are used in an interdisciplinary manner to monitor and explore a creeping reservoir slope. Finally, a 3-dimensional numerical model (Fig. 6.1) was set-up to predict the deformation pattern and potential slope failure (landslide) for different precipitation scenarios. Important input for the numerical model set-up was the detection of the sliding surface obtained by geophysical measurements confirmed locally by borehole investigations and an exploration tunnel. Fig. 6.2 shows seismic velocity profiles which indicate clearly the location of the sliding plane inside the reservoir slope.

Jongmans et al. (2007) and Deparis et al. (2011) provide an overview about the application of different geophysical methods for landslide and rockfall investigations.

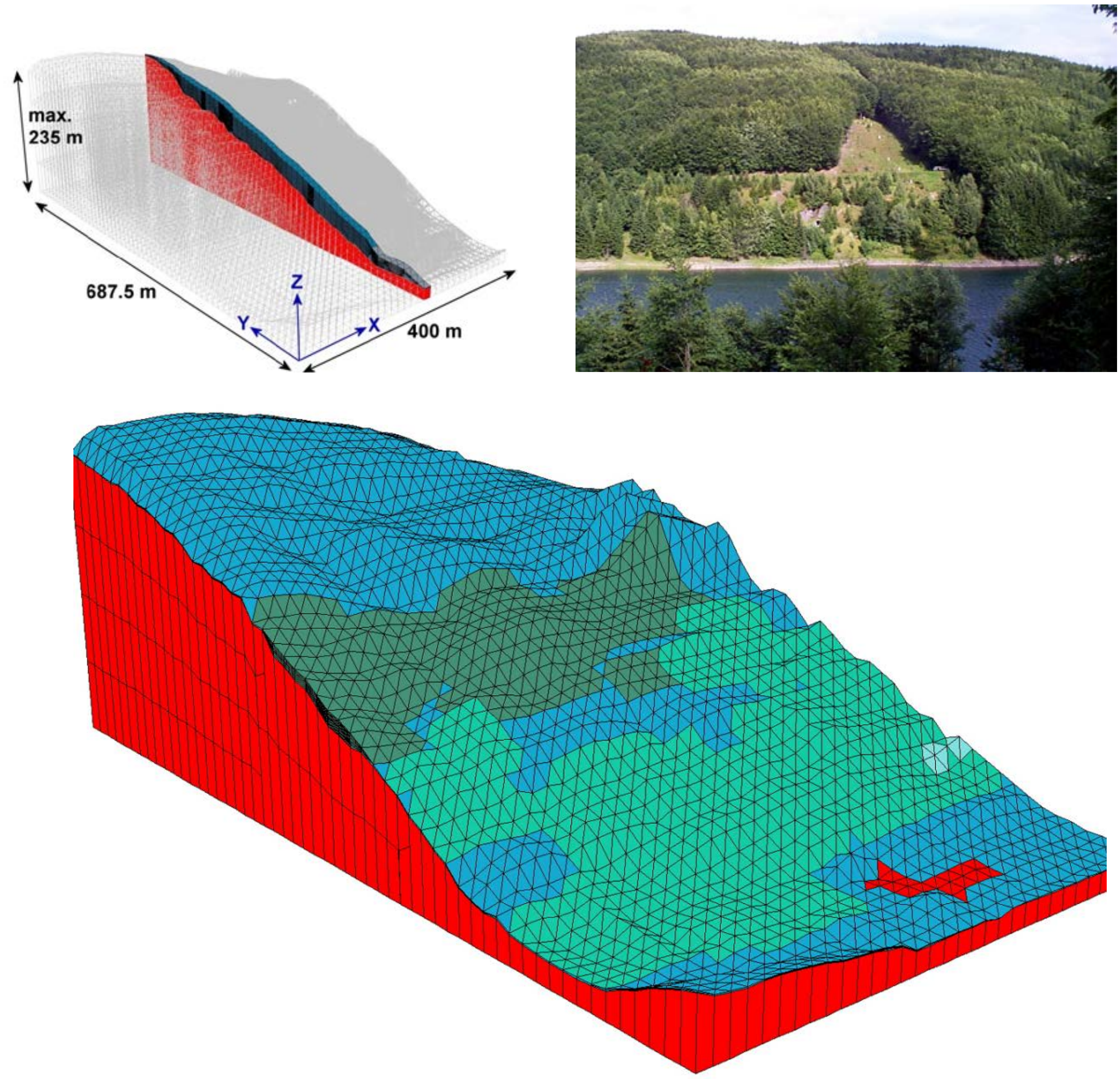


Fig. 6.1: Photo and numerical model of creeping reservoir slope (Konietzky 2004a,b et al. & TFV, 2007)

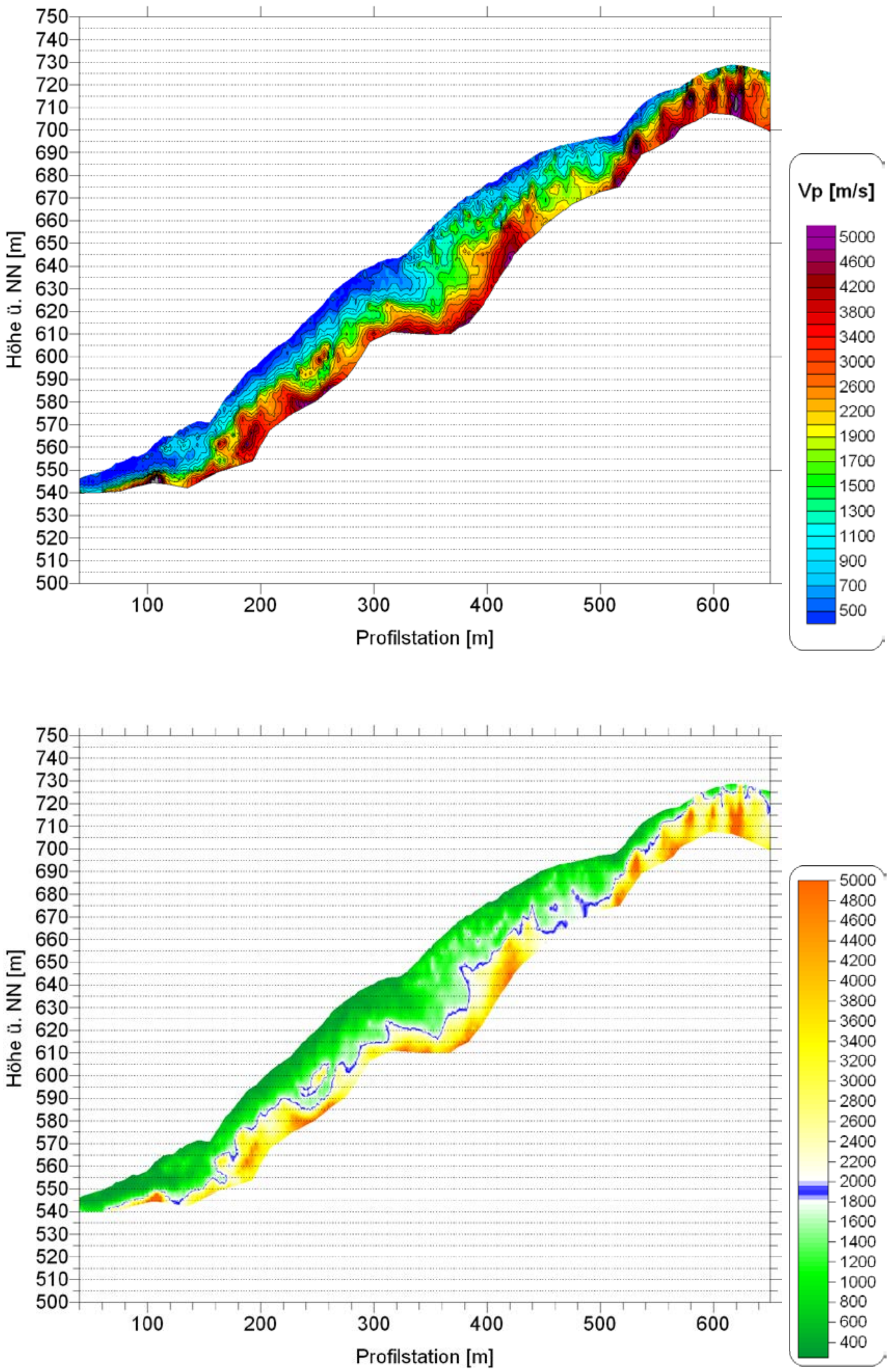


Fig. 6.1: Result of seismic tomography to detect sliding surface shown in blue in lower plot and indicated as boundary between red and green colors in upper plot, seismic velocity values in m/s (Konietzky et al., 2004a,b & TFV, 2007)

7 Examples: borehole measurements

Takahashi et al. (2006) provide an overview about geophysical borehole measurements applied in rock engineering. They distinguish between:

- Velocity logging (measurements along the borehole)
- Electric / electromagnetic logging
- Nuclear logging
- Vertical seismic profiling (VSP)
- Seismic tomography
- Resistivity tomography

Fig. 7.1 illustrates different constellations to perform velocity measurements along a borehole, either conducted complete inside the borehole or in combination with a source or receiver at the surface. Exemplary, Fig. 7.2 shows typical log results in form of velocity-depth profiles. A clear correlation between RQD and velocity becomes visible.

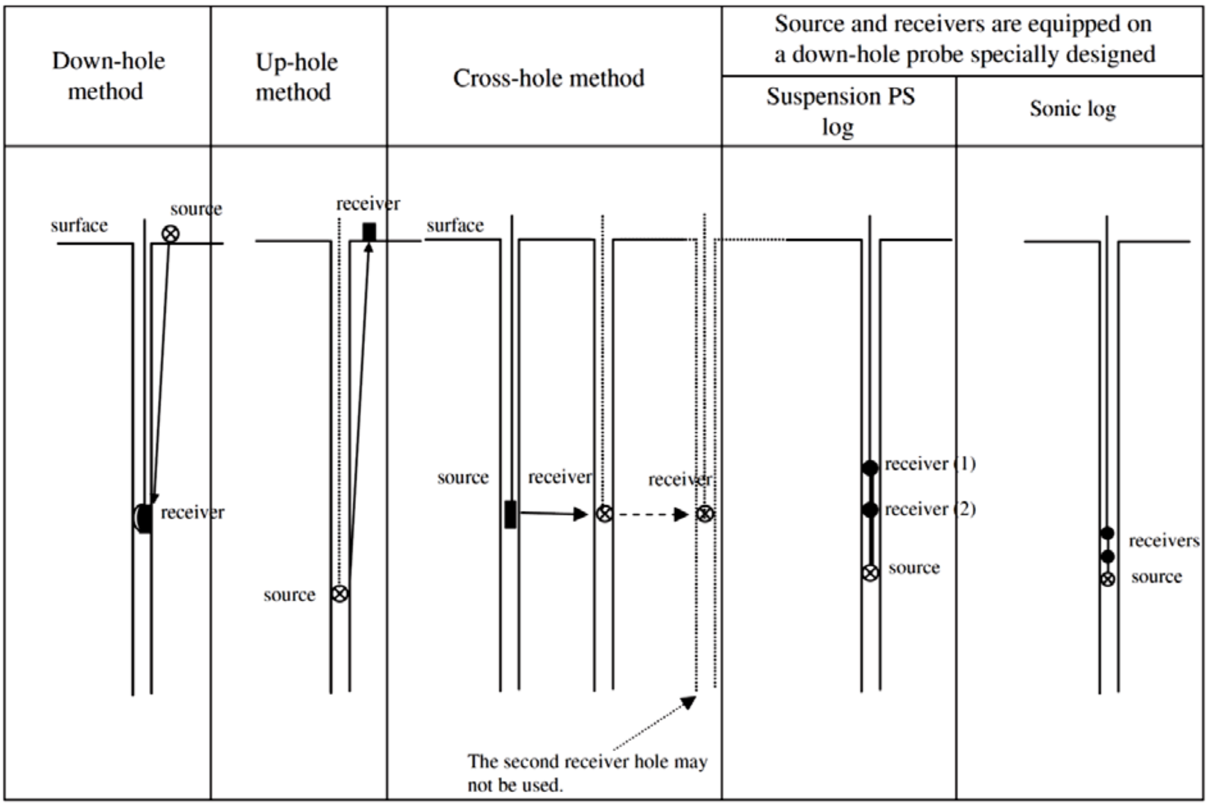


Fig. 7.1: Different set-ups for velocity logging (Takahashi et al., 2006)

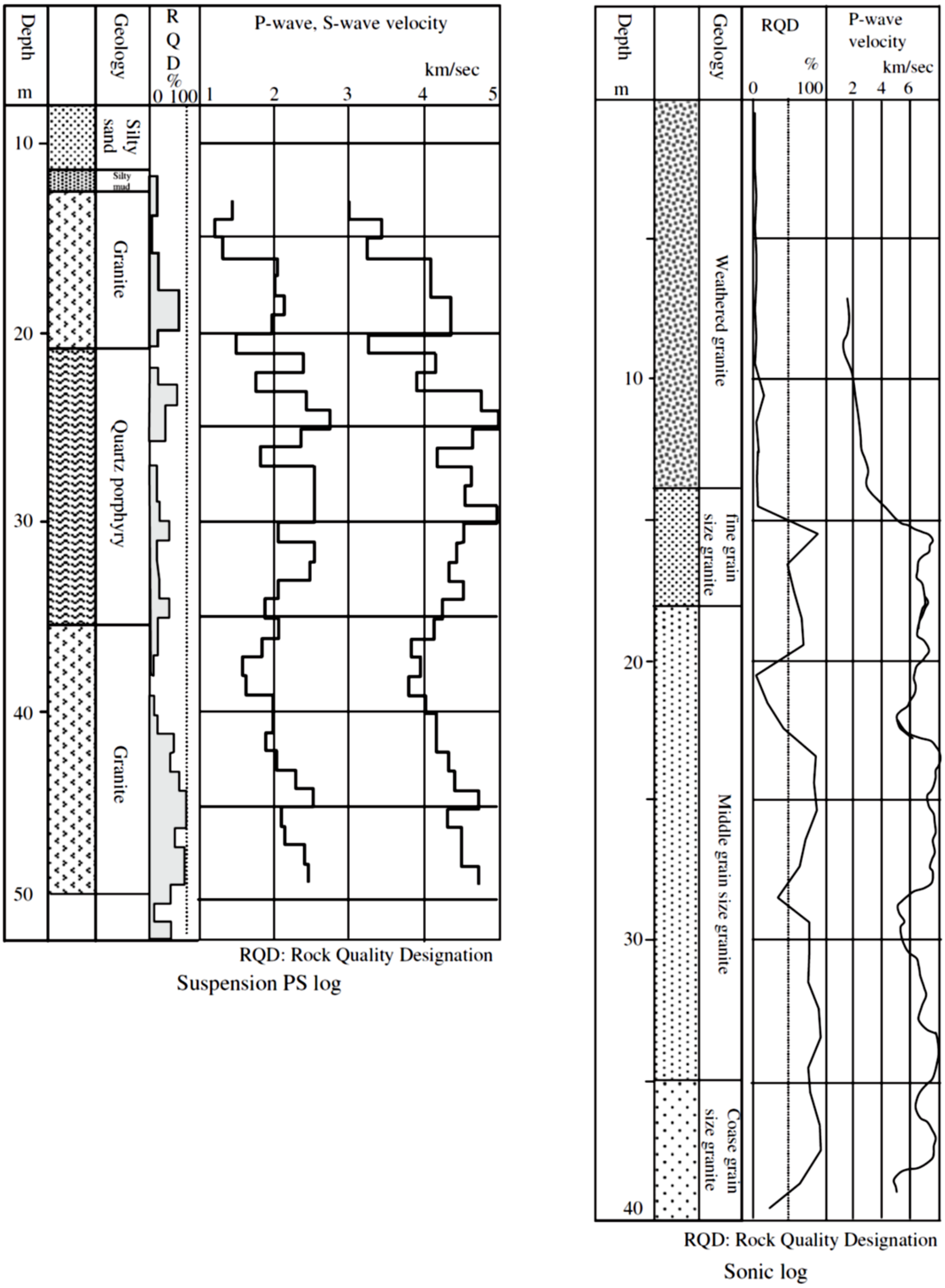


Fig. 7.2: Example for PS logging (P- and S-wave velocities) and Sonic log (high frequency P-wave velocity) (Takahashi et al., 2006)

VSP is based on receiver and sender locations along the borehole and at the surface like illustrated in Fig. 7.3. Whereas velocity logging considers only first arrivals, VSP uses the whole seismic trace and allows to construct 2-dimensional velocity profiles. Seismic tomography (see Fig. 7.4) can be conducted – depending on layout – either 2-dimensional or 3-dimensional.

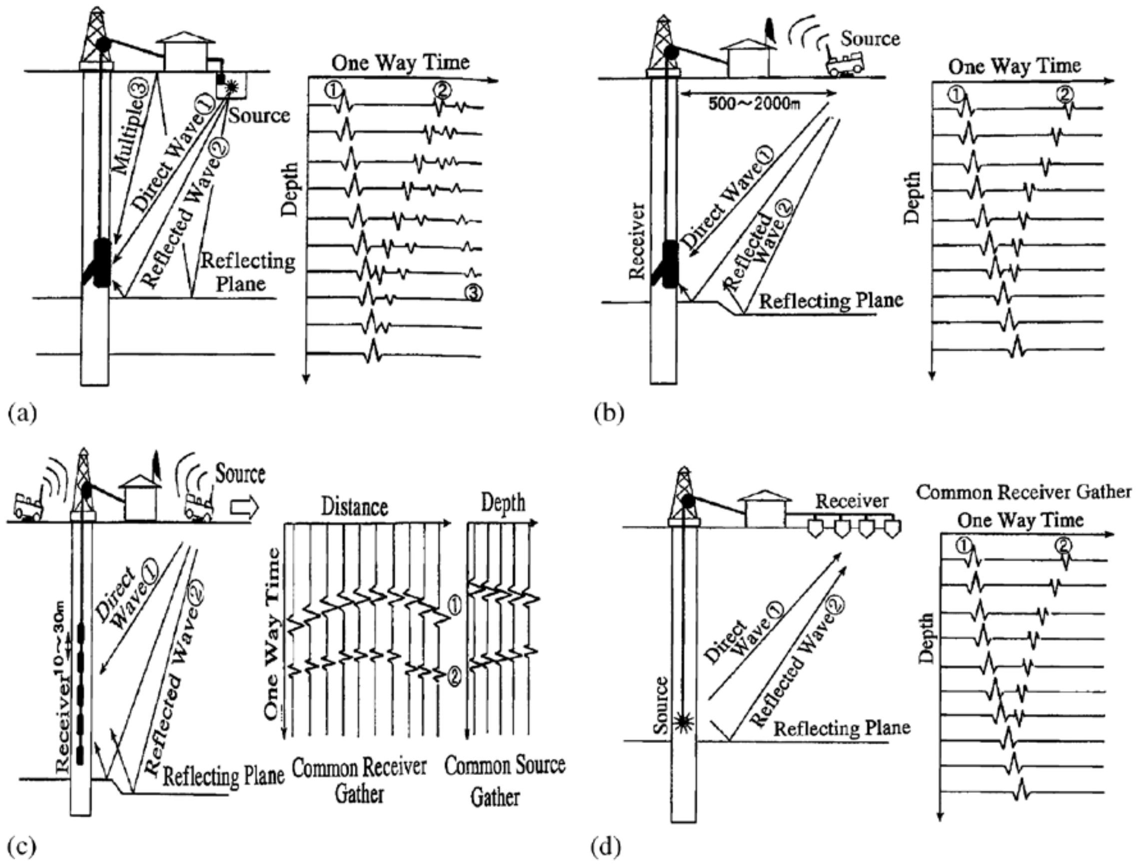


Fig. 7.3: Different VSP measurement constellations (Takahashi et al., 2006)

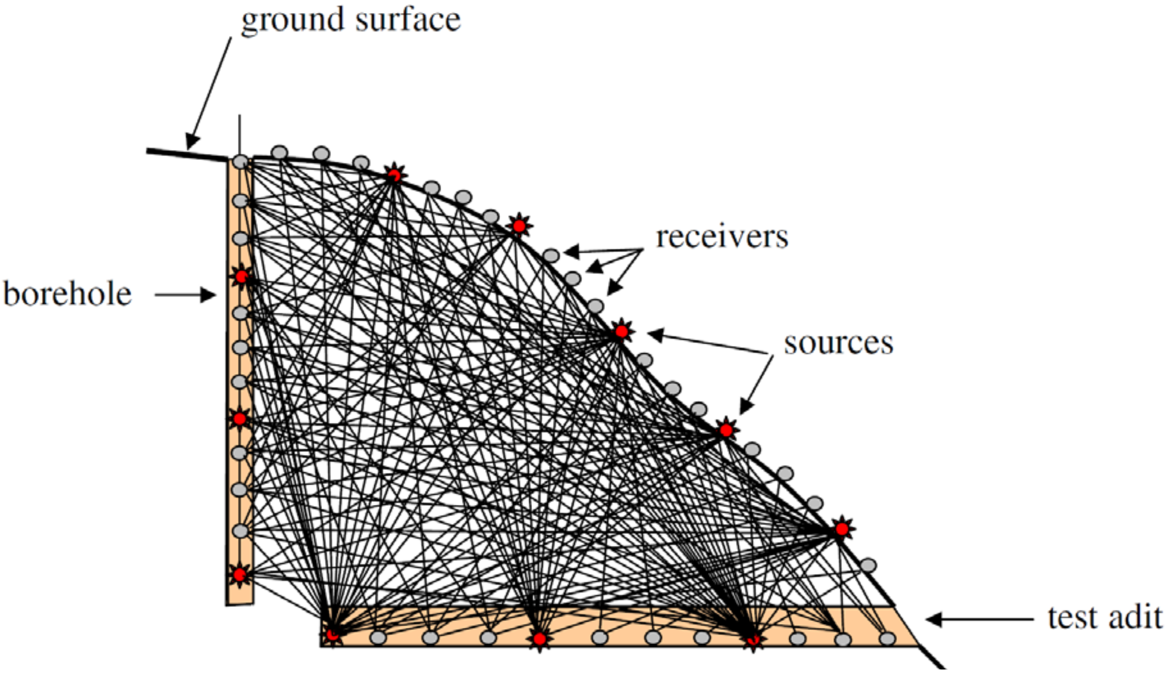


Fig. 7.4: Seismic tomography scheme using borehole and underground drift (Takahashi et al., 2006)

8 Examples: fracture detection via ground penetration radar

Molron et al. (2020) demonstrate the potential of ground penetration radar (GPR) to detect fractures in hard rock and compared with televiewer data and core evaluation. For fractures with areas between 1 and 10 m^2 the analysis revealed that percentage of fractures detected by GPR is (see Fig. 8.1 and 8.2):

- 5.5% of all the observed fractures regardless of orientation or if they are open or sealed
- 42% of the fractures dipping less than 25°
- 80% of open fractures dipping less than 25°.

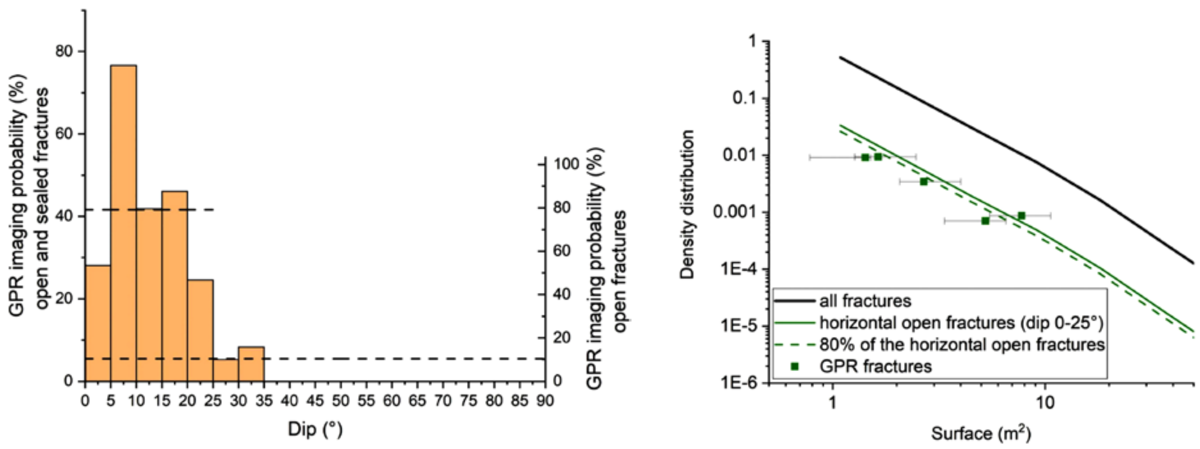


Fig. 8.1: Fracture size and orientation distribution incl. GPR data (Molron et al., 2020)

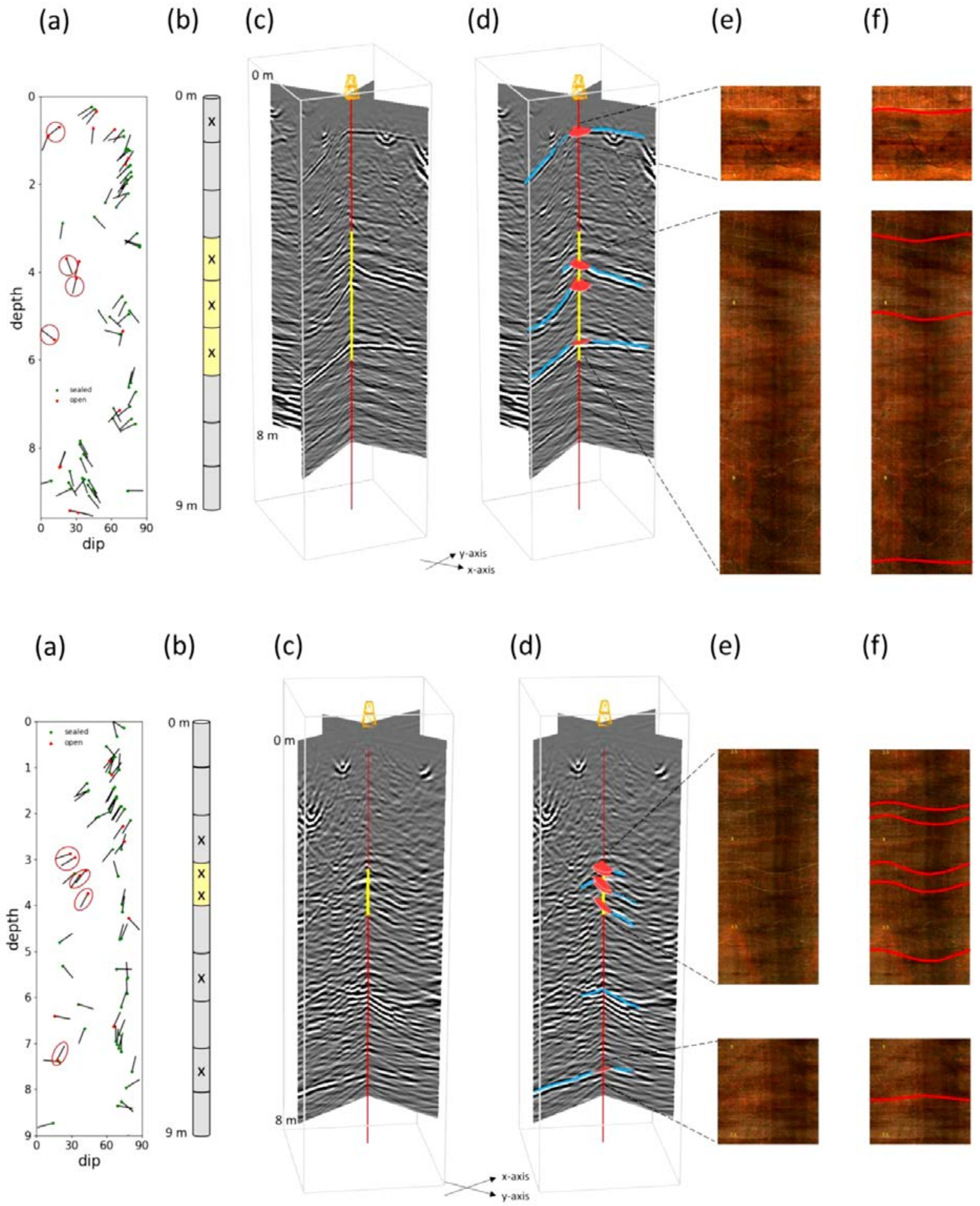


Fig. 8.2: Comparison of core log, hydraulic and GPR data for two boreholes, (a) tadpole plot representing the fracture characteristics (depth, orientation and aperture) along the borehole. Red and green colors correspond to the open and sealed fractures, (b) borehole representation with transmissive sections (yellow), (c) uninterpreted and (d) interpreted GPR data, (e) uninterpreted and (f) interpreted optical televiewer images showing the fracture traces on borehole walls. Fractures matching with GPR reflectors are underlined in red lines (Molron et al., 2020).

9 Examples: borehole logging

From the geomechanical point of view natural and induced fractures, stratigraphic information as well as borehole breakouts are the most important features detectable in boreholes. These features provide information about rock mass classification, stress field and rock mass properties. Besides that a lot of tectonic, sedimentary of diagenetic features (stratigraphy, layering etc.) can be obtained from such logging. The most popular logging techniques are:

- Optical borehole camera / optical televiewer
- Acoustic televiewer
- Electrical image tools (Formation Micro Scanner: FMS or Formation Micro Imager: FMI)

The working principle of these techniques is documented in Fig. 9.1. Please note, borehole cameras are available at nearly any size, whereas acoustic and optical televiewer as well as FMS/FMI are bigger tools. The borehole camera is the by far the cheapest and most easy technique in terms of data collection and evaluation. However it works only in clean water or under dry conditions. The same holds for optical televiewer, although they are more sophisticated tools. Because most boreholes are filled with mud, acoustic televiewer or FMS/FMI have to be used.

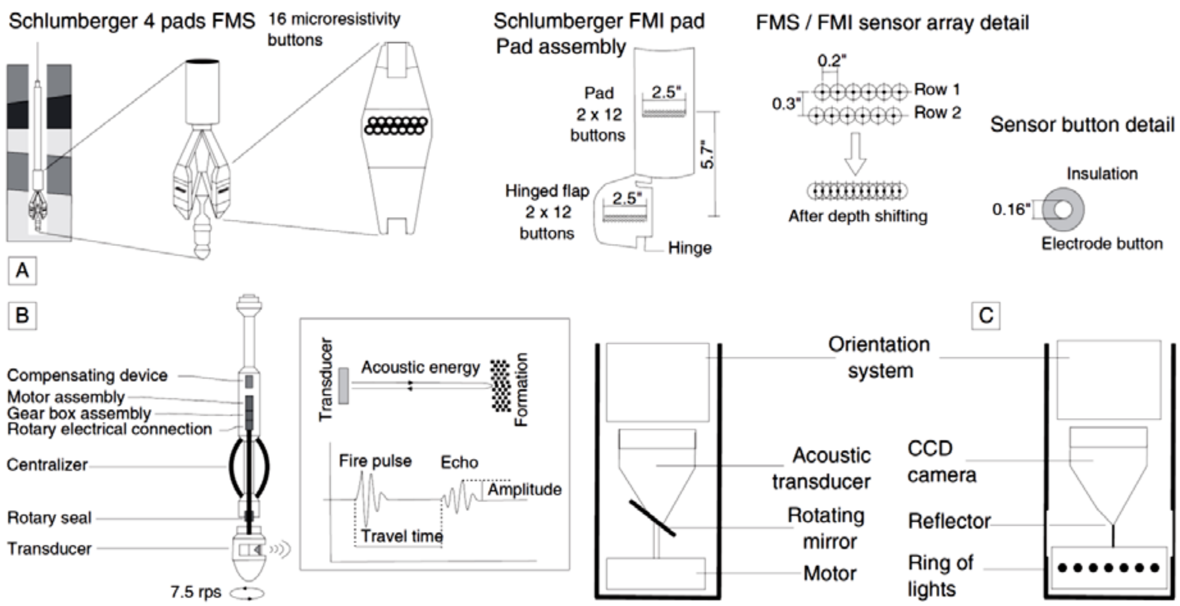


Fig. 9.1: Schematic of electrical (A), acoustic (B) and optical (C) borehole image tools (Gaillot et al. 2007)

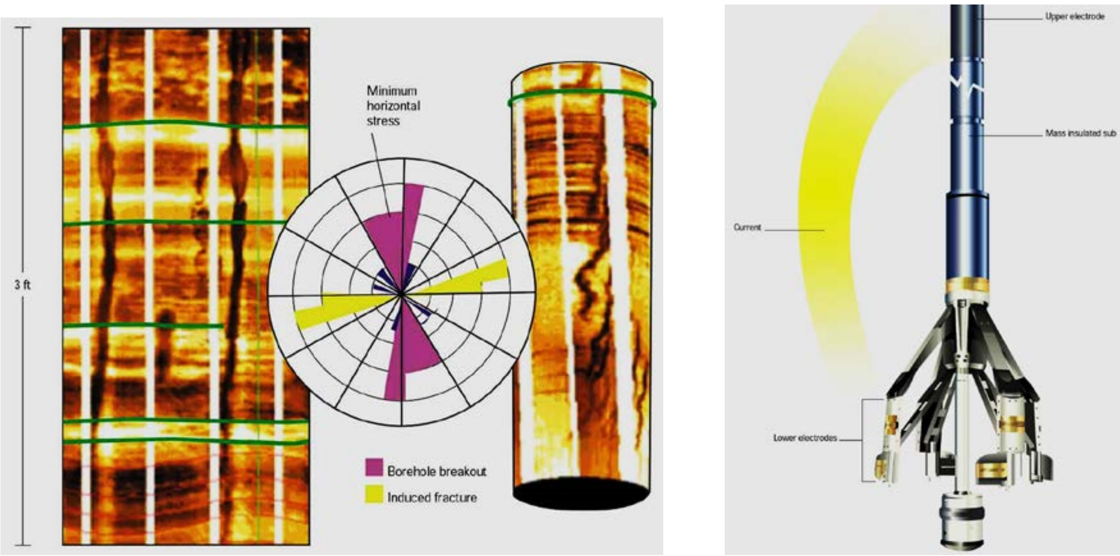


Fig. 9.2: Left: FMI formation image indicating fractures and breakouts, right: FMI tool (Schlumberger: company material)

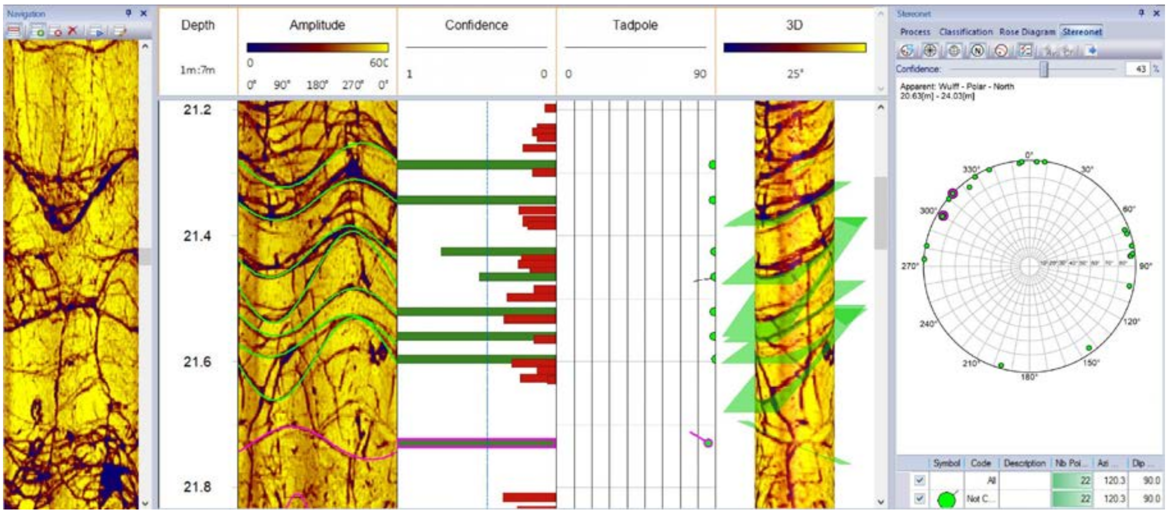


Fig. 9.3: Acoustic televiewer image indicating fractures (Mount Sopris Instruments: company material)

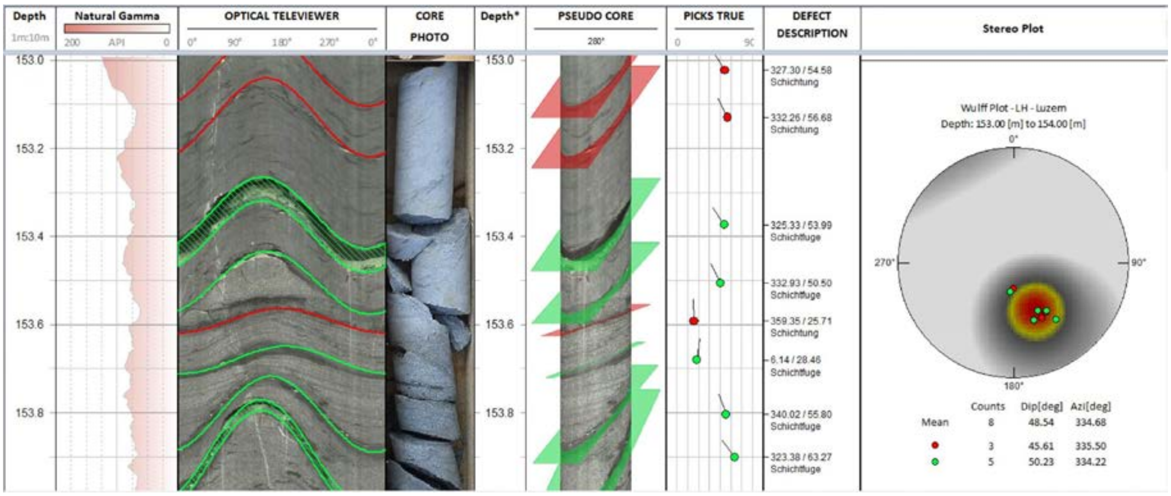


Fig. 9.4: Optical televiewer image indicating stratification (Mount Sopris Instruments: company material)

Fig. 9.5: Optical televiewer (Mount Sopris Instruments: company material)

Davatzes & Hickman (2005) and Gaillot et al. (2007) provide a good overview about pros and cons of acoustic televiewer and FMS/FMI.

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