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BBT, Lot Mules 2–3. Management of data gained by the pilot tunnel drive for the twin main tubes

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ABSTRACT: Along Lot Mules 2–3 of the Brenner Basis Tunnel the Client BBT choose to improve geological knowledge along the alignment by a pilot tunnel to be excavated contemporarily but in advance to the main twin tubes. BTC (JV from Astaldi-Ghella-Pac-Cogeis) was awarded this project based on a tender where all the three tubes will be excavated using a DS TBM. The management of the data provided by the complex system of investigation and monitoring through the pilot tunnel ahead is a key point of the tunnel construction with the aim (1) to give instruction for the excavation of the pilot tunnel to explore what was never directly investigated and (2) to prepare the "engineered as built profile" of the pilot to use as a guide for the two bigger machines. The paper shows how this system is going to be organized and which parameters and correlations seems to be relevant for the purpose.

1 INTRODUCTION

Lot Mules 2–3 of BBT is linking the area of the Isarco underpass with the underground Italy-Austria State border for a length of the main tunnels of 21+927 m (East tube). The main access to the underground construction site is done by the Mules adit that connects the National Road SS 12 to the underground logistic area from where the 5 advancing faces start:

- two fronts are used to excavate the main twin tunnels direction South
- two fronts are used to excavate the main twin tunnels direction North
- one front is used to excavate the pilot tunnel direction North (CE in the following, started in May 2018 by TBM)

From the same logistic area one more front has been designed to connect the Mules Adit to the node of Trens emergency stop as well as to connect the level of the main tunnels with the level of the pilot tunnel placed 11 m underneath.

The pilot tunnel reaching this point from South is already excavated being the well-known tunnel Aicha-Mules connecting directly with the open air logistic area of Unterplatter.

Figure 1 and Figure 2 show the schematic layout of this construction Lot and the typical transversal section of the three running tunnels in correspondence of a cross passage.

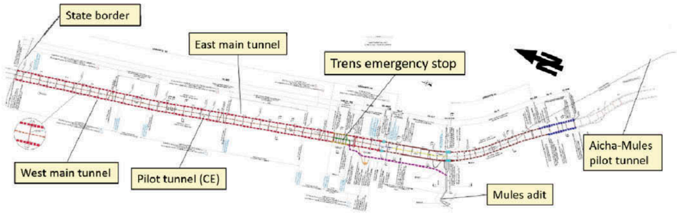

Figure 1. Layout of Lot Mules 2–3.

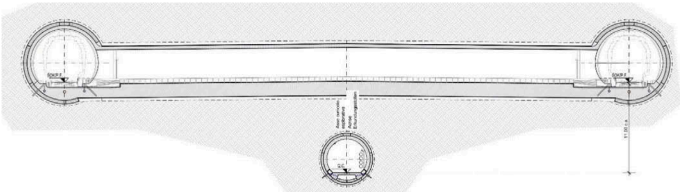
Figure 2. Transversal section of the running tunnels along a cross passage.

The pilot tunnel and the twin tubes are excavated at the same time with a distance between the pilot and the more advanced of the main tunnel which cannot be less than 500 m.

The geological investigation performed during the design phase was done by several long and even inclined boreholes, but the relevant length of these tunnels still left uncovered many portions of the alignment, thus the pilot tunnel has the main function to explore in advance what has been never investigated before. To assist the construction of the three tubes and specifically to properly organize all the possible information that can be obtained by the drive of the pilot tunnel, a thorough investigation and monitoring plan has been organized.

The purpose of this paper is to illustrate the main elements of the investigation and monitoring plan, how they are linked together, and which results have been obtained so far.

2 THE GEOLOGICAL CONTEXT OF LOT MULES 2–3

2.1 *General overview*

The Brenner Basis Tunnel crosses the central part of the Eastern Alps and the main tectonic nappes involved in the collision zone between the European and the Adriatic (African) plates, thanks to the presence of the huge antiform fold coinciding with the Tauern Window.

The Tauern Window, indeed divided into two different nuclei, the Tux at North and the Tinnertal at South, is constituted by the uplifted southern limit of the European continent, the complex of the Sub-Penninic nappes, namely the so-called Central Gneiss with its Mesozoic cover sediments of the lower Schiefe-rhülle.

Upward, the Central Gneiss and its cover are wrapped by the complex of the Penninic nappes, the upper Schiefe-rhülle, mainly calcschists (Bündner Schiefer) and ophiolites, the rocks of oceanic origin which overthrusted above the subpenninic nappes at the moment of the subduction phase. At the edge of the Tauern window, either on the north on the south side, the Austroalpine nappes are present, once constituting the Adriatic (African) continental border.

On the south side of the Periadrial line fault system, the Southern Alps nappes, on the contrary of all the so far mentioned tectonic units, have not been involved in the subduction process, are not characterized by alpine metamorphism and show only brittle alpine deformation (Frisch 1976, 1979, Ratschbacher et al., 1991, Fügenschuh et al., 1997 Lammerer & Weger, 1998).

According to the geological setting described here above, the excavation of the Brenner Base Tunnel and specifically the sector corresponding to the Lot Mules 2–3, crosses the rocks/tectonic units summarized in the following table.

The overburden is ranging between 595 and 1715 m.

Table 1. Tectonics units and lithologies along the alignment of Lot Mules 2–3.

Tectonic units	Lithological units	Sector Lgth (m)
Upper Austoalpine Crystalline basement	Paragneiss	1510
Upper Austoalpine Crystalline basement	Amphibolites	400
Penninic upper Schieferhülle	Calcschists, Ophiolites, Triassic horizons, Marbles	2290
Penninic lower Schieferhülle	Kaserer Form. with triassic rock interbedding	350
Penninic upper Schieferhülle	Triassic rock, Calceschist	390
Penninic upper Schieferhülle	Kaserer Form. With triassic rock interbedding 26	775
Penninic upper Schieferhülle	Triassic at the base of Vizze nappe 27	105
Penninic upper Schieferhülle	Kaserer Form. with triassic rock interbedding 26	40
Penninic upper Schieferhülle	Triassic rock, Carbonate quarzites and carbonate calcschists, Marbles, Prasinites, evaporitic sequence, silicoclastic sequence	4875
Penninic upper Schieferhülle	Triassic rock, marbles, calcareous marbles	295
Sub-Penninic lower Schieferhülle	Central gneiss and pre-granitic basement	3902

Table 2. Main hazards and uncertainties.

Typical hazard	Where it is expected
Waters infiltrations and interstitial pressure: sudden water incoming and possible invasions of material	Along main fault zones and/or highly fractured horizons
Excavation in mixed lithotypes: inhomogeneous rock mass behavior, transition zones with different permeability or gas presence	Within lower and upper Penninic tectonic units, especially close to Tux and the Tinnertal antiforms nuclei, where several different kinds of rocks are present.
Swelling conditions	With huge overburden and rock mass poor geomechanical conditions
Rock burst	With huge overburden and rock mass very good geomechanical conditions
Interferences between neighboring cavities	Within karst conditions, within marbles and calcareous rocks
High temperatures	With huge overburden and at main fault zones crossing along which hydrothermal waters can raise from deep crustal sectors.
Impact on water resources	Within karst conditions, within marbles and calcareous rocks

From the hydrogeological point of view, the carried studies foresee water incomings flows, for 10 m of tunnel, of 0,4 to 2 l/s within little or no calcareous rocks, 0,4 to 10 l/s/10m within calcareous rocks and larger than 10 l/s/10m within fault zones.

2.2 *The main hazards and uncertainties*

Referring specifically to the portion of the CE alignment excavated using the DS-TBMs (i.e. from Pk 13+075,95 to State border at pk 27+217 m) and considering the geological setting described with the corresponding overburden/state o stress, the main hazards and uncertainties along the alignment can be summarized as follows in Table 2.

3 CHARACTERISTICS OF THE SELECTED TBMS

Given the picture described in chapter 2, the TBMs have been designed and equipped to face most of the risks coming from the highlighted hazards, starting from the basic choice to use a Double-Shield TBM for both the pilot tunnel (CE) and the main tunnels (GLEN and GLON) direction North.

The principal focus points to further customize the machines were:

- minimum length of the shields
- overcutting capacity
- conicity of the shields
- thrust force for the principal and auxiliary cylinders
- torque
- number of drilling positions through the cutter-head and the shields
- equipment for geotechnical monitoring

The TBMs are equipped to install a universal ring made of:

- CE: 5+1, 30cm thick, 1500mm long, 5820mm ID segments with single gasket at extrados
- GLEN/GLON: 6+1, 45cm thick, 1750mm long, 9270mm ID segments with double gasket at intrados and extrados

The following table gives a synthesis of the main strategic characteristics of the three machines.

Table 3. DS-TBM for the excavation of the three tunnels.

CHARACTERISTICS	HK TBM – S1054 - CE	HK TBM – S1071/72 - GL
Machine type	Double Shield TBM	Double Shield TBM
Installed power	approx. 4 900 kW	approx. 4 200 kW
Length of shield and cutterhead	12195 mm	12480 mm
Conicity (cutterhead-tail shield)	220 mm (difference in diameter)	290 mm (difference in diameter)
Cutterhead Nominal boring diameter	6850 mm	10710 mm
Overcutting (tool at crown)	224 mm	224 mm
Torque (nominal to breakaway, kNm)	3619 to 14013	13600 to 30636
N. of main cylinders and max thrust	n. 10 – 42750 kN at 420 bar	n. 18 – 95000 kN at 420 bar
N. of auxiliary cylinder and max thrust	n. 16 – 97000 kN at 600 bar	n. 38 – 212700 kN at 550 bar
N. of drillings through the cutterhead	n.22 diam 125 mm	n. 22 diam 125 mm
N. of drillings through the shield	n. 22 diam 125 mm and n. 2 diam 152mm	n. 10 diam 125 mm
Auxiliary geotechnical equipment	n. 5 fontimeters, n. 3 pressure cells	n. 1 fontimeters, n. 3 pressure cells

4 THE INVESTIGATION AND MONITORING SYSTEM

Although the DS-TBMs have characteristics that allow to face a wide range of geotechnical behavior while tunneling, the need to investigate ahead remains a main point to excavate long and deep tunnel where the possibility of a wide and extensive direct investigation during design phase is anyhow limited.

Therefore, systematic investigations are carried out aimed to detail and verify the information provided by the geotechnical profile while tunneling as per the following list:

- probe drilling (with possibility of core recovery if required);
- seismic geophysical investigation, using Tunnel Seismic While Drilling (TSWD) and Tunnel Seismic Prediction (TSP) techniques;
- geo-electric investigations, using BEAM system+;
- acoustic emissions measurement by means of geophones (only for main tubes)
- recording and analysis of main TBM excavation parameters;
- gas and radiation monitoring;
- water flow measurements.

The philosophy of the system is to check with one direct punctual investigation (the probe drilling) the general condition far ahead of the excavation face to detect well in advance zones with potential relevant hazards (poor geotechnical conditions associated with faults area or water inflow, ecc..) and to further detail the mechanical characteristics close to the TBM cutterhead while advancing with indirect investigations. The data obtained are checked against the performance of the TBM so that the overall system can learn while advancing.

4.1 *Probe drilling*

Core destruction boreholes are generally carried out every 100 m for a depth of roughly 150 m, so, with a roughly 50 m overlap between followings boreholes.

The probe drillings are carried out by an Eurodrill RH11–6 rotary percussive drilling machine (with DTH hammer - Wassara W70 or W100 model, respectively, with Φ 82 or 115 mm bit) installed on the TBM bridge, which allows an inclination up to 8°-9° and a 120° contour distribution; the use of preventer connected to the shield and sealed into the rock is also foreseen.

The overall drilling parameters are recorded so that the performance and hence the characteristics of the rock mass is investigated. The main information that allow the interpretation of the probe drill are the followings from which the specific energy is derived:

- water flow (l/min)
- percussion pressure (bar).
- rotation speed (g/min);
- rotation pressure (bar).
- penetration speed (m/h);
- thrust (kN);
- torque (kNm)

Eventually, it would be possible to carry out direct and indirect tests within the borehole to better characterize the rock mass (geophysical tests, temperature measurements, pressure gauges and/or transducers), as well as to verify the rock mass in situ stress conditions or deformations by means of borehole extensometers.

Moreover, in case of crossing of particularly critical zones (main fault zones, zones characterized by main uncertainties, etc.) and in accordance with the supervision responsible, it is foreseen the possibility to carry out a borehole with core recovery, radial core destruction boreholes, hydrogeological survey and rock mass deformation measurements by means of n° 3 radial multi-base extensometers.

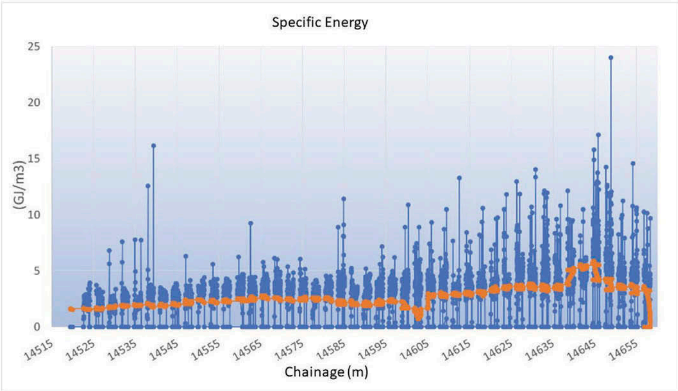

Figure 3. typical example of Specific Energy graph, for probe drill n. 15.

4.2 *Geophysical investigation*

The systematic geophysical investigations performed within the CE are the TSWD and TSP methodologies, this last being normally executed during boreholes drilling.

4.2.1 *TSP*

The TSP methodology, aims for determining any variations in the rock mass quality, namely discontinuities (faults, pervasive joint systems etc.) beyond TBM face with a test done in correspondence of the stops for the probe-drilling.

For this purpose, the seismic source signal is generated by detonation of explosive micro-charges into dedicated short holes drilled through the segmental lining (or by means of a hitting hammer. The seismic signal, generated by the detonations or by the hammer hits and reflected by the rock mass discontinuities are recorded by 2 pairs of triaxial geophones, inserted as well into dedicated holes. The acquired data are afterward processed by means of a specific software, separating from the acquired 3D axes signals, the P (compressional) and S (shear) waves as well as the converted SH and SV.

From seismic waves velocities and their related ratio, other rock mass parameters are evaluated/derived, such as Poisson coefficient, static and dynamic Young modulus, as well as the shear modulus.

4.2.2 *TSWD*

The TSWD methodology can derive the same parameters of the TSP but with a continuous acquisition since it uses as source signal the elastic waves generated by the cutter-head vibrations during excavation. Such continuous signal is transformed into a classic seismogram thanks to the use of a pilot signal directly measured at the source.

The TSWD procedure avoids downtime since no explosive is used and with the cutter-head vibrations allow to get a high frequency signal, reflected by geological discontinuities related

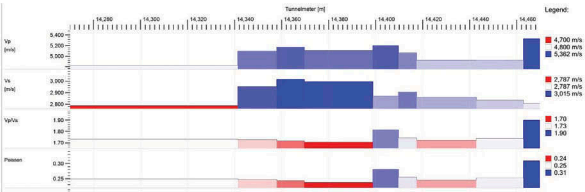

Figure 4. Example of executed TSP investigation by Akron (software TSP303 from Amber SA).

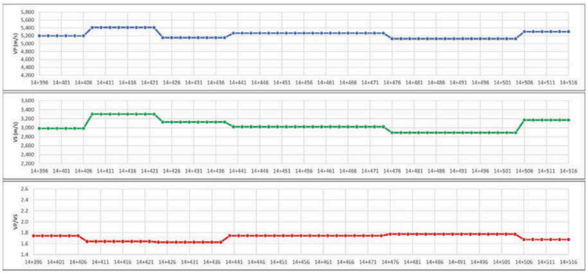

Figure 5. Example of one of last executed TSWD report by Akron Srl.

to faults, competence variations, voids, highly fractured horizons, etc., which can be easily extracted from background noise.

The TSWD methodology allows to get spatial and temporal continuity information from reflecting horizons because the investigation is carried out permanently moving forward the measuring stations and keeping continuously the same distance from the cutter head: in this way an overlap between following reports is kept allowing continuous updating of the information.

The comparison between the two methodologies TSP and TSWD allows a calibration of the two systems.

4.2.3 *BEAM*

The BEAM (Bore tunneling Electrical Ahead Monitoring) is a geophysical investigation methodology, consisting to induct polarization, at different frequencies, through the rock mass, to measure related resistivity. The BEAM configuration is constituted by 3-electrodes, being:

- A0+ can be the cutter-head itself, one of the single elements in contact with ground,
- A1+, the tail shield or one of the safety constructional components,
- returning one B (-), positioned on the rings (or at the portal).

The generated static electric field leads to the identification of rock mass volumes characterized by a roughly homogeneous conductivity capacity and thus it is possible to highlight the presence of underground waters and/or poor geomechanical conditions.

4.3 *TBM parameters analysis*

The overall parameters recorded by the PLC of the TBM are stored in the Tunneling Process Control (TPC) software, which allows to further plot, analyze and correlate all of them, filtering by time, ring, chainages (pk), and time. Routinely, main TBM key performance parameters are considered and examined to verify interpretations got from drilled boreholes and performed geophysical investigations, always with the aim to verify rock mass conditions foreseen in the geotechnical profile and to improve the interpretation ability to steer CE excavation and the knowledge along the alignment to facilitate the drive of the two big TBMs. The TBM key performances parameters are:

- Cutter-head rotation speed (rpm);
- Cutter-head advancement speed (mm/min)
- Cutter-head penetration (mm/rev);
- Cutter-head rotation torque (kNm);
- Main cylinders thrust (kN);
- Specific excavation energy [kWh/m^3];
- Excavated volumes (m^3);
- Volumes (bi-component grout) injected at shield bottom tail (m^3);
- Volumes (pea-gravel or expanded clay) injected behind ring segments (m^3);

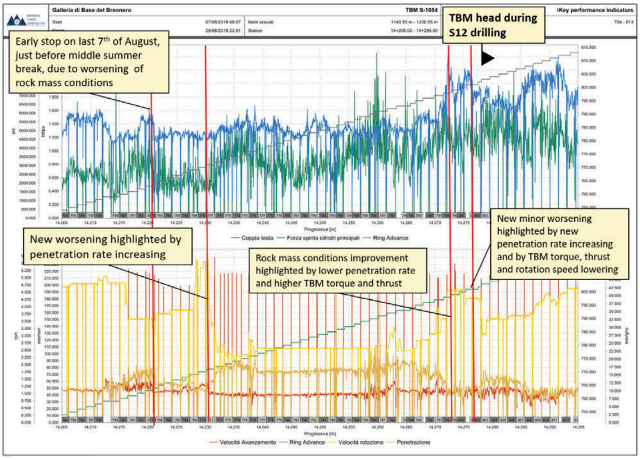

Figure 6. Example of interpreted TBM key performances parameters chart.

4.4 *Convergence monitoring*

The CE convergence monitoring plan in intended to check after the excavation the effective stability of the tunnel and supporting system; this is obtained by implementing different instruments with different aims:

- Convergence monitoring by TBM shield.
- Monitoring annular gap behind ring extrados;
- Convergence measures with optical targets and with AWCS system.

Monitoring by TBM Shield

The rock mass tendencies to close against the shield is checked to monitor the risk of shield blockage using:

- N° 5 extendable jacks (fontimeters) for the automatic reading of the annular gap above the shield extrados, n° 3 of them placed on the frontal and n° 2 on the gripper shield
- N° 6 pressure cells, n° 3 of them placed on the frontal shield and n° 3 on the gripper shield.

Monitoring annular gap behind ring extrados

The annular void filling behind the rings is performed by a bi-component grout in the invert and pea-gravel or expanded clay on crown and sidewalls; as knonw this system typical of a DS.TBM operation has the intrinsic risk of leaving empty volumes, which need to be detected and filled to assure the long-term stability of the rings. This check is carried out using a

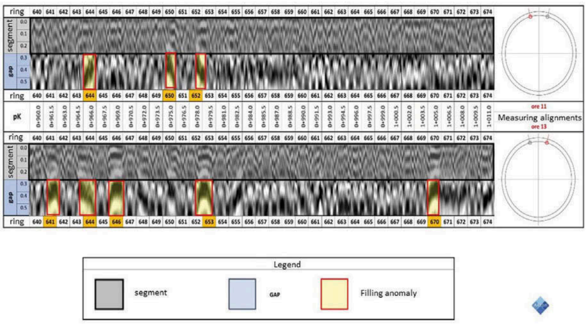

Figure 7. Example of georadar report at 11 and at 13 o’clock from Akron Srl.

georadar with double frequency antenna (200 and 600 MHz) along two 50m long profiles placed at 11 and at 13 o'clock.

Segments convergence measures with optical targets and with AWCS system

Eventual movements of the segmental lining are monitored by the classical topographical monitoring using optical targets specifically placed at in sensitive areas.

Moreover, also the AWCS (Automatic Wireless Convergence System) system is implemented with the aim to follow the movement of the rings just after the installation inside the back-up up to stabilization in an area where optical target is ineffective for a TBM drive.

5 THE TYPICAL FLOW OF INFORMATION FROM THE TUNNEL

The information is flowing from two main sources:

- from TPC software
- from deliverables done by specialized subcontractors

In the frame of such huge quantity of available data, the management of those concerned to rock mass geological conditions interpretation, have been so far organized according to what detailed hereunder.

Daily analysis:

- analysis of TBM advancement key parameters from TPC
- analysis of possible over-excavations/convergence from TPC such as excavated volumes, fontimeters, shield pressure cells, etc.

Just after every probe drilling (almost weekly):

- drilling parameters analysis and interpretation
- geophysical investigations analysis and interpretation (TSP/TSWD)

Weekly, all the recorded, analyzed and interpreted data, are presented and discussed with the Engineer team.

6 THE CONSTRUCTION OF THE ENGINEERED AS BUILT PROFILE

The main recorded and analyzed data concerning investigations, as-built excavation parameters etc., are finally condensed in a summarizing engineered as-built profile drawn up by means of excel software.

Within the engineered as-built profile the following basic information are collected:

- Ring installation data: number, key segment location, date of installation, initial and final pk, relevant TBE head pk and CE absolute pk

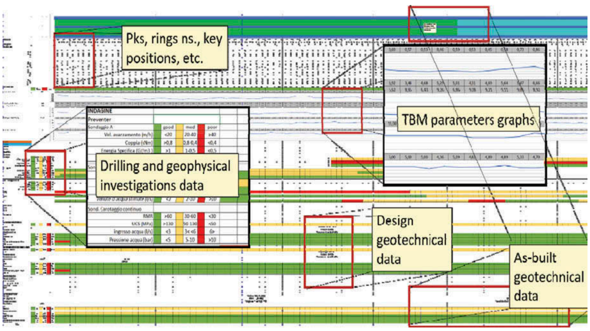

Figure 8. Extract from the final summarizing engineered as-built profile.

- Main TBM excavation parameters: average for ring values of cutter-head rotation torque, Main cylinders thrust, Auxiliary cylinders thrust, cutter-head penetration and rotation speed;
- Investigation results highlighted, by means of colored legends, for probe drilling and geophysical investigations (for probe drilling, advancing speed, torque, Specific Energy and estimated water incomings flow.
- Simplified geology as-built which is actually the result of all the above-mentioned interpretation

7 CONCLUSIONS

While writing the paper (September 14th, 2018) the CE TBM reached to excavate the 11,2% of its drive at pk 14+653 (ring 1052) well inside the calcschists tectonic unit, while the following investigations has been carried out:

- n° 15 core destruction boreholes have been drilled
- n° 12 TSP investigation have been executed
- n° 26 TSWD investigation reports are already produced with a usual overlapping, between closing reports of 40–50 m.
- BEAM reports are produced, on average, every advancing meter and cover an investigation depth of 20 in front of TBM head.
- n° 8 instrumented rings have been installed

Along this first stretch of alignment the DS-TBM never faced really critical situations, not even along the passage between Austroalpine paraschists and amphibolites to the calcshists tectonic unit, whose relevant contacts were supposed to be faulted.

On the other hand, some limited problems have been related to the crossing of Afens fault system, approximately between PK 14+210 and 14+270 m, approached just before the middle August stop and completely crossed just after.

Such fault system was detected by probe drills n. 10 and 11, which allowed to advice the crew well in advance thus being prepared to this condition.

Before this, only one significant water incoming has been crossed, at rough 70 m depth (about pk 13+840 m) during the drilling of core destruction boreholes S7, for an approximate flow of 10–20 l/s (which, at the end of borehole drilling was already significantly reduced).

The short story recorded so far and the possibility to detect in advance the few critical points crossed is considered a good achievement and a signal that the overall system of investigation is organized to react and put in place the proper counter-measures.

REFERENCES

Frisch, W., 1976. Ein Modell zur alpidischen Evolution und Orogenese des Tauernfensters. Geologische Rundschau, 65: 375–392. Berlin:Springer Nature

Frisch, W., 1979. Tectonic progradation and plate tectonic evolution of the Alps. Tectonophysics, 60: 121–139. Amsterdam: Elsevier

Fügenschuh, B., Seward, D. & Mancktelow, N.S., 1997. Exhumation in a convergent orogen: the western Tauern window. Terra Nova, 9 (5–6):213–217. Hoboken NJ USA: Wiley

Lammerer, B. & Weger, M., 1998. Footwall Uplift in an Orogenic Wedge - The Tauern Window in the Eastern Alps of Europe. Tectonophysics, 285 (3–4):213–230. Amsterdam: Elsevier

Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S.M. & Neugebauer, J., 1989. Extension in compressional orogenic belts: the Eastern Alps. Geology, 17: 404–407. McLean, VA, USA: Geological Society of America

Ratschbacher, L., Frisch, W., Linzer, H.-G. & Merle, O., 1991. Lateral extrusion in the Eastern Alps, Part 2: Structural Analysis. Tectonics, 10 (2):257–271. Hoboken NJ USA: Wiley

Selverstone, J., 1988. Evidence for east-west crustal extension in the eastern Alps: implications for the unroofing history of the Tauern Window. Tectonics, 7 (1):87–105. Hoboken NJ USA: Wiley