Τεχνικογεωλογική αξιολόγηση και διαχείριση κατολισθητικών φαινομένων κατά μήκος αγωγών φυσικού αερίου. Εμπειρίες από τον αγωγό TAP

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***Αν. Καθηγητής ΑΠΘ**

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3ο Επιστημονικό Forum για τη Μείωση της Διακινδύνευσης από Καταστροφές στην Ελλάδα

Hellenic Disaster Risk Reduction Forum
HDRRF

ΤΜΗΜΑ ΓΕΩΛΟΓΙΑΣ ΑΠΘ

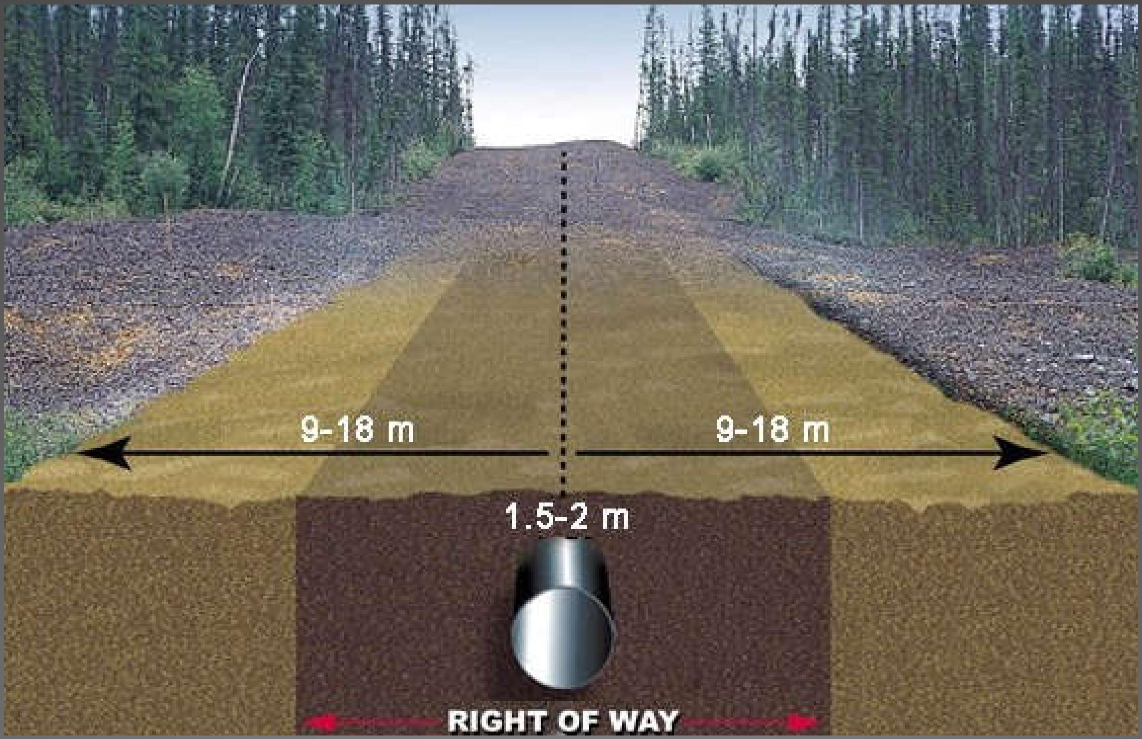
OUTLINE

I. General characteristics – Requirements
II. Landslide hazard and pipelines
III. Landslide Management Plan: Avoidance / Analysis / Mitigation
IV. Experiences from TAP pipeline
V. Discussion

I. GENERAL CHARACTERISTICS - REQUIREMENTS

- Steel tubes with inner diameter up to 1.2m. Most of them are buried in a 1-2m depth.
- Compressor Station: located along the line to move the product through the pipeline and retain the pressure
- Block valve station: first line of protection for pipelines. Isolate any segment of the line for maintenance work or isolate a rupture or leak. Located every 50Km aprox.

RoW: Right of Way



- A right-of-way (ROW) is a strip of land usually between 18 m and 36 m wide, containing one or more pipelines.
- Access for inspection, maintenance, testing or in an emergency; Identifies an area where certain activities are prohibited to protect public safety and the integrity of the pipeline.
- Activities such as paving, building permanent or temporary structures, and planting deep-rooted shrubs and trees are not allowed on the right-of-way

I. GENERAL CHARACTERISTICS - REQUIREMENTS

Trench excavation

Trenchless techniques

Boring/jacking, auger bore, HDD (horizontal directional drilling) and micro-tunnelling

I. GENERAL CHARACTERISTICS - REQUIREMENTS

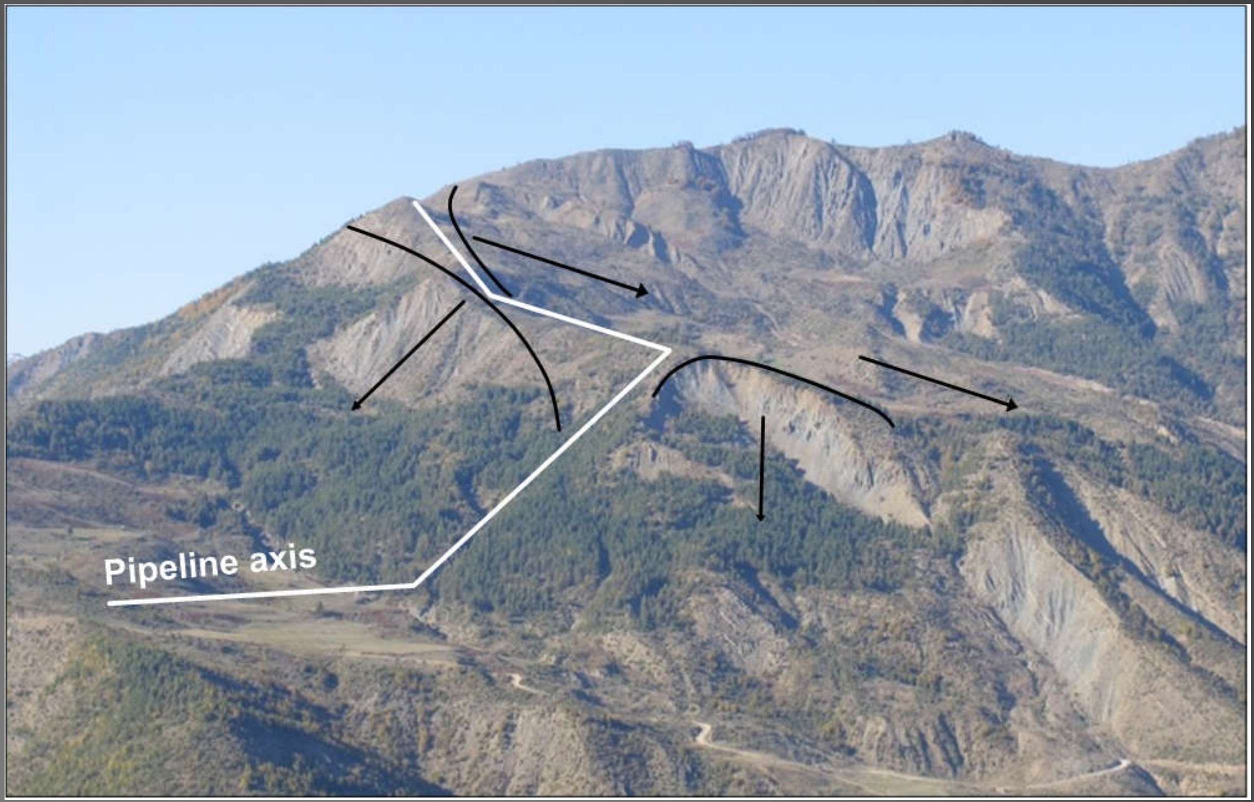
Morphology Challenges: Narrow ridges and Steep slopes

Lee, personal communication

Lee, personal communication

II. GEOHAZARDS AND PIPELINES

- Landslides
- Liquefaction
- Active faults
- Karst



Landsliding is a major factor for pipeline route selection in mountainous regions

II. LANDSLIDE HAZARD AND PIPELINES

A significant hazard for pipelines - A significant operational risk

- They can generate permanent ground displacement
  - tend to result in complete failure
  - significant leaks
  - major environmental impacts
  - long periods of service disruption
- In mountainous areas: landslides the *most common cause of pipeline rupture*
- !!!!! a buried pipeline must deform both axially and in bending to accommodate the movement (Nyman et al., 2008)

Trans-Ecuador Pipeline, from Petroecuador

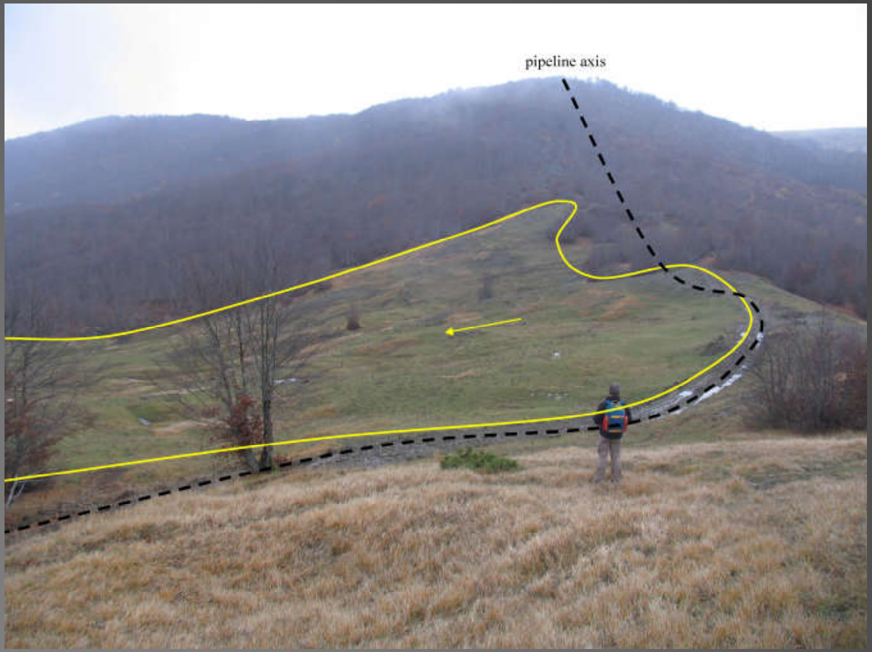
- Destruction consequences in few Km range
- Very high cost/per day (!) service disruption

II. LANDSLIDE HAZARD ASSESSMENT

- Identify "hot spots" along the pipeline route:
  - International practice: Avoidance of landslide-prone areas is the hazard reducing option both in terms of cost and time saving
- Investigation and stabilisation is not the best international practice due to time and cost constraints (Sweeney, 2005)
- When re-routing is not possible: Prioritise risk reduction measures after detailed evaluation of all site conditions
- An important factor for the finalisation of the route

II. LANDSLIDE HAZARD ASSESSMENT

- First-time failures: characterised by large, rapid displacements
  - high velocity, large events to slowly developing very small, shallow features
- Reactivation of pre-existing landslides: movements, along pre-existing shear surfaces, (can include expansion)
  - occurs more frequently than the generation of new landslides



Pre-existing landslide on the flank of a ridge, where a pipeline route runs

Triggers can be anything from major earthquakes, rainfall or the effects of man.

II. LANDSLIDE HAZARD ASSESSMENT

Event reaches the RoW influenced by:

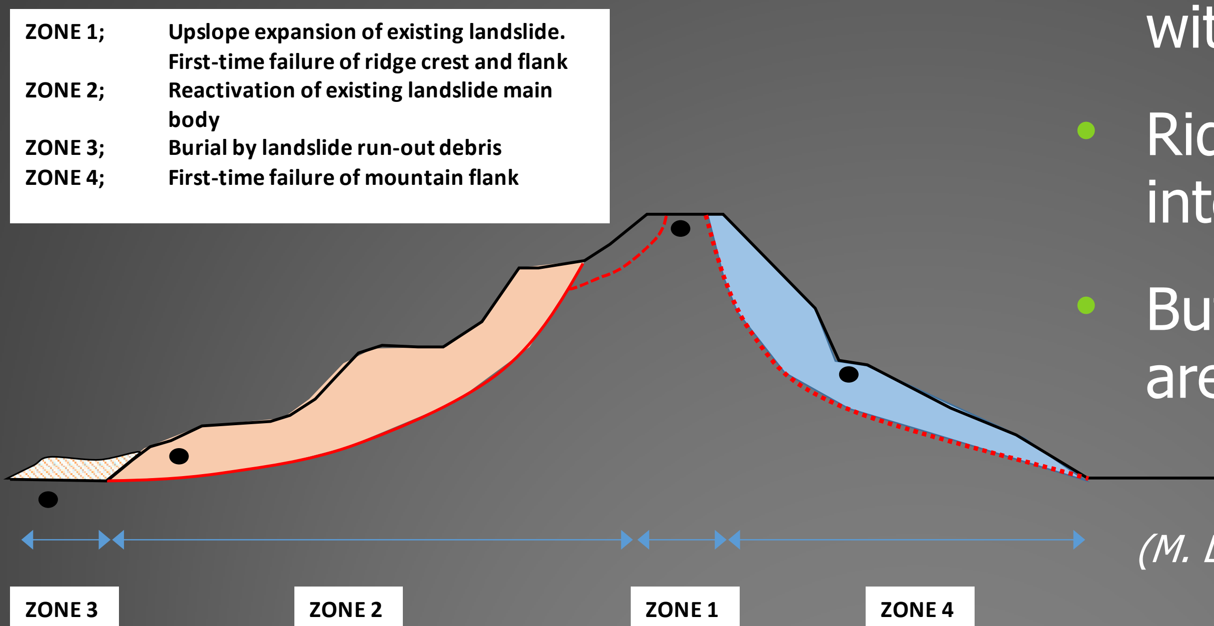
- Nature and size of the landslide event (controlled by the site geology and geomorphology)
- Proximity to the pipeline
- Position of the pipeline relative to the landslide

Credible initiating event

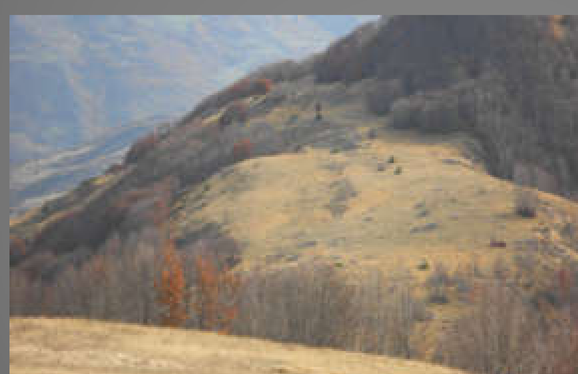
1. Increased pore-pressures (heavy rainfall or snow melt)
2. Seismic ground shaking
3. Removal of support by erosion of the landslide or slope toe
4. Loading the head of the landslide or slope

II. LANDSLIDE HAZARD ASSESSMENT

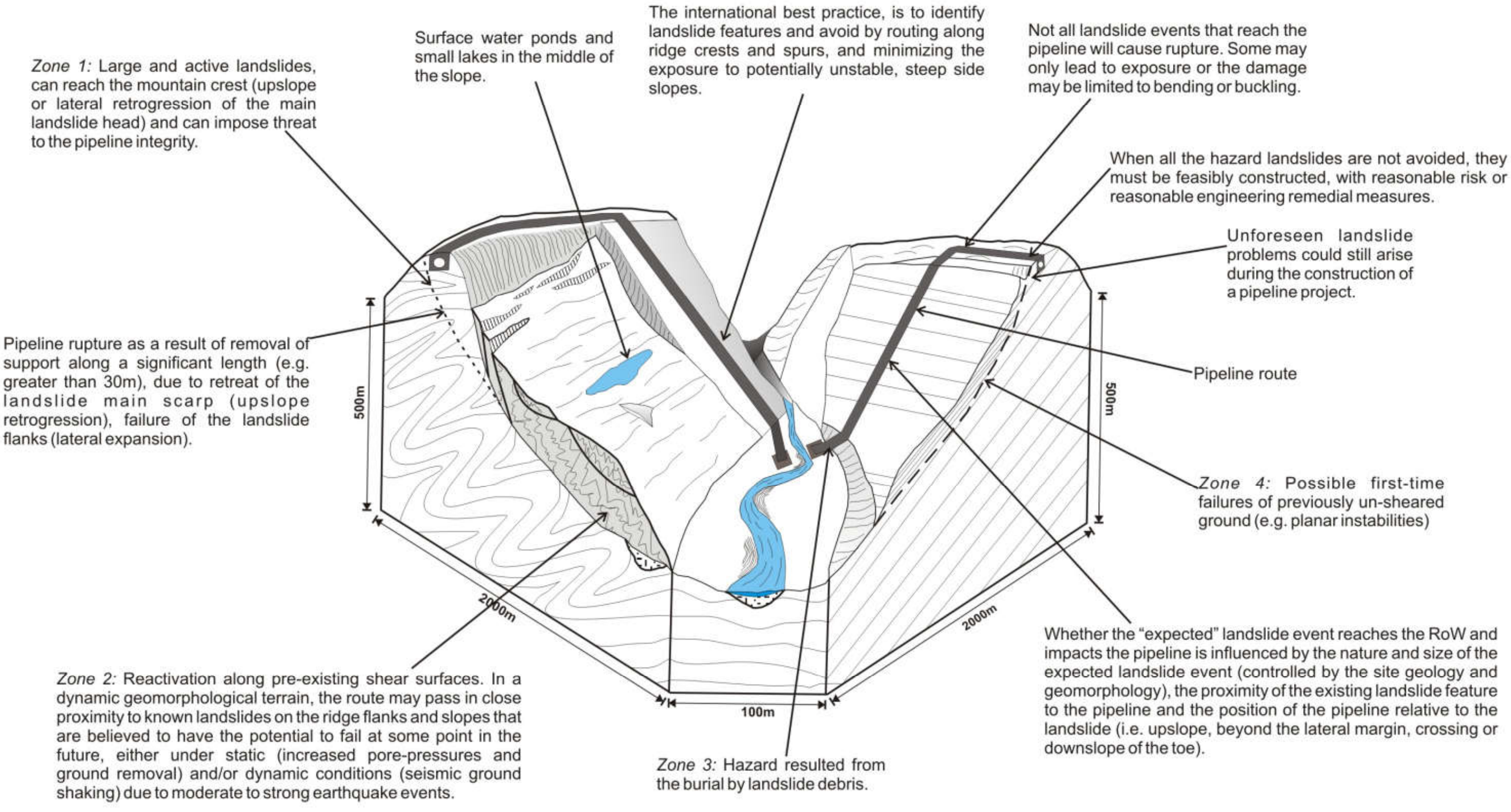
- Landslide hazard varies with the terrain setting.
- Ridge crests best international practice
- But ridge crest alignments are not risk free.



(M. Lee, personal communication)



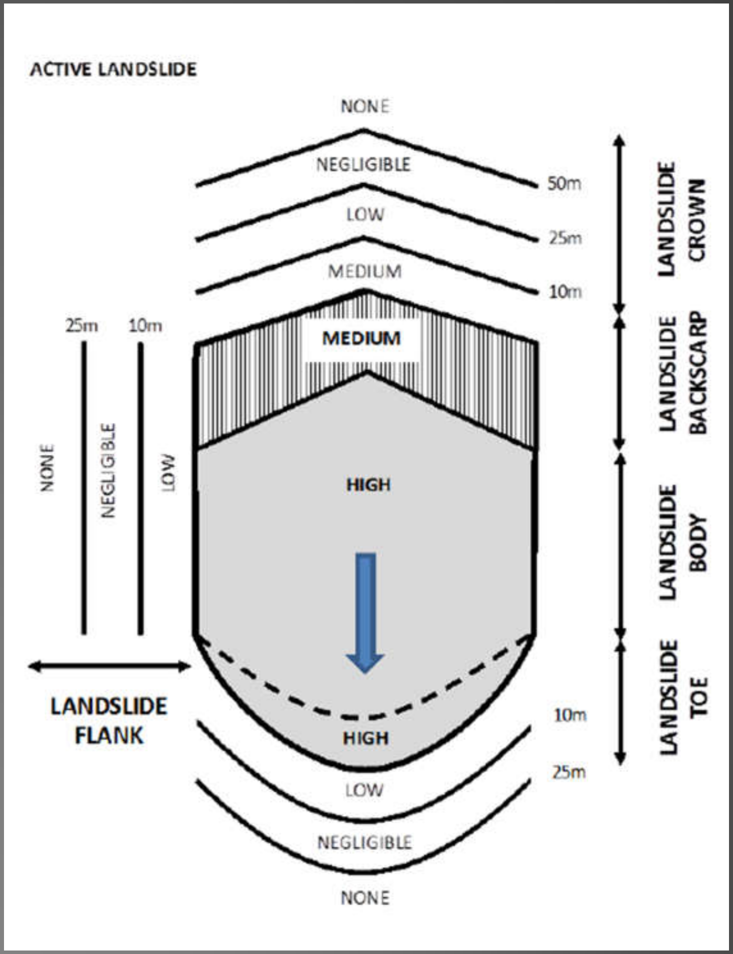
POSSIBLE FAILURE EVENT SCENARIOS ASSOCIATED WITH PIPELINE RUPTURE



II. LANDSLIDE HAZARD ASSESSMENT

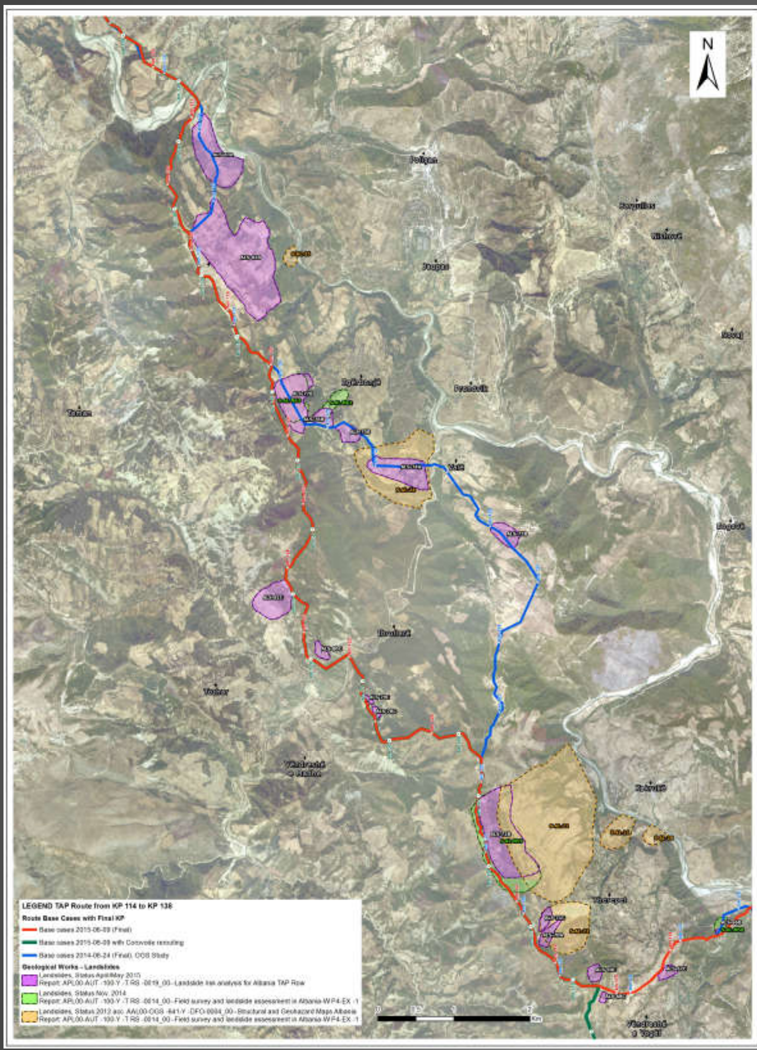
Hazard rating according to the engineering geological judgment:

- None: No hazard
- Negligible: Slide can happen under extreme circumstances
- Low: Slide is impossible to happen during the project life
- Medium: Sliding can happen during the project life
- High: Sliding is expected to happen during the project life



Hazard classes relative to landslide body and proximity to pipeline (M. Lee 2013)

Identify "hotspots" along the route



<u>Create criteria - Classify landslides based on:</u>

- Distance from the pipeline
- Relevant location
- Landslide Activity
- Sliding depth
- Mechanism of failure
- Triggering factor

LANDSLIDE INVENTORIES

LANDSLIDE EVALUATION SHEET

Trans Adriatic Pipeline - Landslide presentation and evaluation sheet

Identification code	Location	Relative position to pipeline
ALS-60B	108+800	Above the pipeline. 12m from the toe.

Landslide area
53689 m^2

Landslide max length
465 m

Landslide max breadth
190 m

Geological setting
Weathered and folded flysch rock mass and in superficial soil materials of significant thickness, various origin and variable engineering geological behaviour, namely a) river deposits, b) alluvial deposits, c) landslide materials, d) terrace deposits and e) scree of flysch origin

Terrain
Moderately steep on the south side of the pipe.

Surface water
None on the landslide mass. River adjacent.

Evidence of sliding
Old back-scarp. River bed erosion of fresh material.

Landslide type
Rotational. Deep.

Secondary slides on landslide body
Yes.

Monitoring evidence
Three inclinometers. Inconclusive readings.

Slide surface depth		
Deep		
estimated	measured at monitoring point	found (borehole data)

Landslide activity state	general	pipeline
Dormant / inactive		
Relatively inactive		
Relatively active		
Periodically active	✓	✓
Seasonally active		

Landslide active zones	
Whole landslide	✓
Limited to specific zones	
Connected to secondary units	

Expected reactivation sequence	
Progressive (head loading and downslope expansion)	
Retrogressive (toe unloading and upslope expansion)	
Lateral expansion of secondary units	
Other (state) ***Toe erosion and downslope expansion***	✓

Potential impact on the pipeline upon activation		
low	moderate	high

Likelihood of activation		
low	moderate	high

Risk assessment		
low	moderate	high

Notes - Actions suggested
Re-route or keep the pipeline below the sliding surface by changing the excavation method (e.g. microtunnelling).

LANDSLIDE HAZARD AND PIPELINES

Likelihood of Risk Event

Severity Level	1	2	3	4	5	6	7	8
	A similar event has not yet occurred in our industry and would only be a remote possibility	A similar event has not yet occurred in our industry	Similar event has occurred somewhere in our industry	Similar event has occurred somewhere within the BP Group	Similar event has occurred, or is likely to occur, within the lifetime of 10 similar facilities	Likely to occur once or twice in the facility lifetime	Event likely to occur several times in the facility lifetime	Common occurrence (at least annually) at the facility
A	8	9	10	11	12	13	14	15
B	7	8	9	10	11	12	13	14
C	6	7	8	9	10	11	12	13
D	5	6	7	8	9	10	11	12
E	4	5	6	7	8	9	10	11
F	3	4	5	6	7	8	9	10
G	2	3	4	5	6	7	8	9
H	1	2	3	4	5	6	7	8
Frequency	10^{-6} /yr or lower	$>10^{-6}$ to 10^{-5}/yr	$>10^{-5}$ to 10^{-4}/yr	$>10^{-4}$ to 10^{-3}/yr	$>10^{-3}$ to 10^{-2} /yr	$>10^{-2}$ to 10^{-1} /yr	$>10^{-1}$ to 1 /yr	>1 / yr
Probability	10^{-6} or lower	$>10^{-6}$ to 10^{-5}	$>10^{-5}$ to 10^{-4}	$>10^{-4}$ to 10^{-3}	$>10^{-3}$ to 10^{-2}	$>.01$ to 0.1	$>.1$ to 0.25	$>.25$

International oil and gas pipelines: geohazard related decision making is risk-based and not driven by Codes.

Challenge is to estimate risk and communicate it to higher management

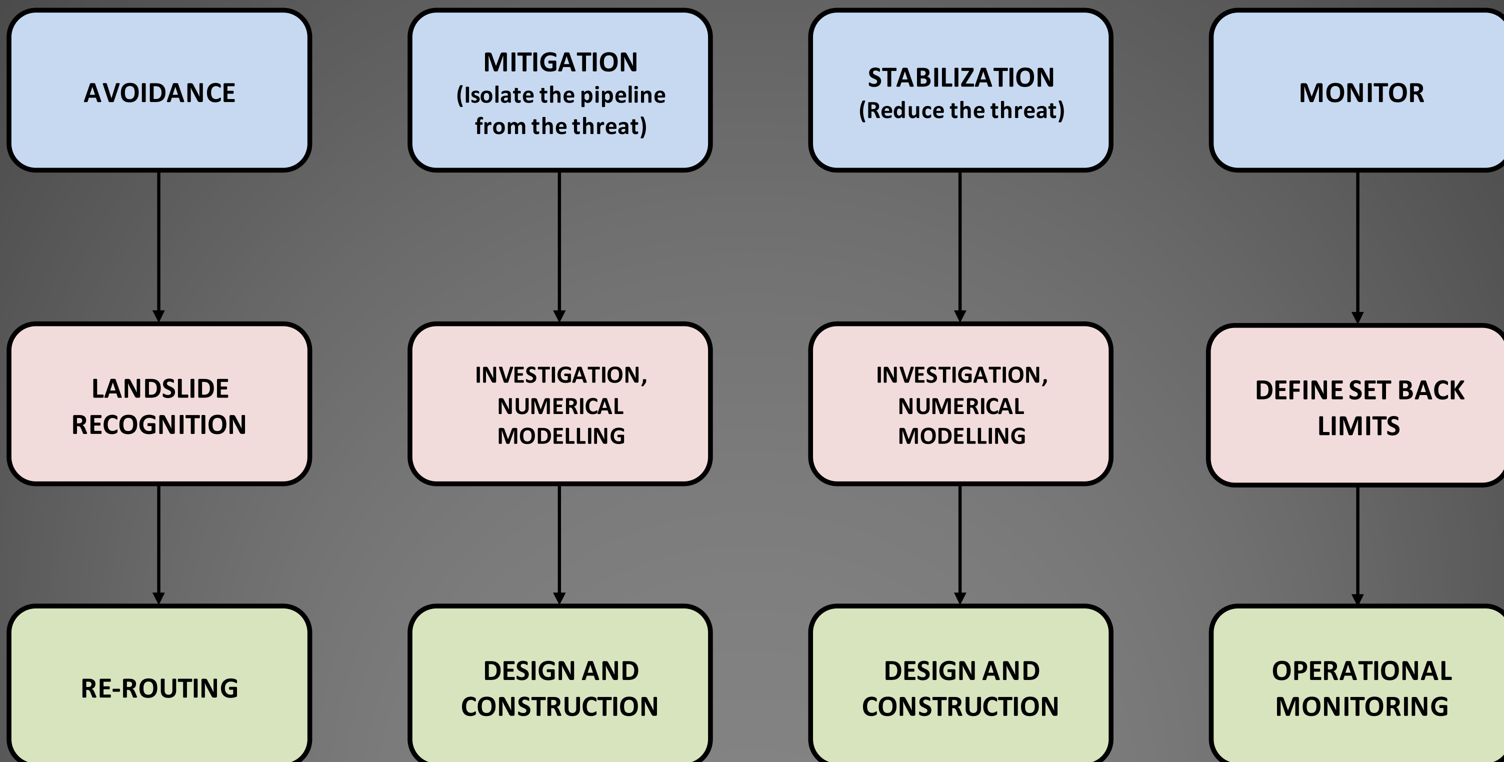
Lee, Personal communication

PROBABILITY

CONSEQUENCE	A	B	C	D	E
I	1	1	1	2	2
II	1	1	2	2	2
III	1	2	2	3	3
IV	2	3	3	3	3

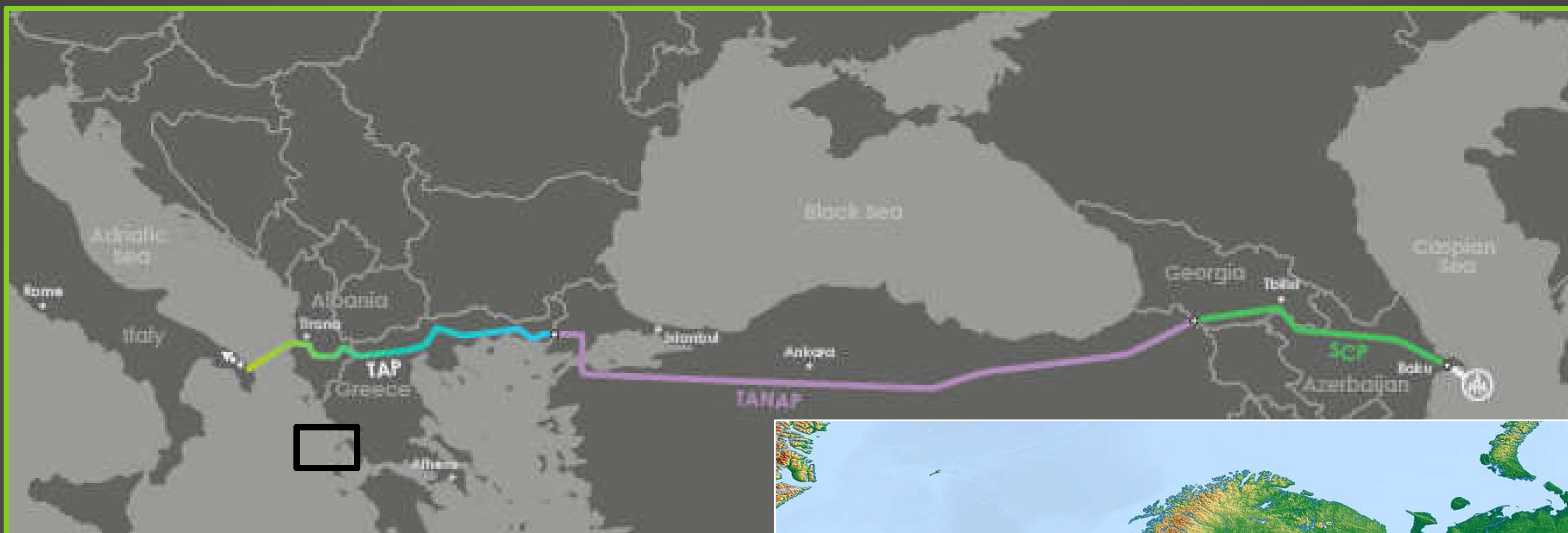
Risk Rating: 1 High | 2 Medium | 3 Low

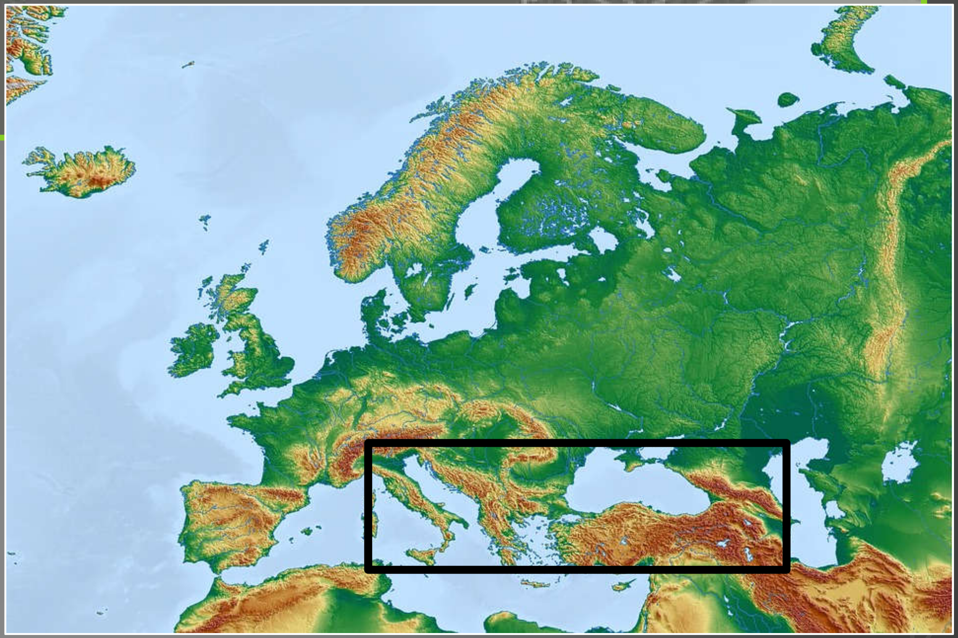
III. Landslide Management: Avoidance / Analysis / Mitigation



M. Lee, personal communication

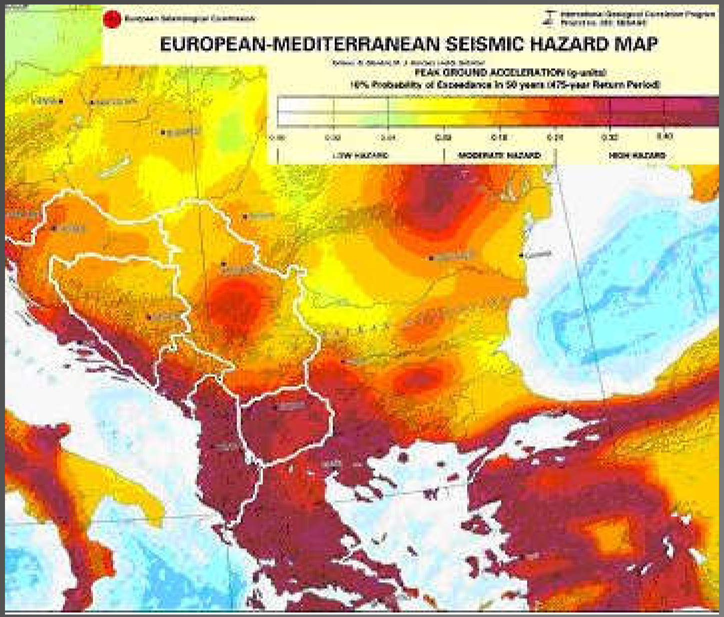
IV. Experiences from TAP pipeline – The Albanian mountain section





The Trans Adriatic Pipeline (TAP) route. The study area (shown with a black rectangle) spans approximately from 70km to 136km (KP70-KP136)

THE ALBANIAN MOUNTAINS: LANDSLIDE CAUSES



PGA 0.4g; 10% chance of exceedance in 50 years (1 in 475 year return period)

Average annual rainfall probably 1500-2000mm

Probably the most challenging onshore section of the SCPX-TANAP-TAP pipeline system: Combination of weak rocks, steep slopes, rainfall and snow melt and strong ground accelerations (earthquakes) creates an environment prone to landsliding.

At a regional level, variations in rock condition play a key role in determining where landslides have occurred.

THE WORK WAS EXECUTED MOSTLY ON THE RIDGE ALONG THE PIPELINE ROUTE

Indicative TAP RoW (dashed line) along steep and narrow terrain in central Albania

GROUND INVESTIGATION AND PIPELINES

Desk Study

- Identification from the topographic map- Sudden changes of slope angle, flat areas or bulge on slopes (square, vis-à-vis contour lines).
- Identification from satellite images – bare with no vegetation and/or steep slopes.
- Identification of surface water ponds and lakes on the slope

GROUND INVESTIGATION AND PIPELINES

Tension cracks on the ridge crest –potential for landsliding to affect the RoW.

Opening at the top and parallel to the ridge indicating movement

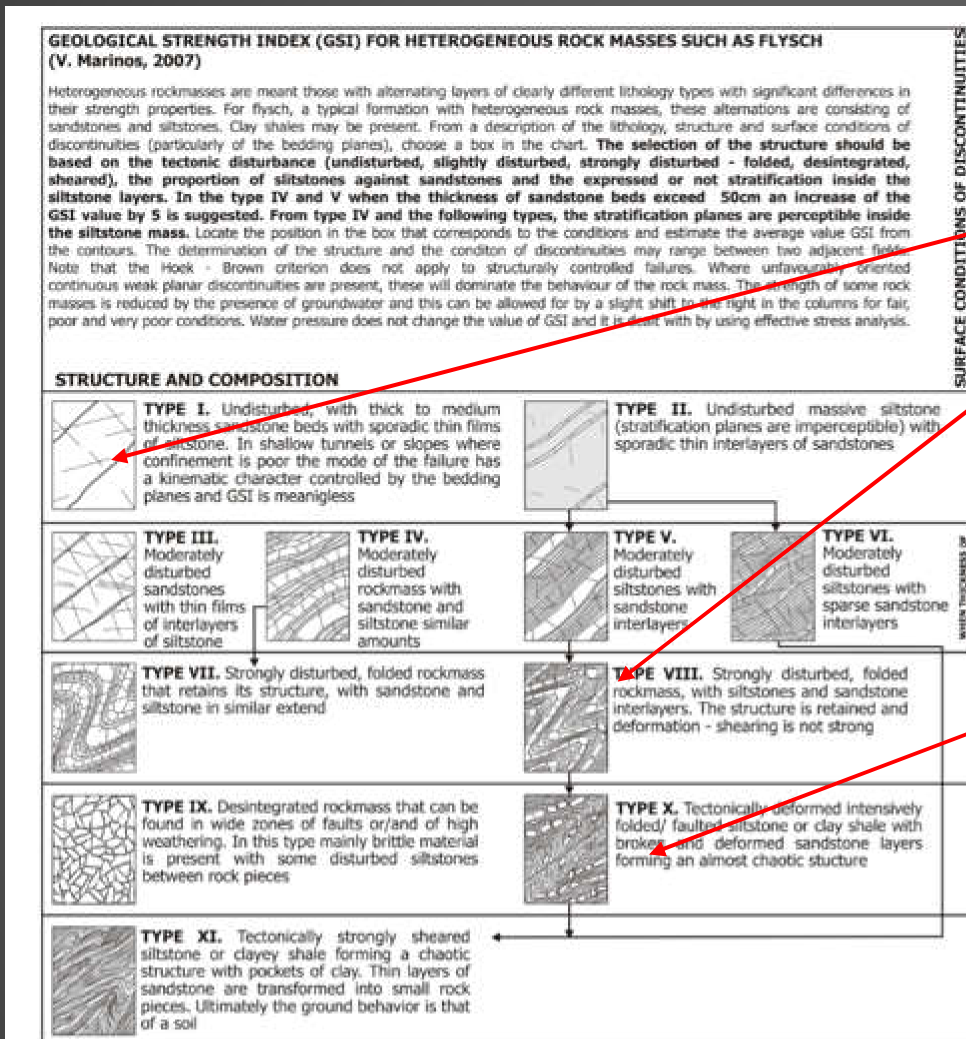
Deformed vegetation due to landsliding

Irregular topography with small hills and back-tilts along the slope

ENGINEERING GEOLOGICAL EVALUATION FOR EVERY GEOHAZARD AREA

- Qualitative characteristics about the quality of the rock mass (lithology, rock mass structure, weathering, strength, joint characteristics, water presence)
- Measurements of key structural elements
- Geotechnical classification with the GSI system
- Estimation of the weathering profile

ROCK MASS CLASSIFICATION
GSI CHART FOR HETEROGENEOUS ROCK MASS LIKE FOR FLYSCH



GEOLOGICAL STRENGTH INDEX (GSI) FOR HETEROGENEOUS ROCK MASSES SUCH AS FLYSCH (V. Marinos, 2007)

Heterogeneous rockmasses are meant those with alternating layers of clearly different lithology types with significant differences in their strength properties. For flysch, a typical formation with heterogeneous rock masses, these alternations are consisting of sandstones and siltstones. Clay shales may be present. From a description of the lithology, structure and surface conditions of discontinuities (particularly of the bedding planes), choose a box in the chart. **The selection of the structure should be based on the tectonic disturbance (undisturbed, slightly disturbed, strongly disturbed - folded, desintegrated, sheared), the proportion of siltstones against sandstones and the expressed or not stratification inside the siltstone layers. In the type IV and V when the thickness of sandstone beds exceed 50cm an increase of the GSI value by 5 is suggested. From type IV and the following types, the stratification planes are perceptible inside the siltstone mass.** Locate the position in the box that corresponds to the conditions and estimate the average value GSI from the contours. The determination of the structure and the conditon of discontinuities may range between two adjacent fields. Note that the Hoek - Brown criterion does not apply to structurally controlled failures. Where unfavourably oriented continuous weak planar discontinuities are present, these will dominate the behaviour of the rock mass. The strength of some rock masses is reduced by the presence of groundwater and this can be allowed for by a slight shift to the right in the columns for fair, poor and very poor conditions. Water pressure does not change the value of GSI and it is dealt with by using effective stress analysis.

SURFACE CONDITIONS OF DISCONTINUITIES

STRUCTURE AND COMPOSITION

TYPE I. Undisturbed, with thick to medium thickness sandstone beds with sporadic thin films of siltstone. In shallow tunnels or slopes where confinement is poor the mode of the failure has a kinematic character controlled by the bedding planes and GSI is meaningless

TYPE II. Undisturbed massive siltstone (stratification planes are imperceptible) with sporadic thin interlayers of sandstones

TYPE III. Moderately disturbed sandstones with thin films of interlayers of siltstone

TYPE IV. Moderately disturbed rockmass with sandstone and siltstone similar amounts

TYPE V. Moderately disturbed siltstones with sandstone interlayers

TYPE VI. Moderately disturbed siltstones with sparse sandstone interlayers

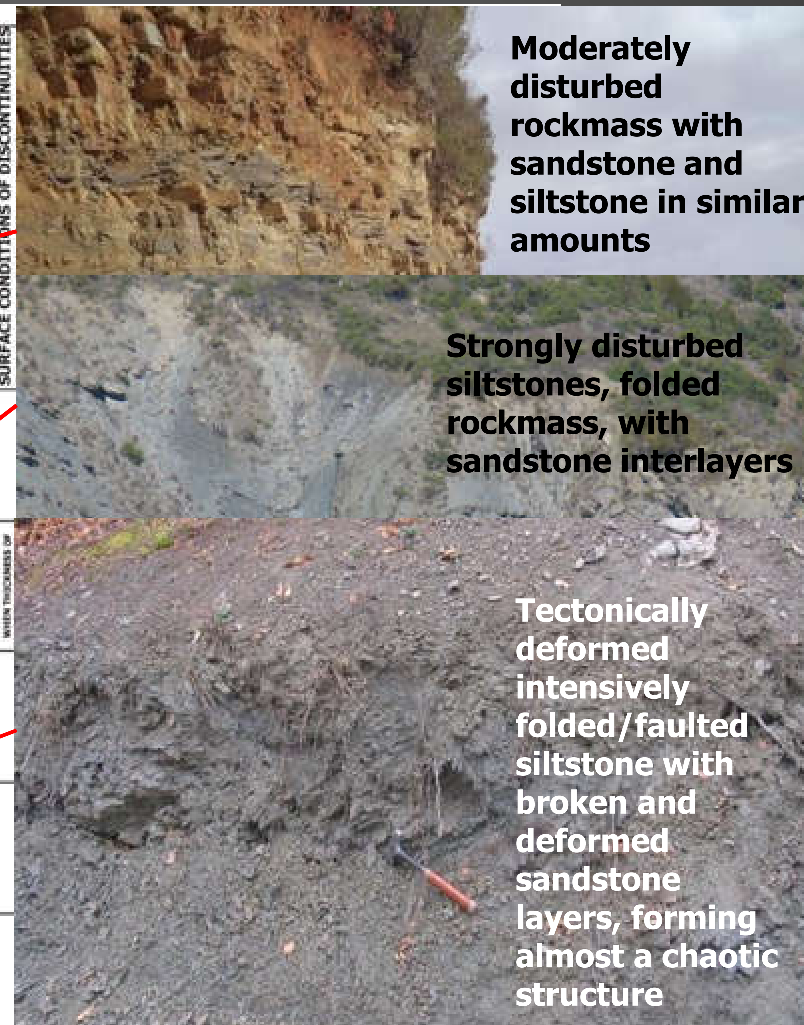
TYPE VII. Strongly disturbed, folded rockmass that retains its structure, with sandstone and siltstone in similar extend

TYPE VIII. Strongly disturbed, folded rockmass, with siltstones and sandstone interlayers. The structure is retained and deformation - shearing is not strong

TYPE IX. Desintegrated rockmass that can be found in wide zones of faults or/and of high weathering. In this type mainly brittle material is present with some disturbed siltstones between rock pieces

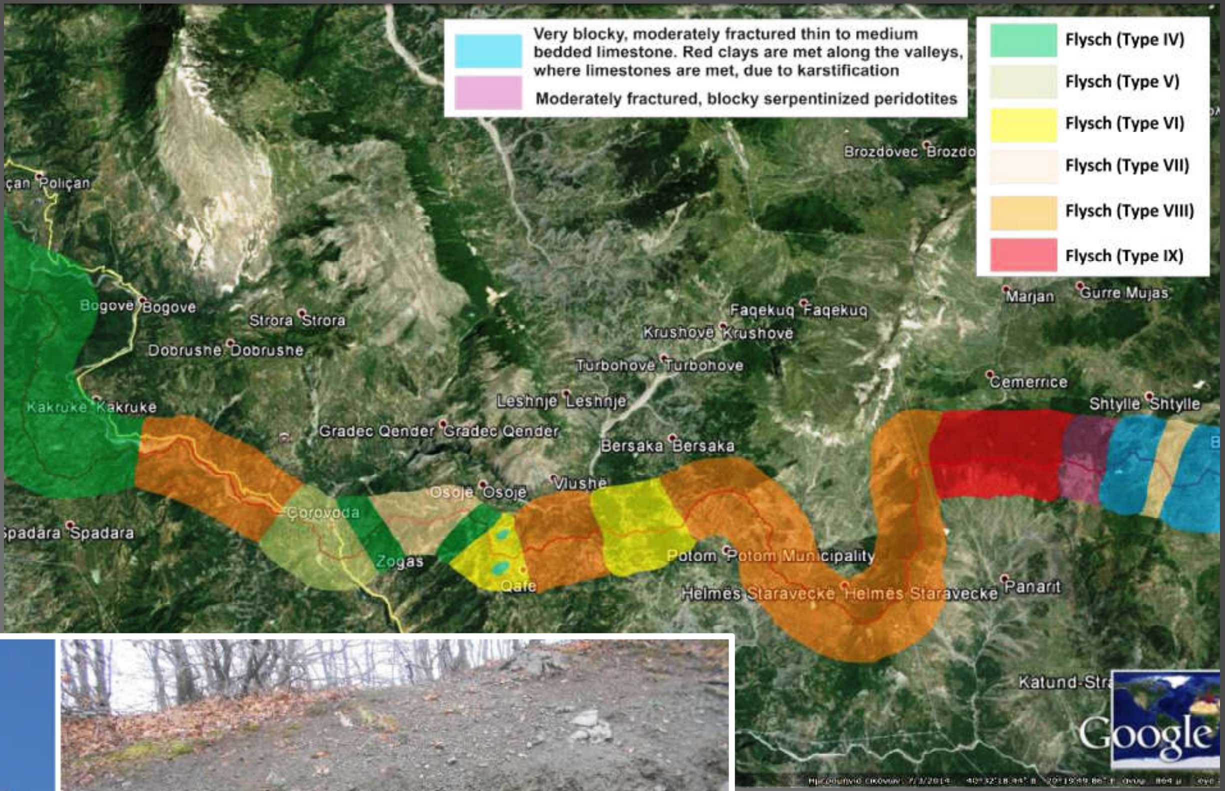
TYPE X. Tectonically deformed intensively folded/ faulted siltstone or clay shale with broken and deformed sandstone layers forming an almost chaotic stucture

TYPE XI. Tectonically strongly sheared siltstone or clayey shale forming a chaotic structure with pockets of clay. Thin layers of sandstone are transformed into small rock pieces. Ultimately the ground behavior is that of a soil



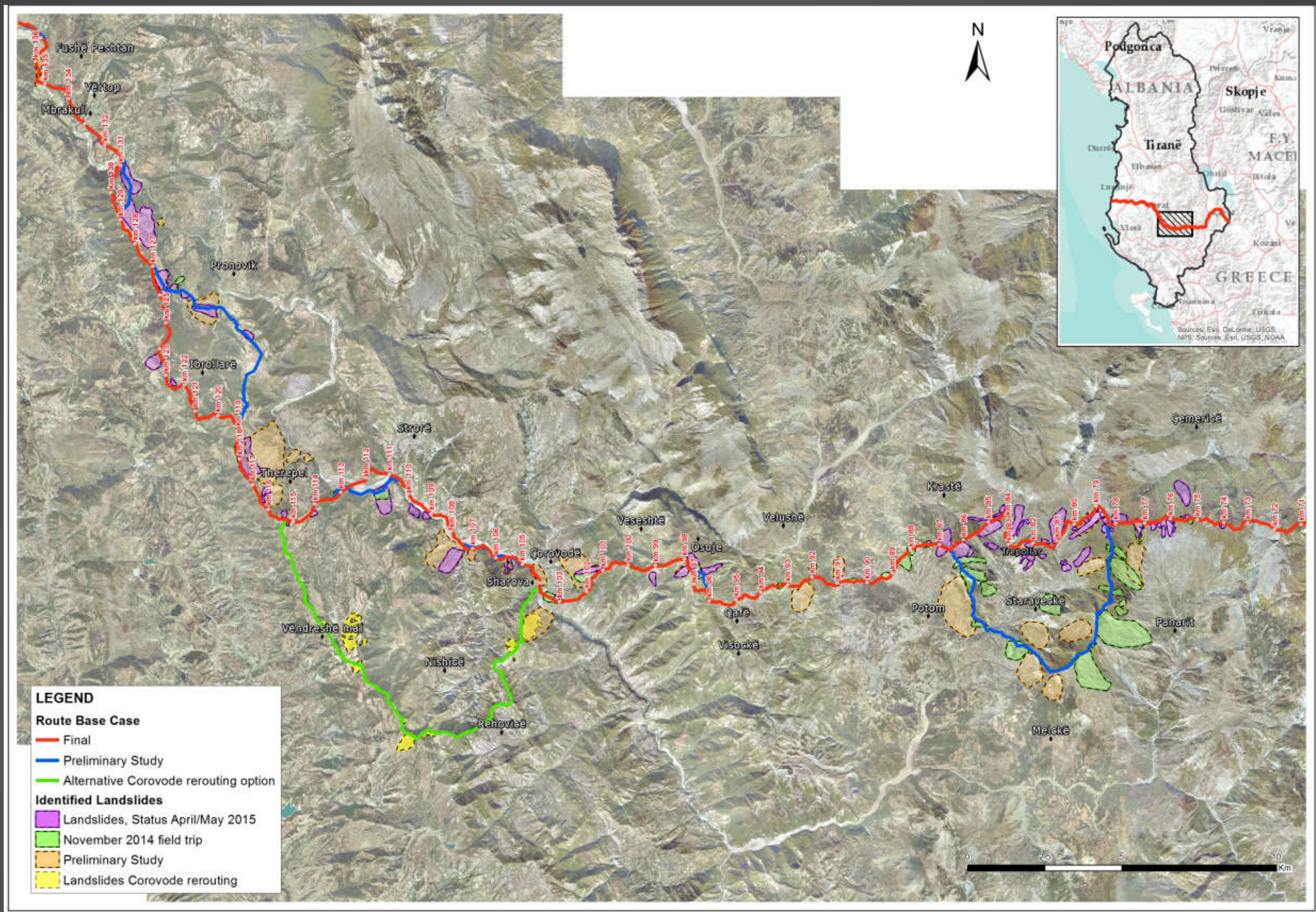
Marinos 2007, 2017

ZONATION OF THE ROCK MASS QUALITY ALONG THE ROUTE



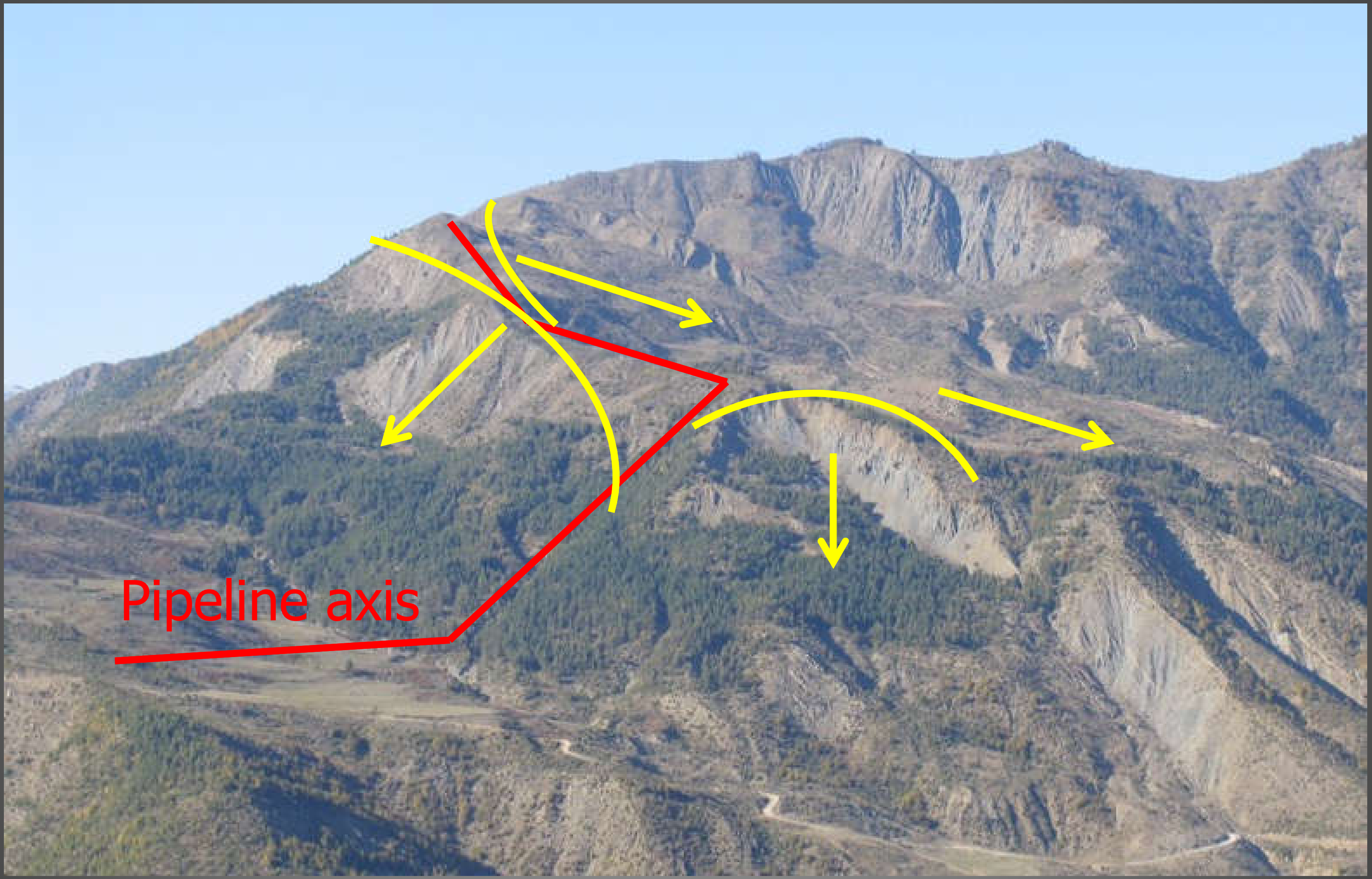
Typical examples of flysch type VIII (left) and flysch type IX (right) at landslide masses.

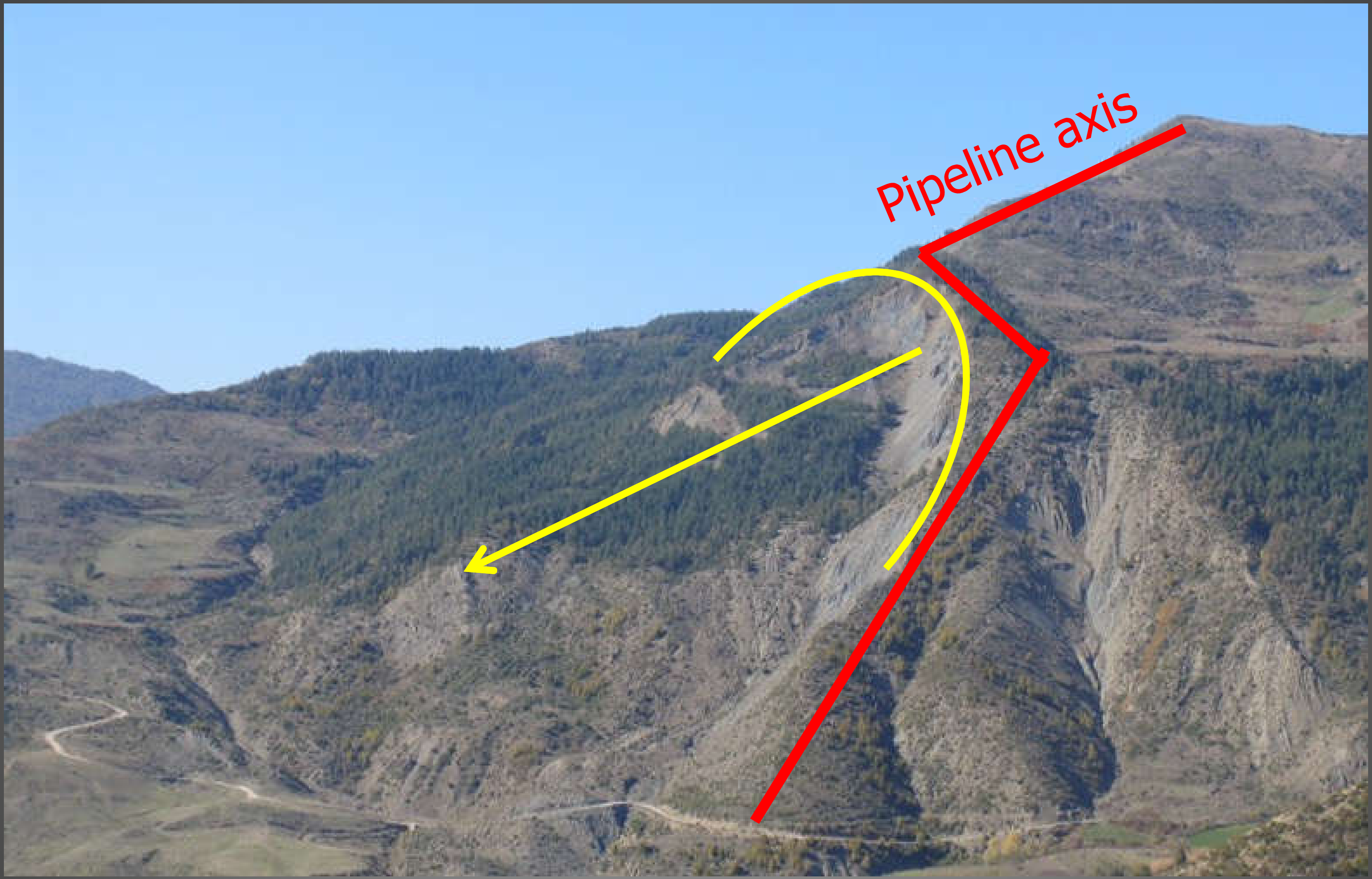
LANDSLIDE INVENTORY



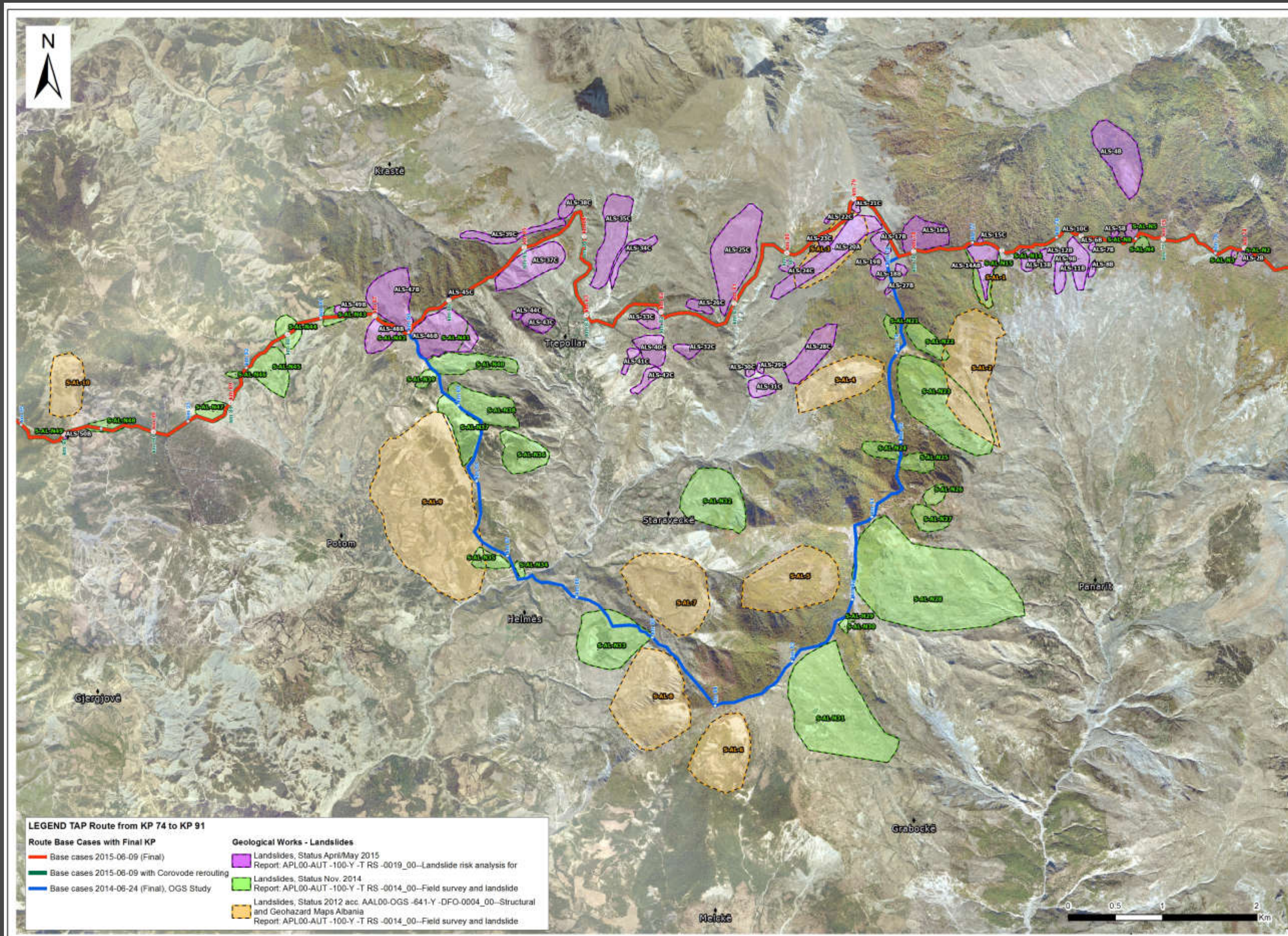
Inventory of 82 landslides compiled from satellite imagery and field survey. Landslides are depicted by polygons

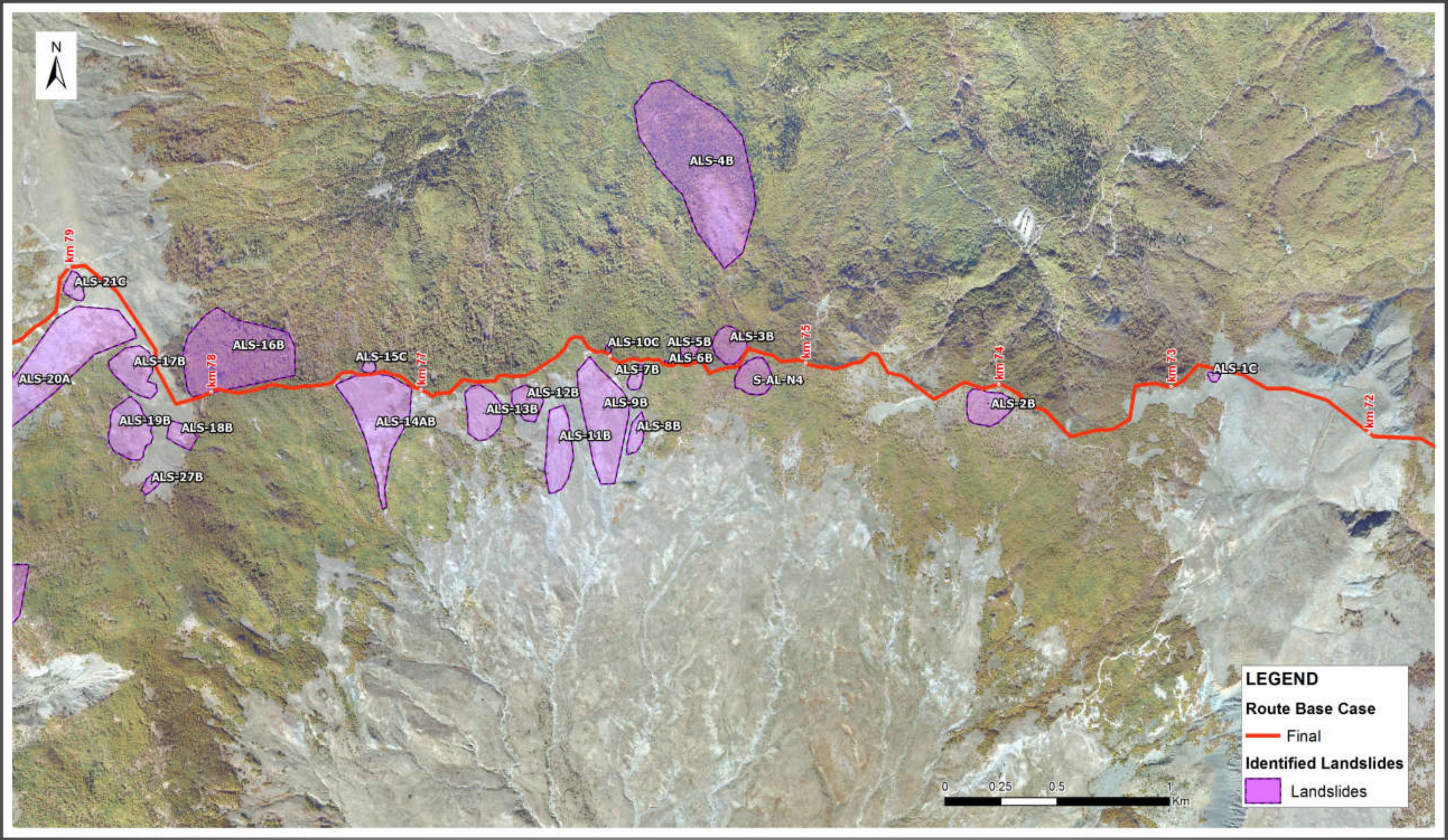
SEVERAL LARGE LANDSLIDES – SOME ACTIVE WITH FRESH CRACKS -




Pipeline axis

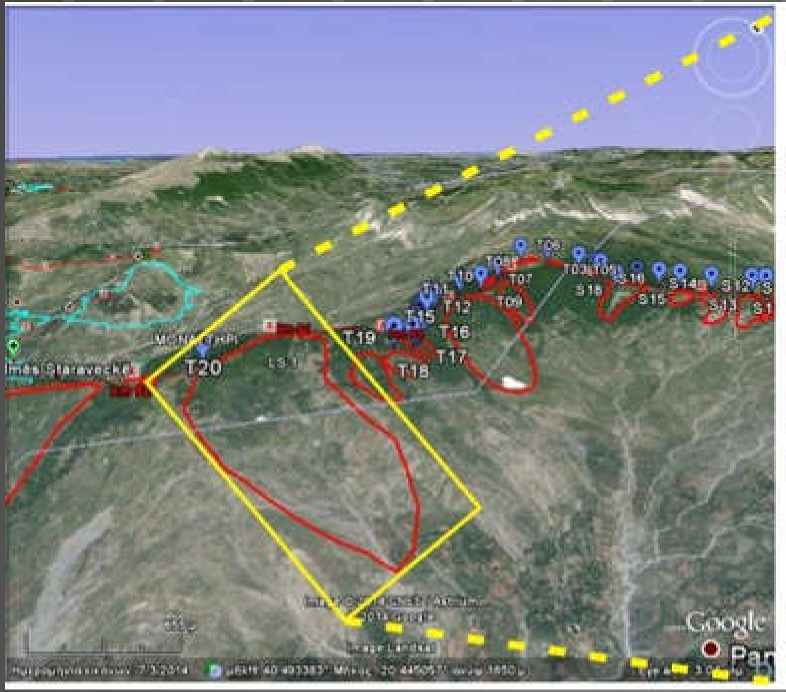
THE MOST HAZARDOUS AREA: 75KM-90KM



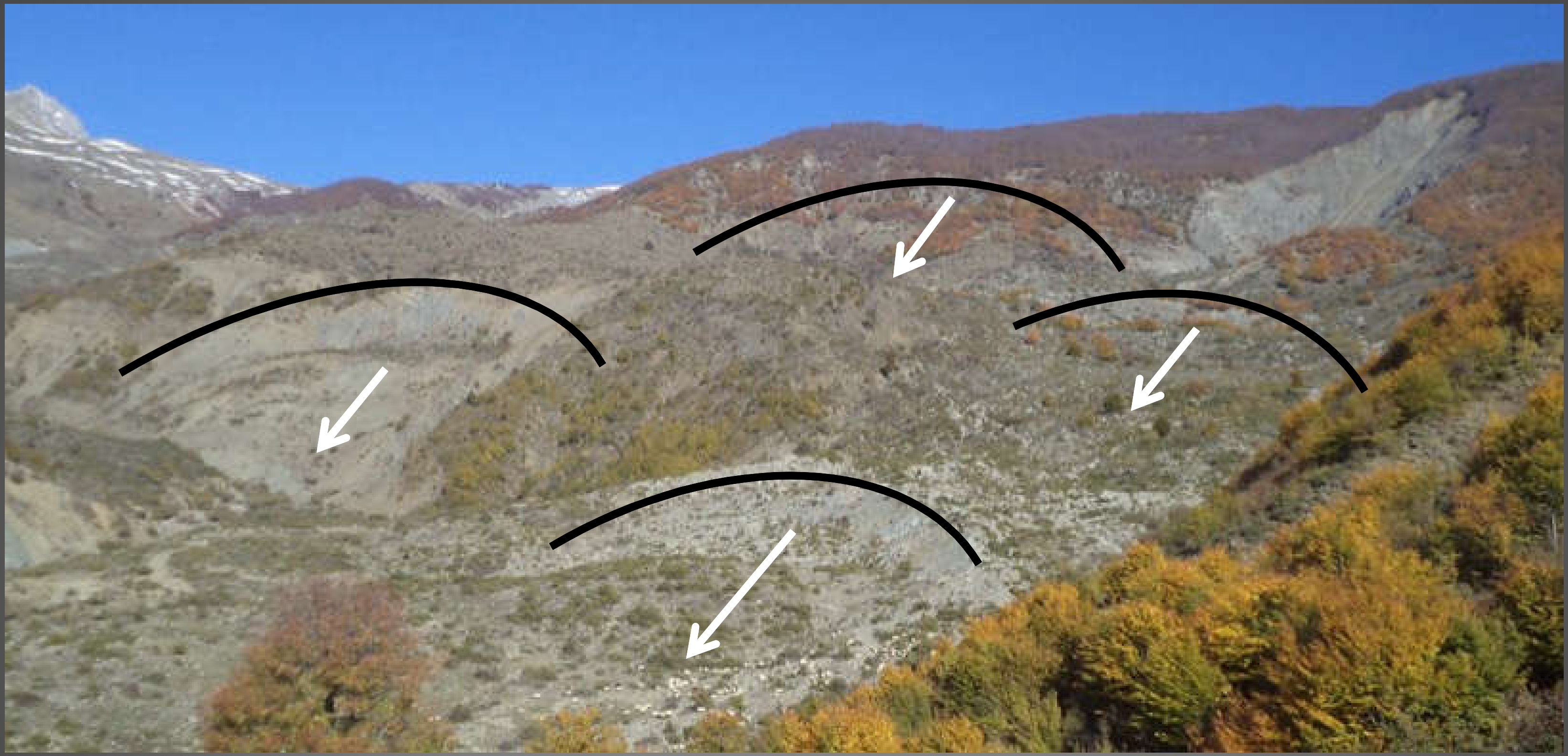


Landslide inventory of the TAP segment between 72km and 79km, where several landslides are located close to the TAP RoW, threatening pipeline integrity

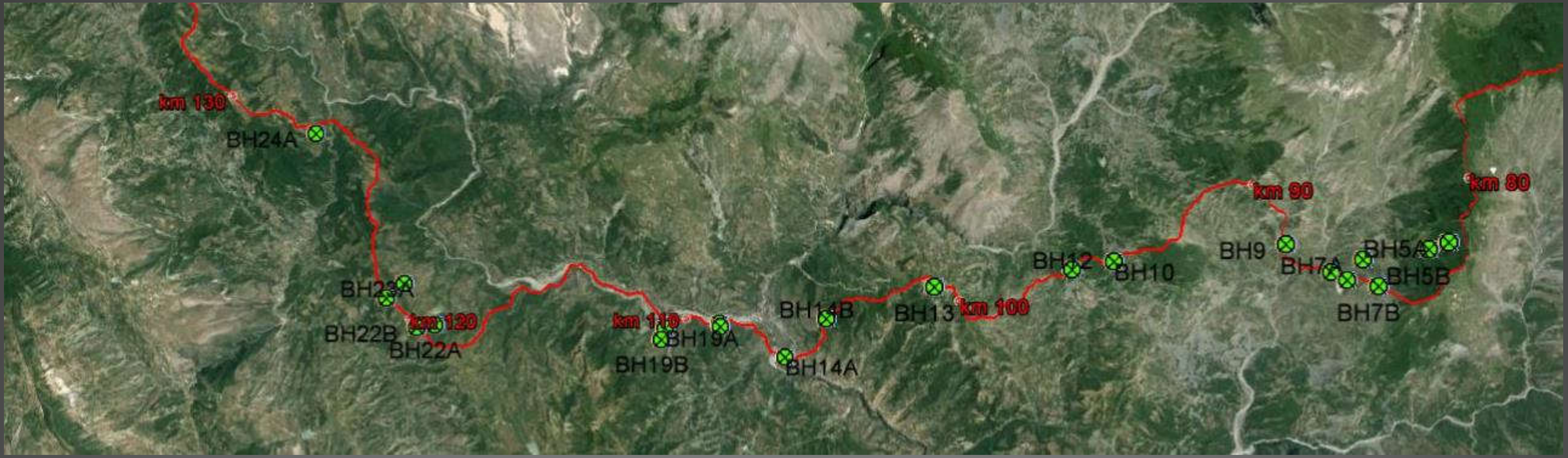
LANDSLIDE S-AL-N23
KM: 81



ONE SLIDE IS OFTEN TRIGGERED BY OTHER SLIDES AT THE BOTTOM OF THE MOUNTAIN



LANDSLIDE INVESTIGATION



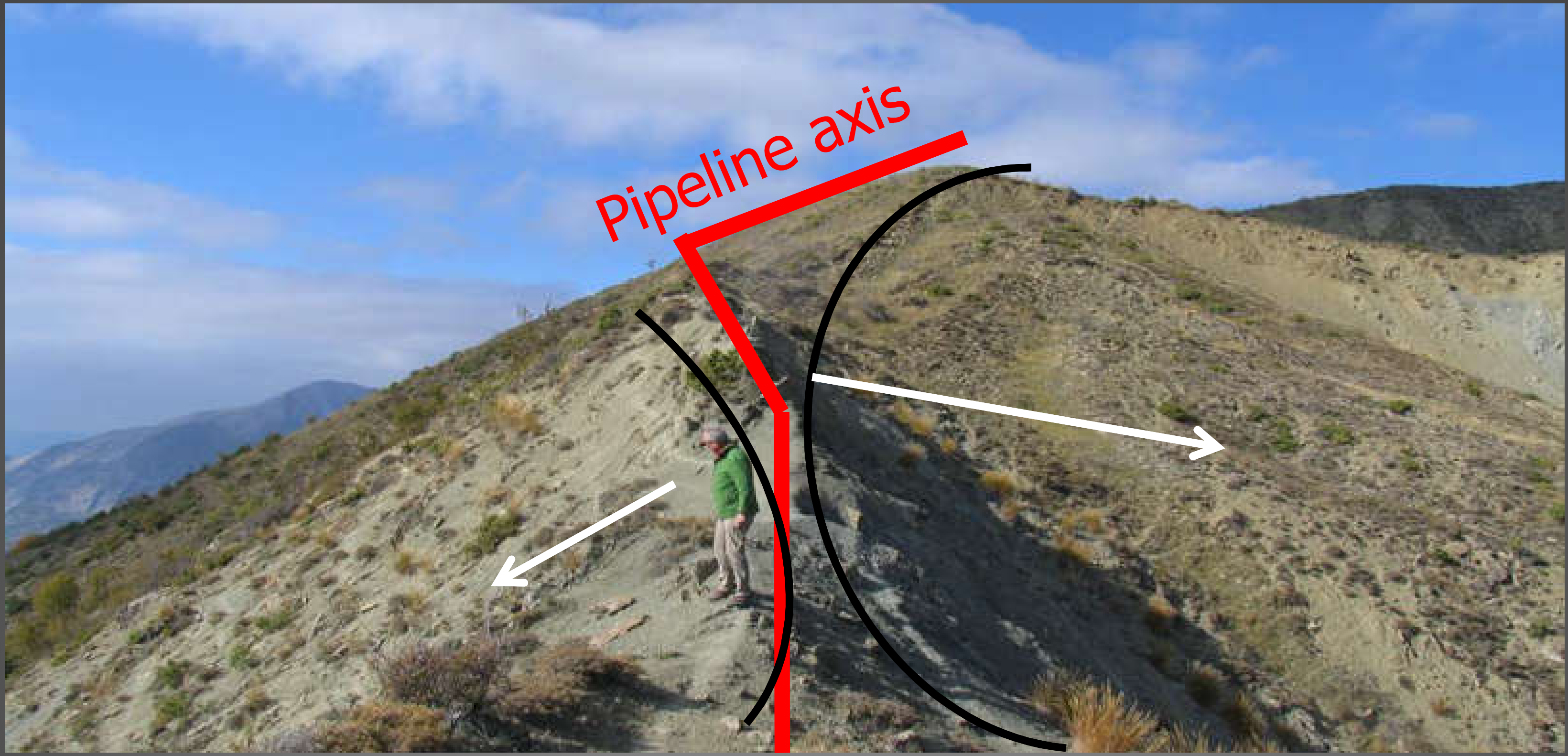
Boreholes have been drilled.

Weather and access constraints.

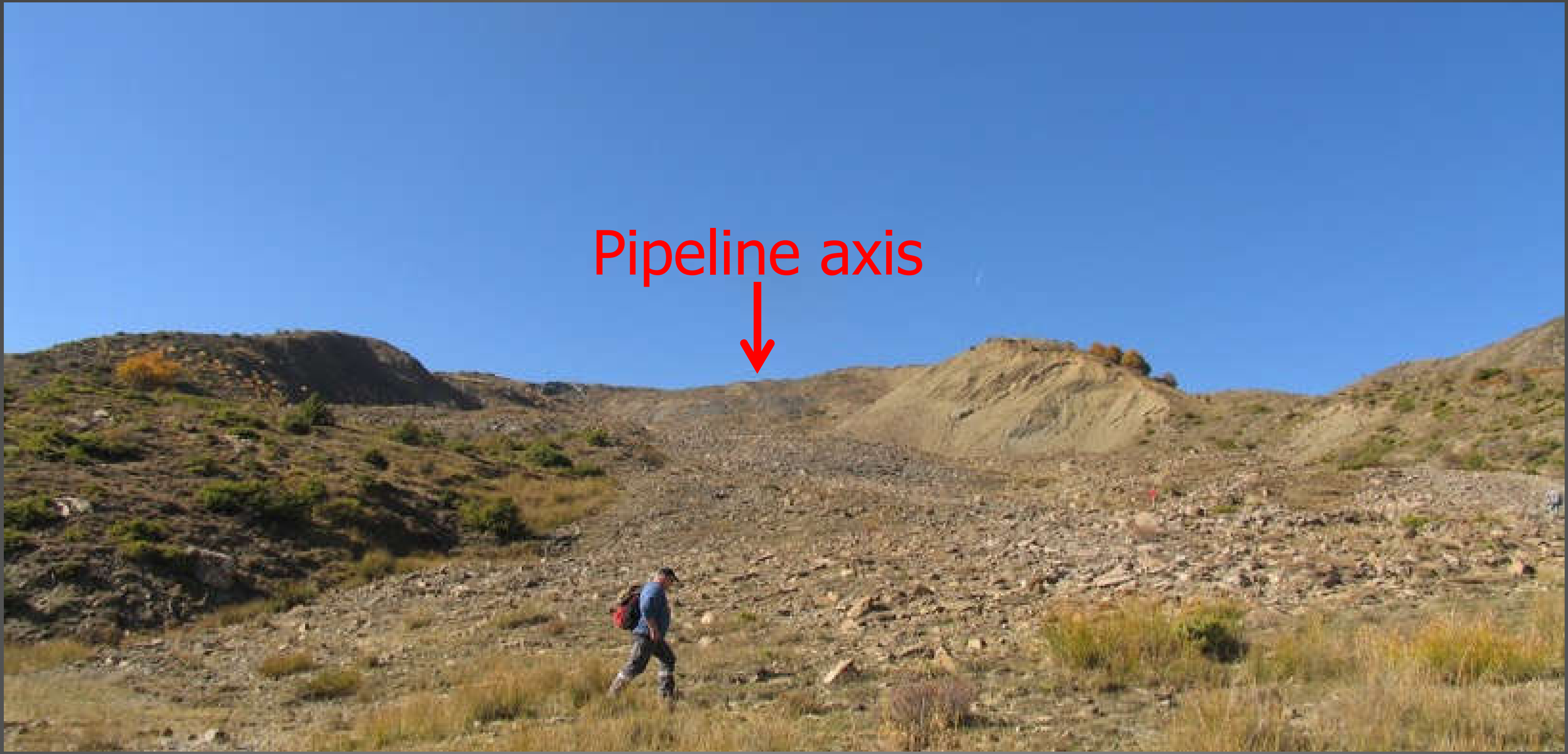
Key findings:

- Landslides are typically deep-seated (>20m to base)
- Multiple shear surfaces likely to be present

A RIDGE WHERE TWO LANDSLIDES ARE MET



GEOHAZARD: N40

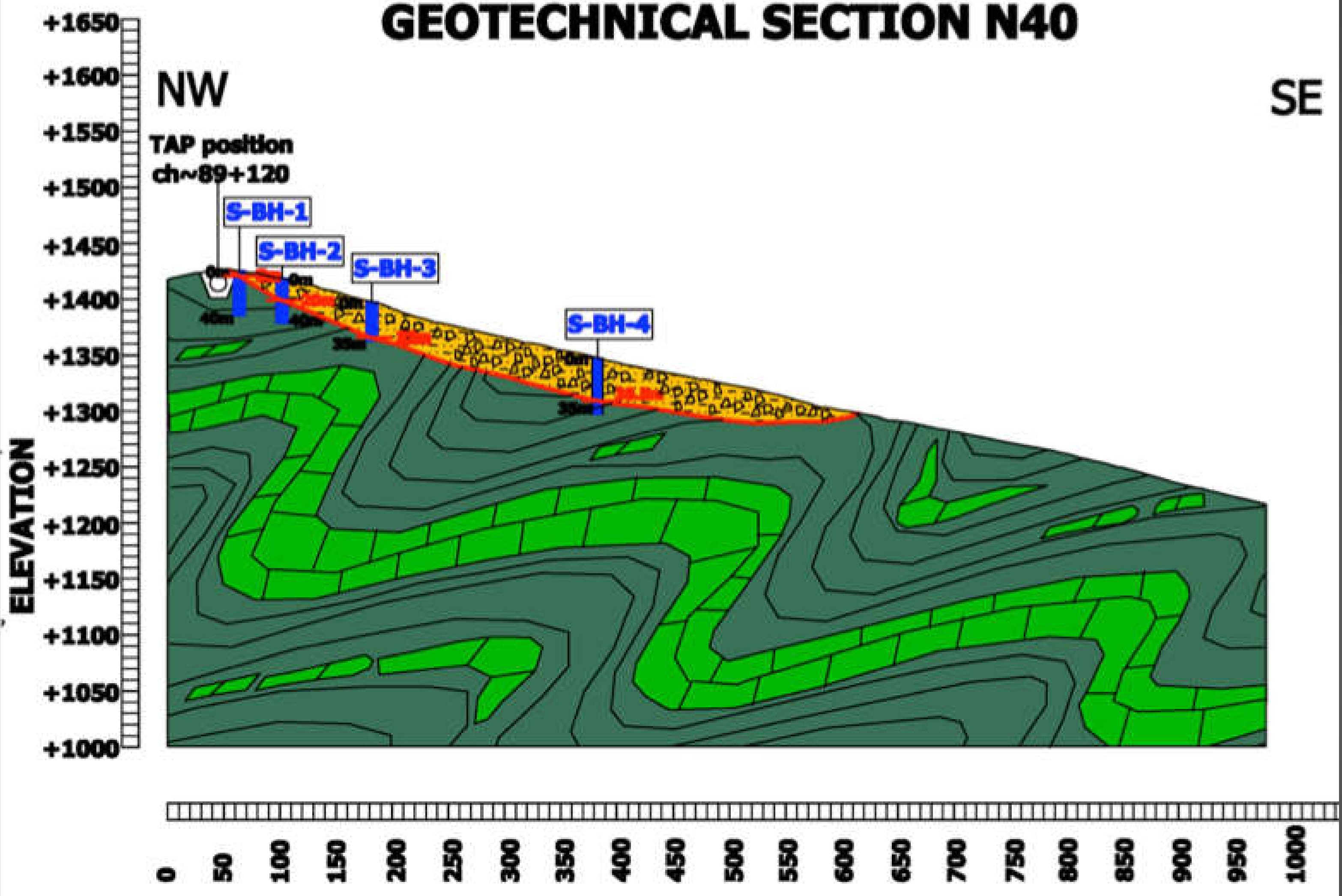


GEOHAZARD: N40

GEOHAZARD: N40 BH-3

GEOHAZARD: N40 BH3

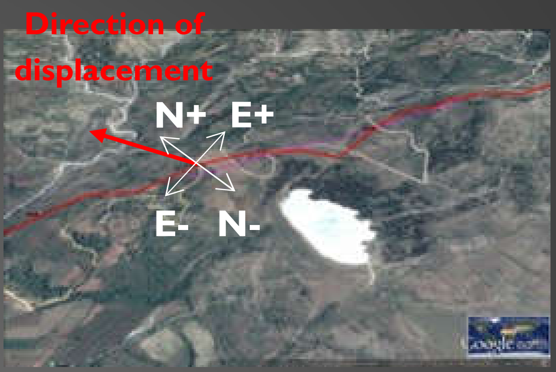
GEOHAZARD S-AL-N40
GEOTECHNICAL SECTION N40

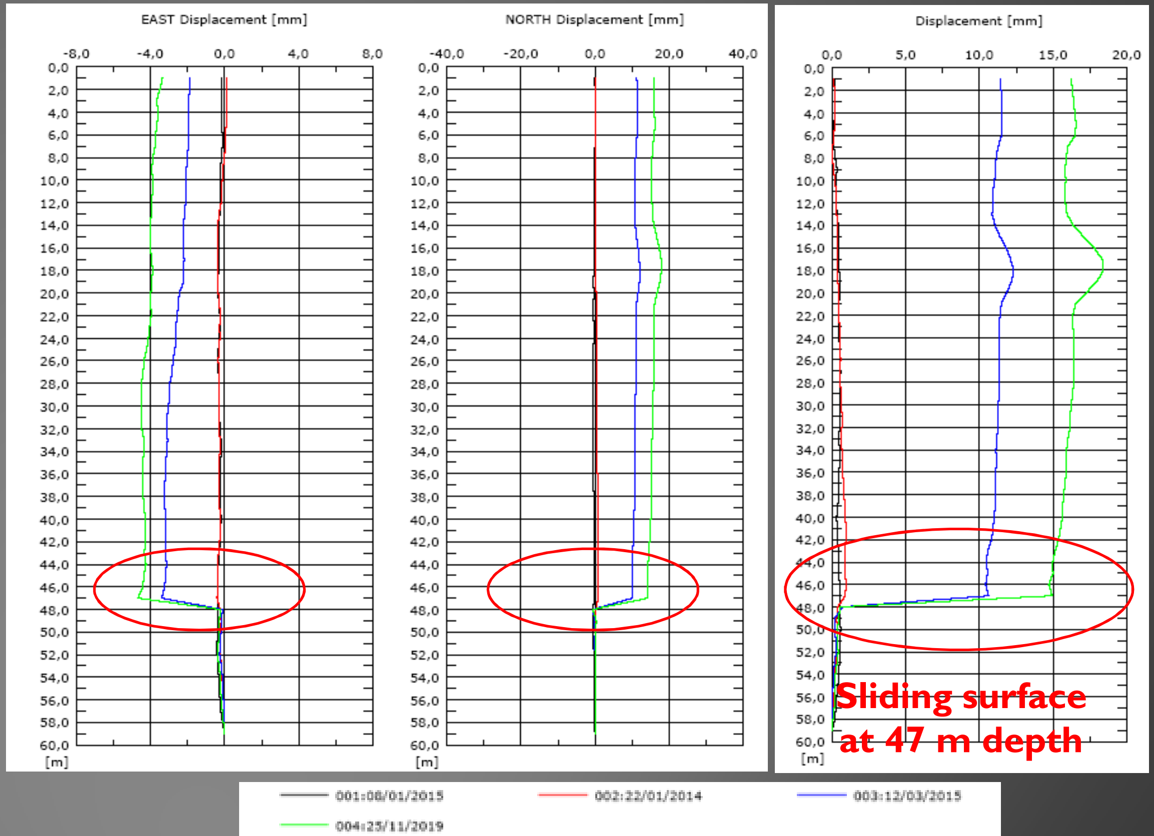


Ground Investigation Campaign - Inclinometers

Inclinometer BH-8B

- Sliding surface at 47 m depth
- Horizontal movement of 16 mm from January 2015
- The horizontal movement was measured between the end of January until mid-March 2015
- Northwest direction of displacement
- Between the two last measurements movement of 5 mm





HAZARD CLASS (TAP AD HOC)

- Based on:
  - landslide area
  - landslide depth
  - proximity to pipeline
  - landslide activity
  - ground quality
  - slope angle

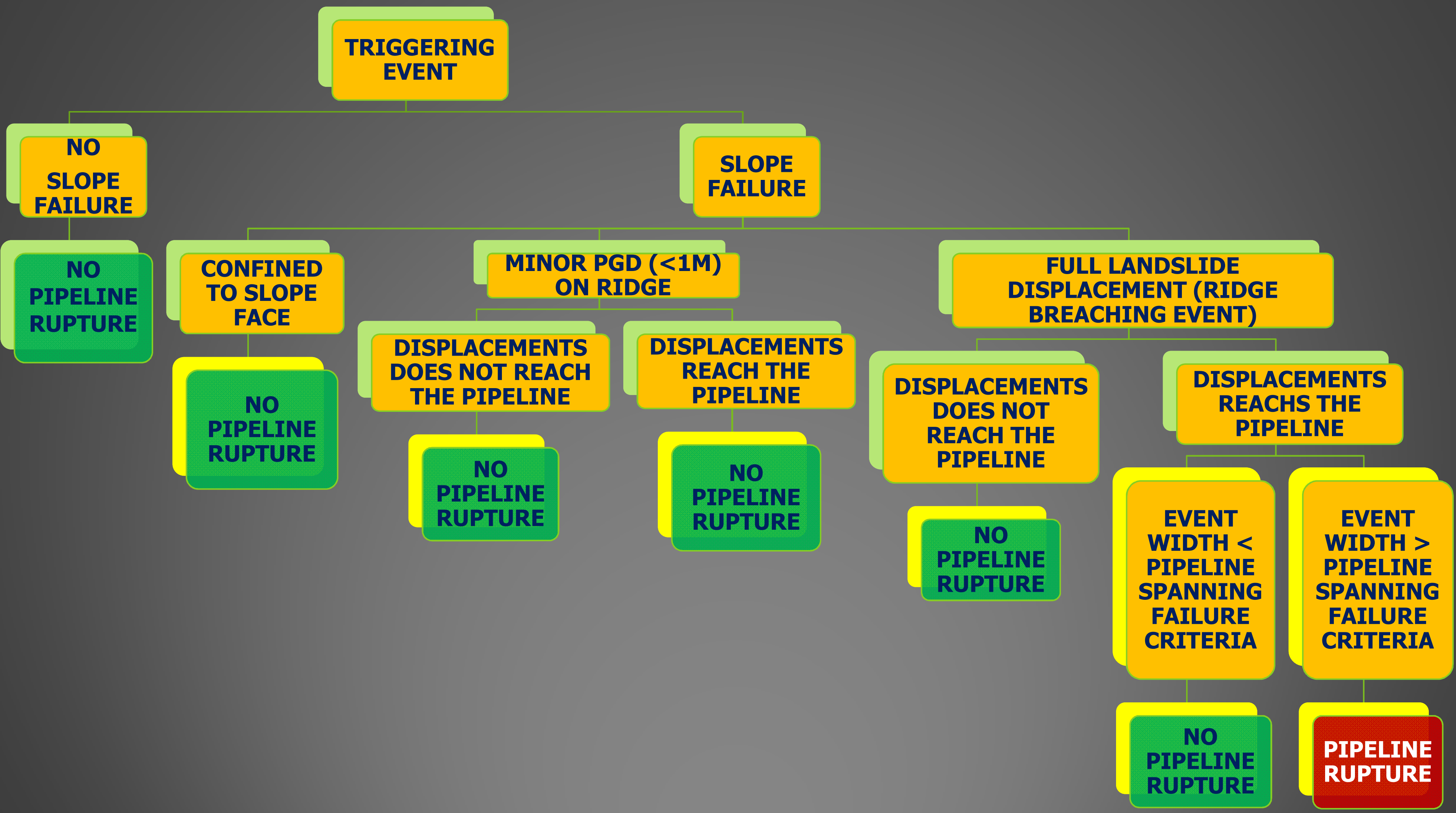
Parameters affecting expected damage to pipeline if landslide is activated (Potential impact on the pipeline upon activation) — landslide area, landslide depth, proximity to pipeline

Parameters affecting possibility of landslide activation (likelihood of activation) — landslide activity, ground quality, slope angle

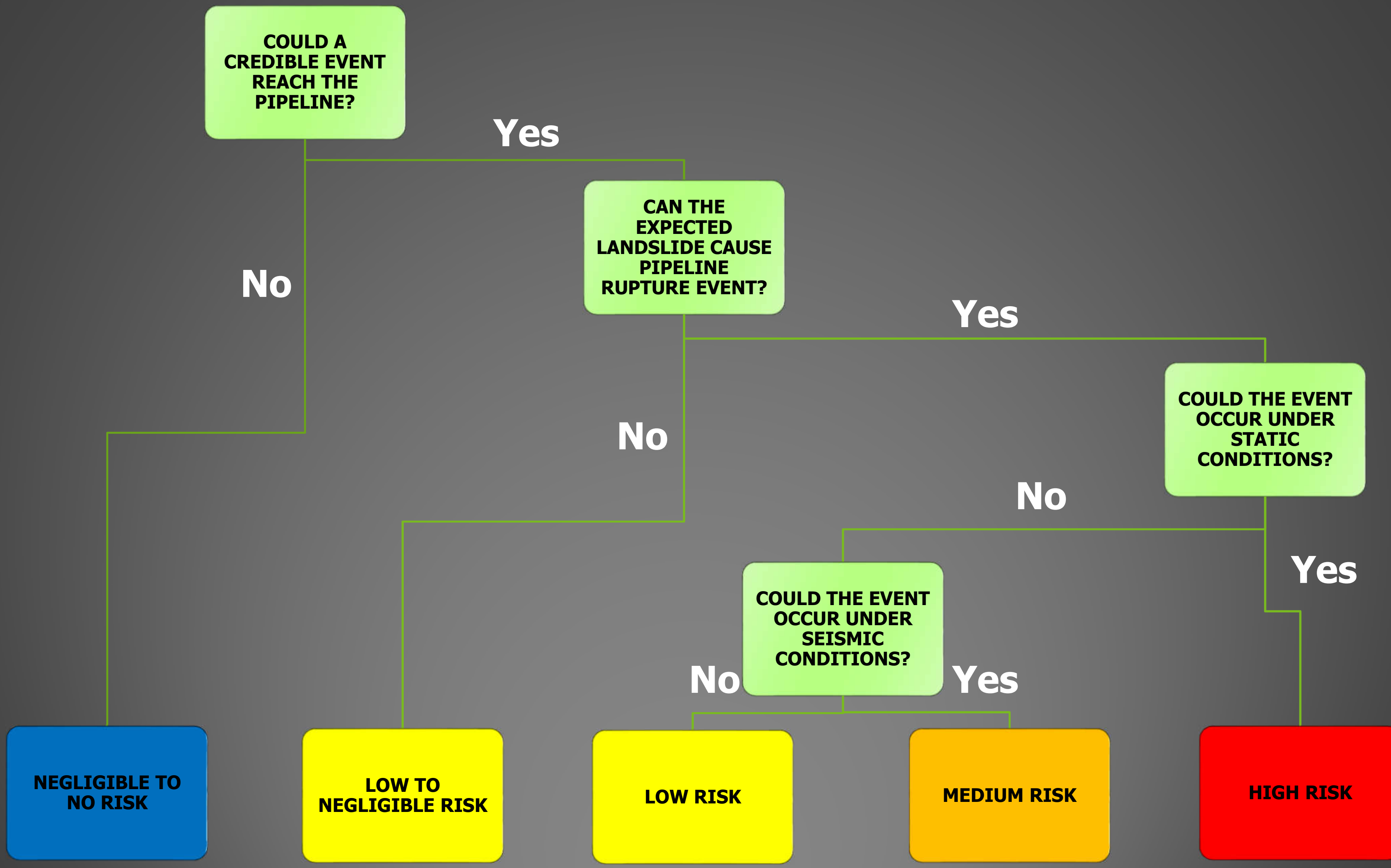
Tension cracks along a ridge flank, indicating potential for upslope retrogression of pre-existing landslides

Very steep landslide back scar extending to the ridge crest, with potential for further upslope retrogression

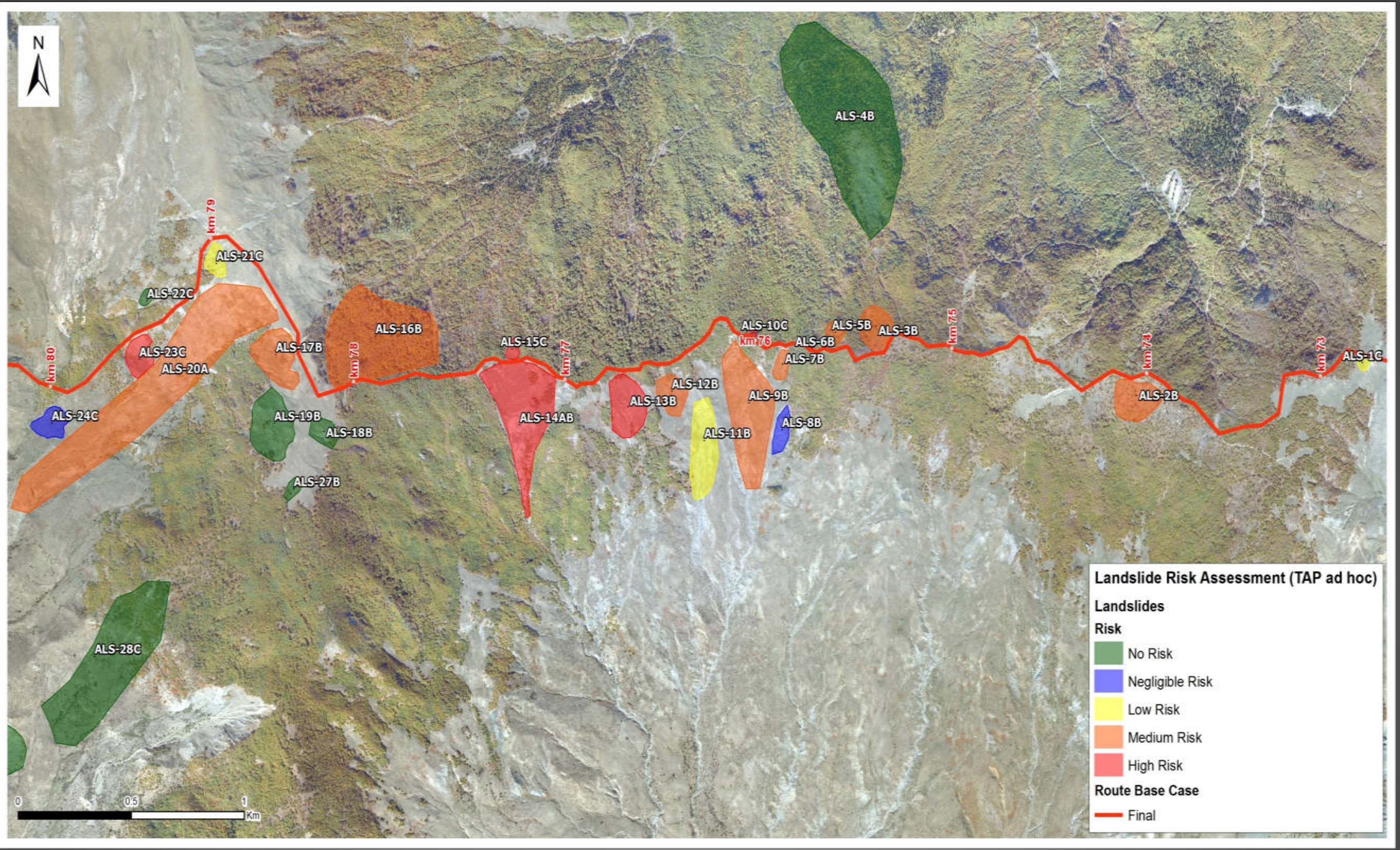
EVENT TREE ILLUSTRATING THE SEQUENCES OF EVENTS INVOLVED IN GENERATING PIPELINE RUPTURE



THE LANDSLIDE RISK MODEL DEVELOPED

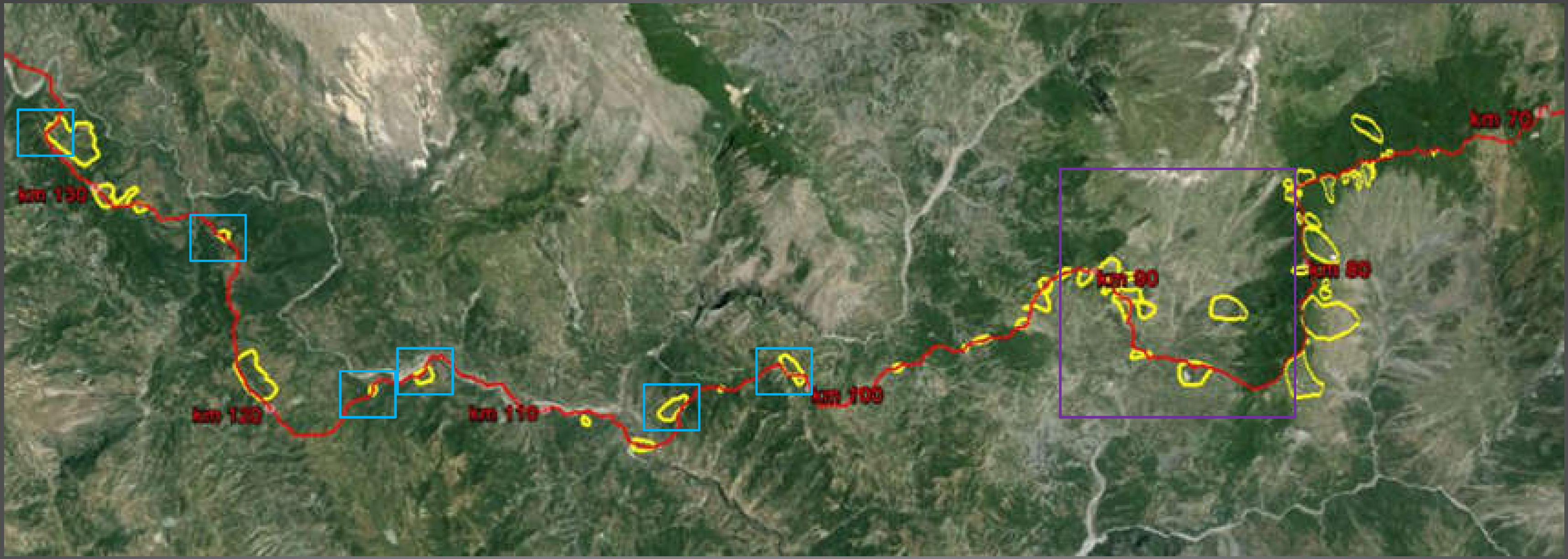


LANDSLIDE RISK ASSESSMENT



Landslide risk assessment results for the pipeline route from approximately 73km to 80km (area north of Panarit village).

LANDSLIDE MANAGEMENT PLAN: AVOIDANCE



Areas requiring re-routes:

- minor route changes (blue boxes)
- significant deviations from the current route are expected (purple box).

All re-routes to be verified in the field for landslide and constructability issues.

LANDSLIDE MANAGEMENT PLAN: MITIGATION

Key areas where mitigation is anticipated

Use of retaining structures and geotechnical measures along long sections of RoW

Unprecedented in the SCPX-TANAP pipeline system (typically piling is done for short sections of 50-100+m) (Lee, Pers. Com)

Identify "hotspots", investigate (mapping and boreholes), followed by conceptual design of mitigation measures.

Mitigation measures to ensure that the RoW is isolated from any landslide activity on the ridge flanks

Photo Courtesy: Mark Lee

V. DISCUSSION

Crucial questions to the geohazard expert:

- Could a credible event breach the ridge?
- Could a credible landslide reach the pipeline?
- Do we expect minor or large permanent ground displacement (e.g. <1m or >1m)?
- If the landslide reaches the pipeline:
    - Event width < pipeline spanning failure criteria?
    - Event width >pipeline spanning failure criteria?
- Could the expected landslide cause pipeline rupture?
    - Could the event occur under static conditions
    - Could the event occur under seismic conditions

Most of the problems arise from the tight schedules that do not allow this whole assessment.

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