LANDSLIDE RISK MANAGEMENT AT BC HYDRO

Experience with Landslide monitoring and drainage

BC hydro
FOR GENERATIONS

Tom Stewart, January 2017

PRESENTATION OVERVIEW

1. BC Hydro - Overview

2. Landslide / Reservoir Slopes Program

3. Landslide Case Histories
   - Downie Slide
   - Dutchman's Ridge
   - Revelstoke Dam

4. BC Hydro Experience – Lessons Learned

1. About BC Hydro

BC Hydro is a “Crown” (State-run) corporation, established in 1961, owned by the Province of British Columbia and regulated by the British Columbia Utilities Commission (BCUC), an independent body.

- one of North America’s leading providers of clean, renewable energy
- largest electric utility in British Columbia
- approximately 1.8 million customers
- serves about 95 per cent of the province’s population

Capacity

- 43 dam sites - 11,300 megawatts (MW) installed capacity
- 97% of generation based on clean, renewable hydroelectricity
- BC Hydro customers enjoy some of the world's lowest electricity rates

Transmission

- 18,600 kilometres of transmission lines
- 57,278 kilometres of distribution lines

BC HYDRO DAMS – GEOGRAPHIC CONTEXT

BC hydro
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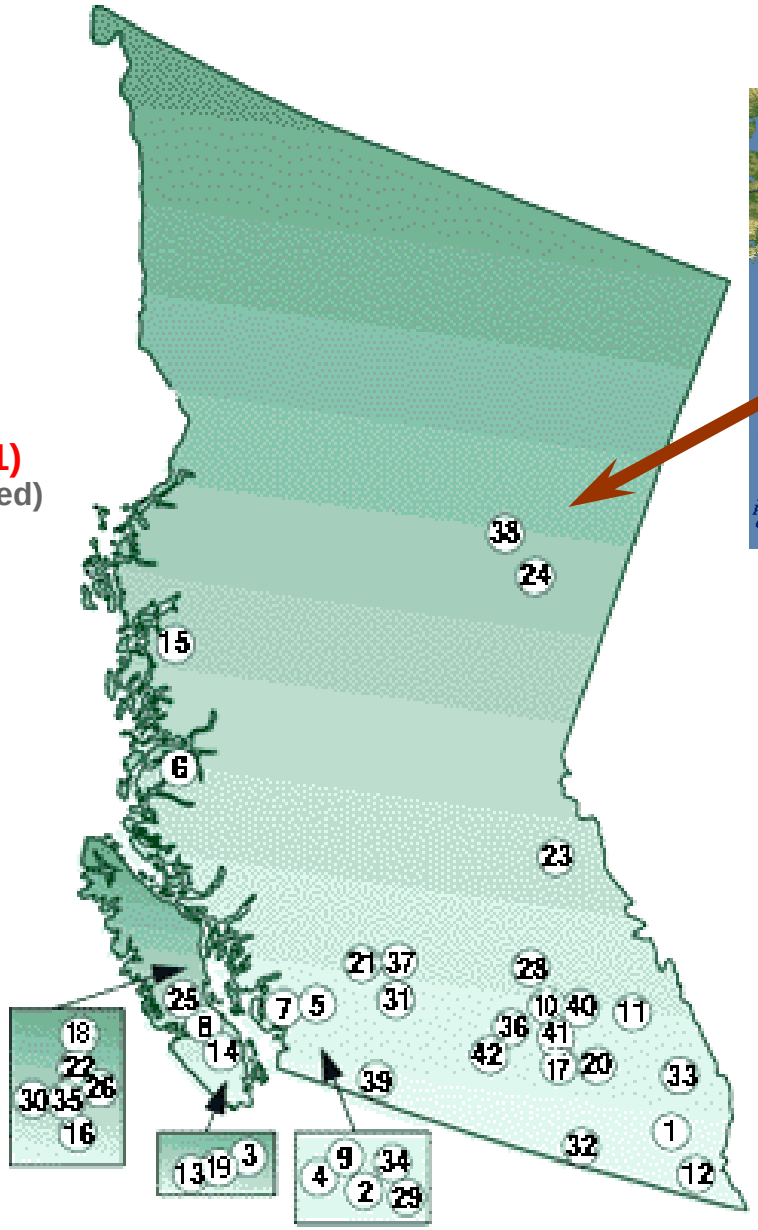
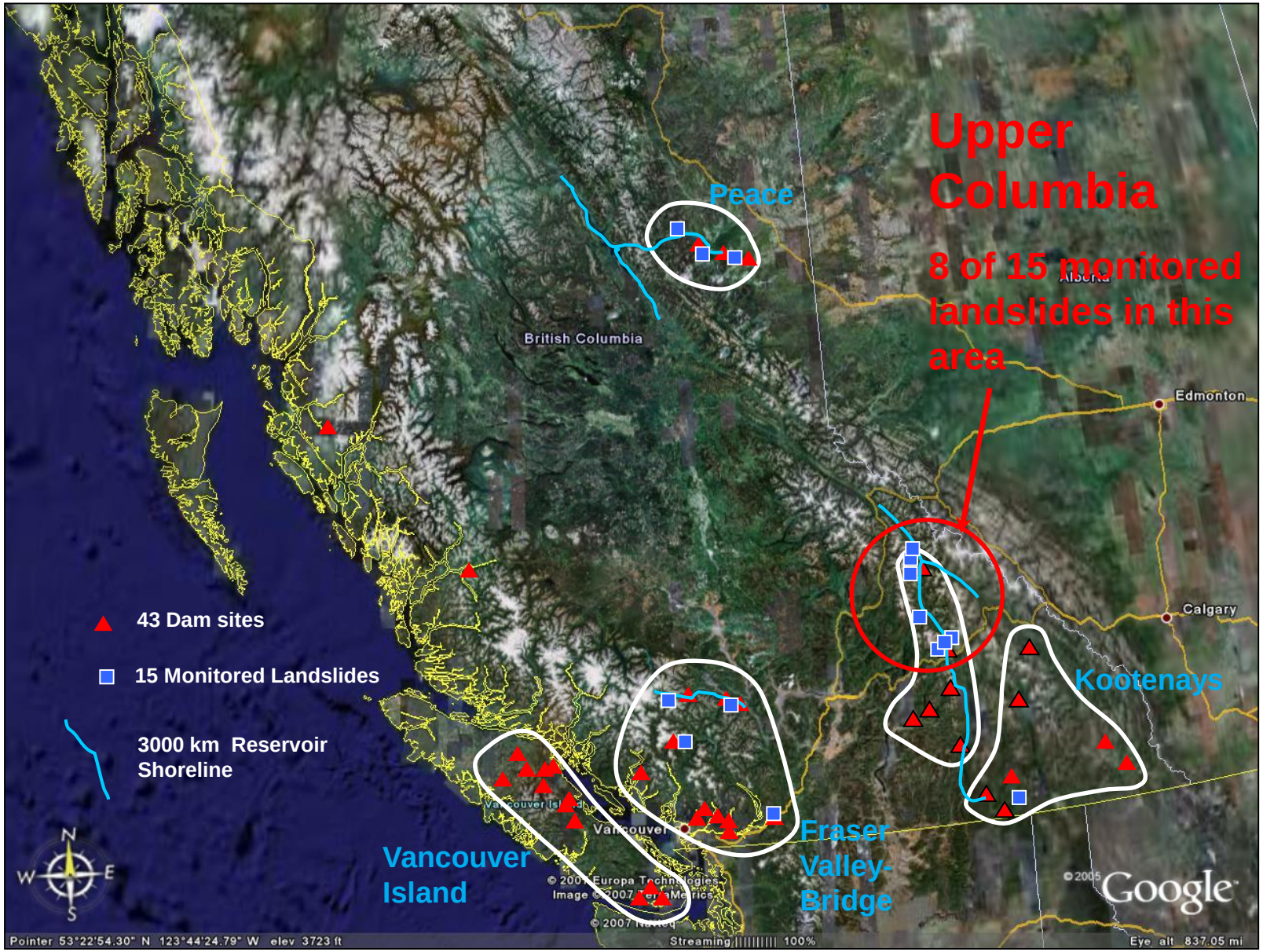
1. Aberfeldie Dam
2. Alouette Dam
3. Bear Creek Dam
4. Buntzen Dam
5. Cheakamus Dam
6. Clayton Falls Dam
7. Clowhom Dam
8. Comox Dam
9. Coquitlam Dam **(1902) (2001)**
10. Coursier Dam (decommissioned)
11. Duncan Dam
12. Elko Dam
13. Elliott Dam
14. Elsie Dam
15. Falls River Dam
16. Heber Diversion Dam
17. Hugh Keenleyside Dam
18. John Hart Dam
19. Jordan Diversion Dam
20. Kootenay Canal Dam
21. La Joie Dam
22. Ladore Dam
23. Mica Dam
24. Peace Canyon Dam
25. Puntledge Diversion Dam
26. Quinsam Diversion Dam
27. Quinsam Storage Dam
28. Revelstoke Dam **(1985)**



29. Ruskin Dam
30. Salmon River Diversion Dam
31. Seton Dam
32. Seven Mile Dam
33. Spillimacheen Dam
34. Stave Falls Dam
35. Strathcona Dam
36. Sugar Lake Dam
37. Terzaghi Dam
38. W.A.C. Bennett Dam
39. Wahleach Dam
40. Walter Hardman Dam
41. Whatshan Dam
42. Wilsey Dam
43. **Site C - current**

2. BC Hydro – Landslide Program

BC hydro
FOR GENERATIONS



3. Upper Columbia - Landslide Factors

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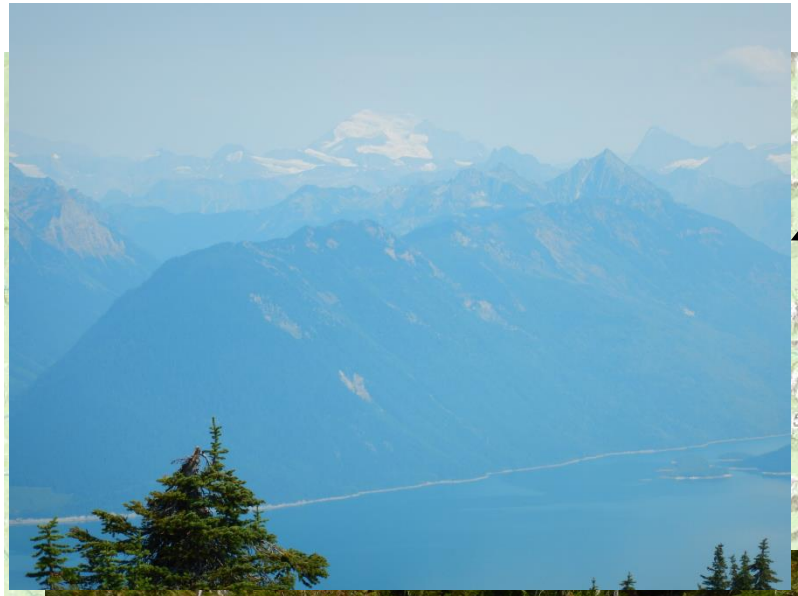
FOR GENERATIONS



Large topographic relief (3500 m+)
steep slopes (20 – 60º)

Adverse geologic conditions
(continuous structures: faults, foliation)

Extensive precipitation 1500 – 2000 mm/yr

Rocky Mountains

3. Landslide - Drainage Case Histories

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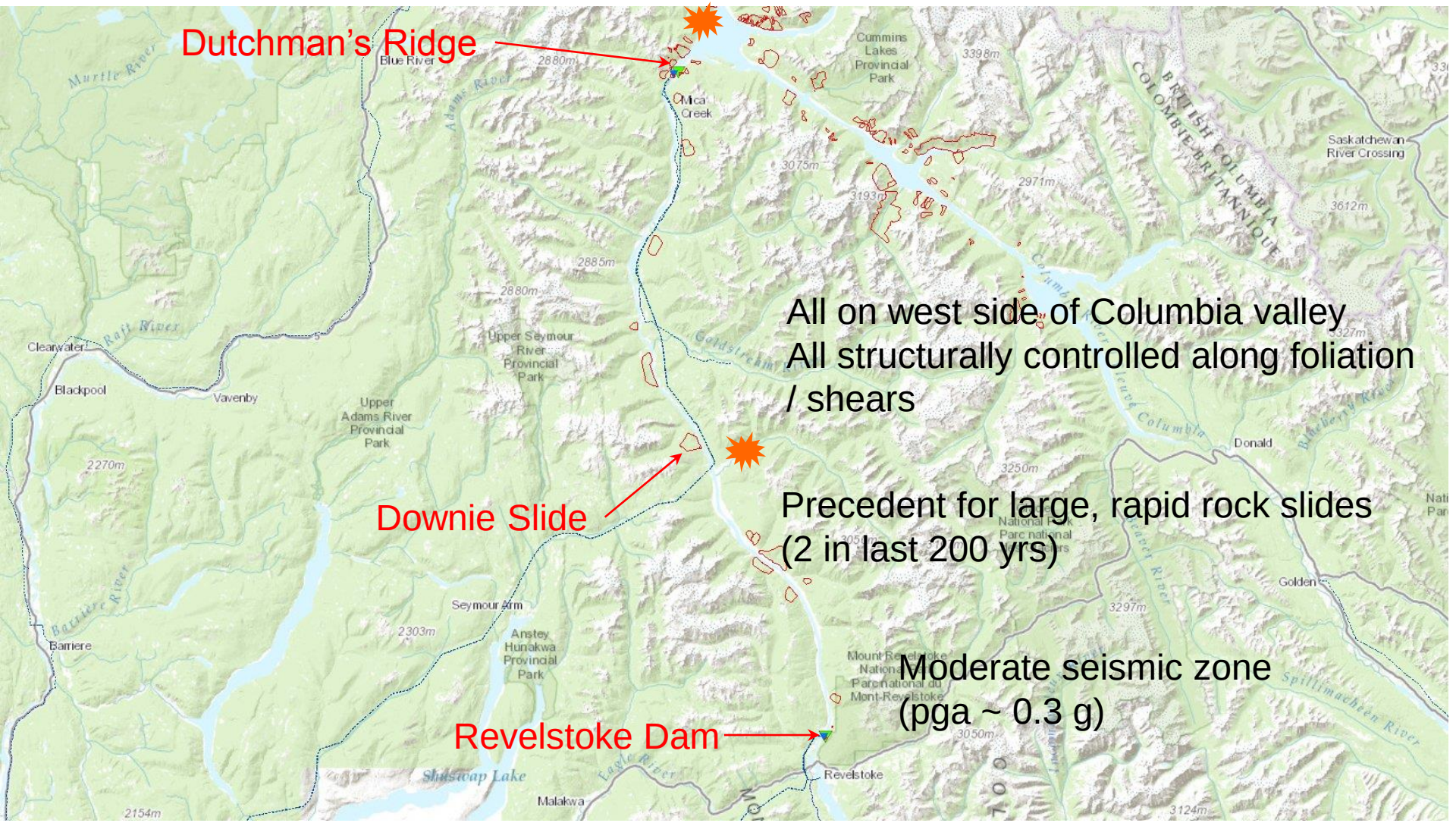
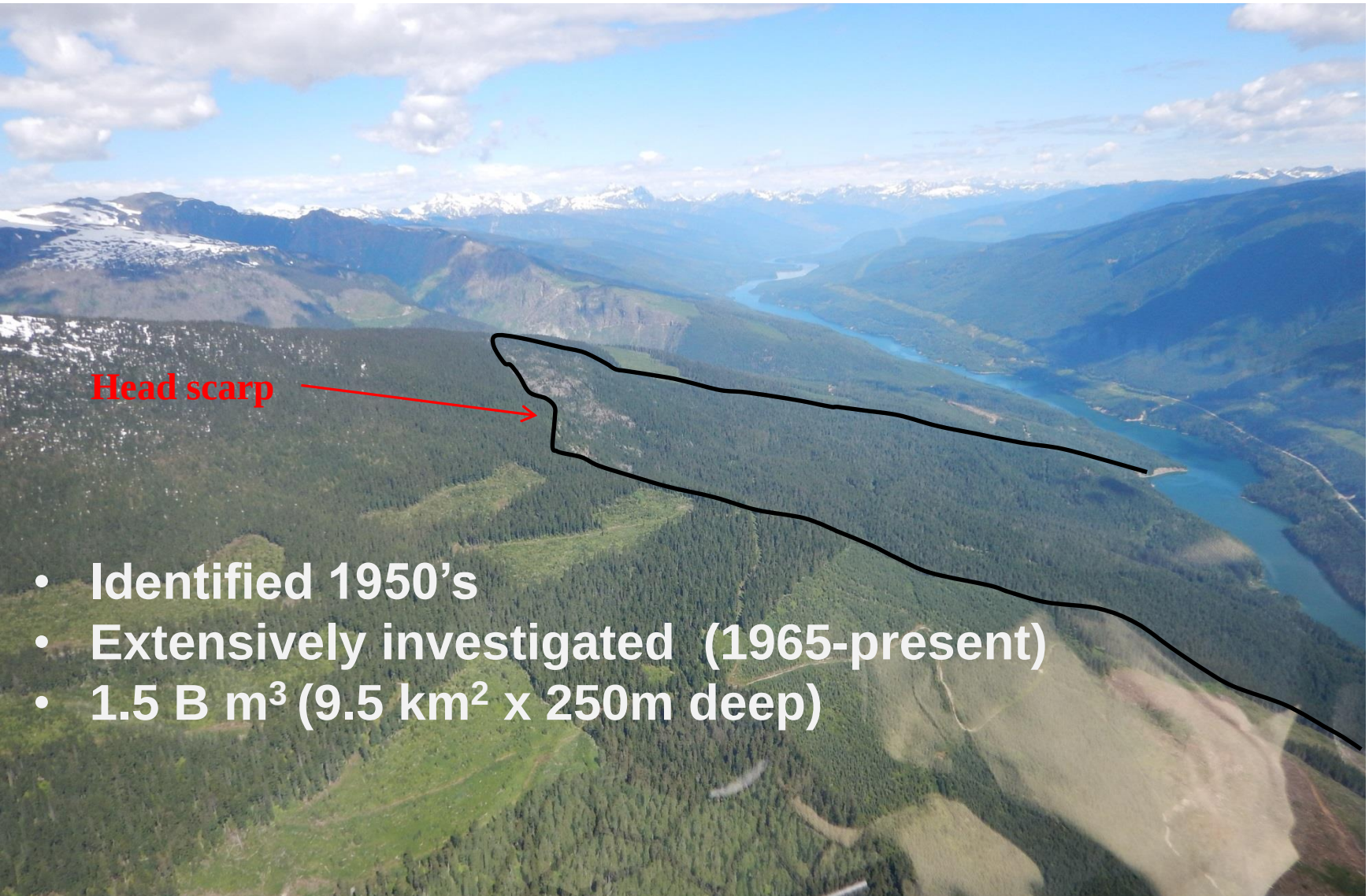


All on west side of Columbia valley
All structurally controlled along foliation / shears

Precedent for large, rapid rock slides (2 in last 200 yrs)

Moderate seismic zone (pga ~ 0.3 g)

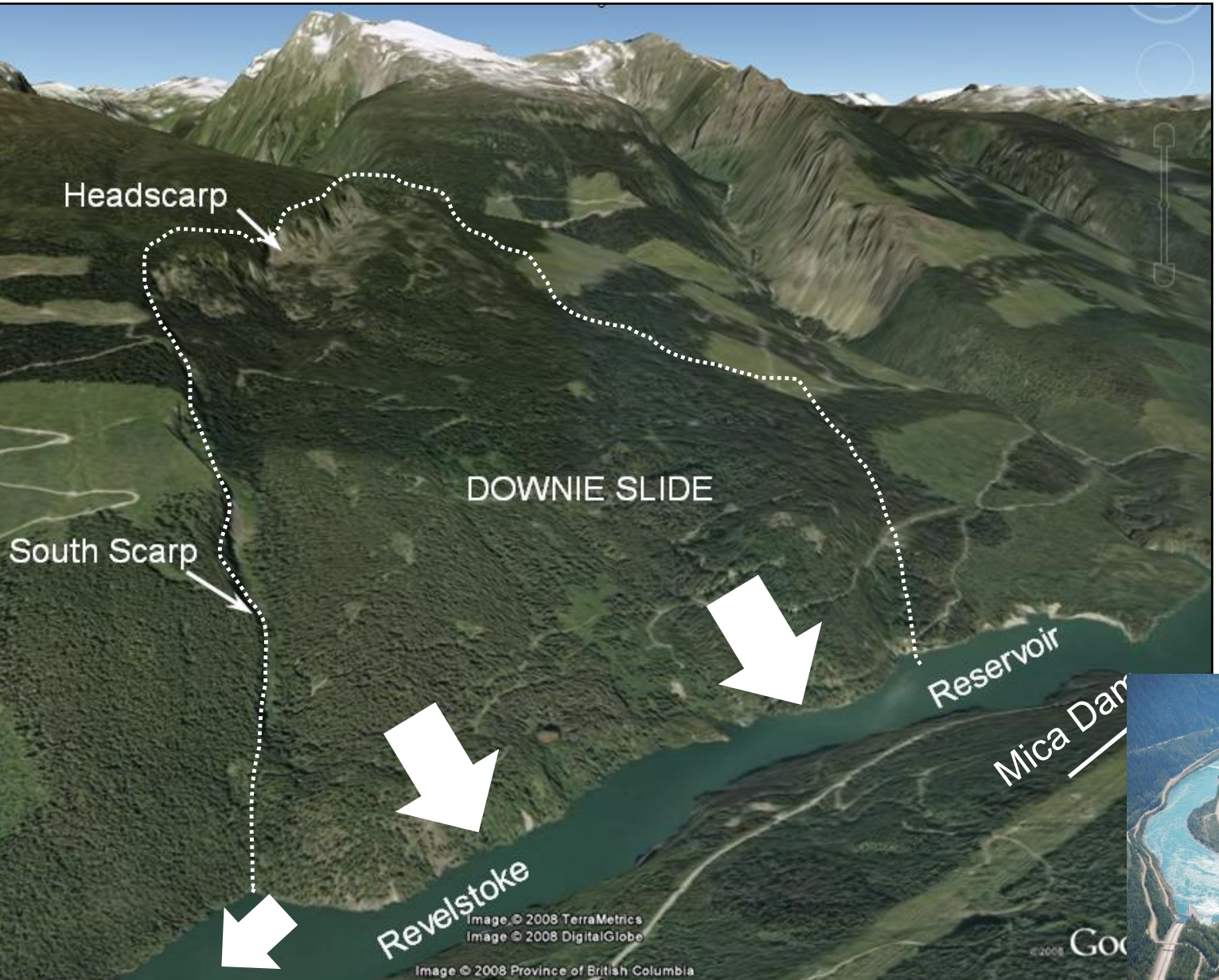
DOWNIE SLIDE - OVERVIEW



- Identified 1950's
- Extensively investigated (1965-present)
- 1.5 B m^3 (9.5 km^2 x 250m deep)

Downie Slide – Key Dam Safety Issues

BC hydro
FOR GENERATIONS

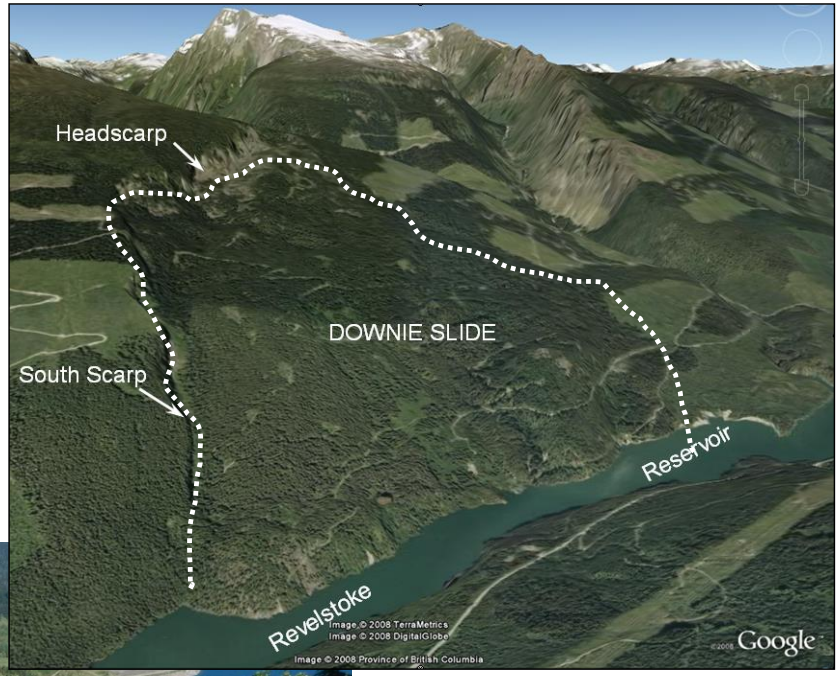


1. Landslide generated wave - Dam over-topping – dam breach

2. Reservoir blockage

3. Dam flooding (Mica)

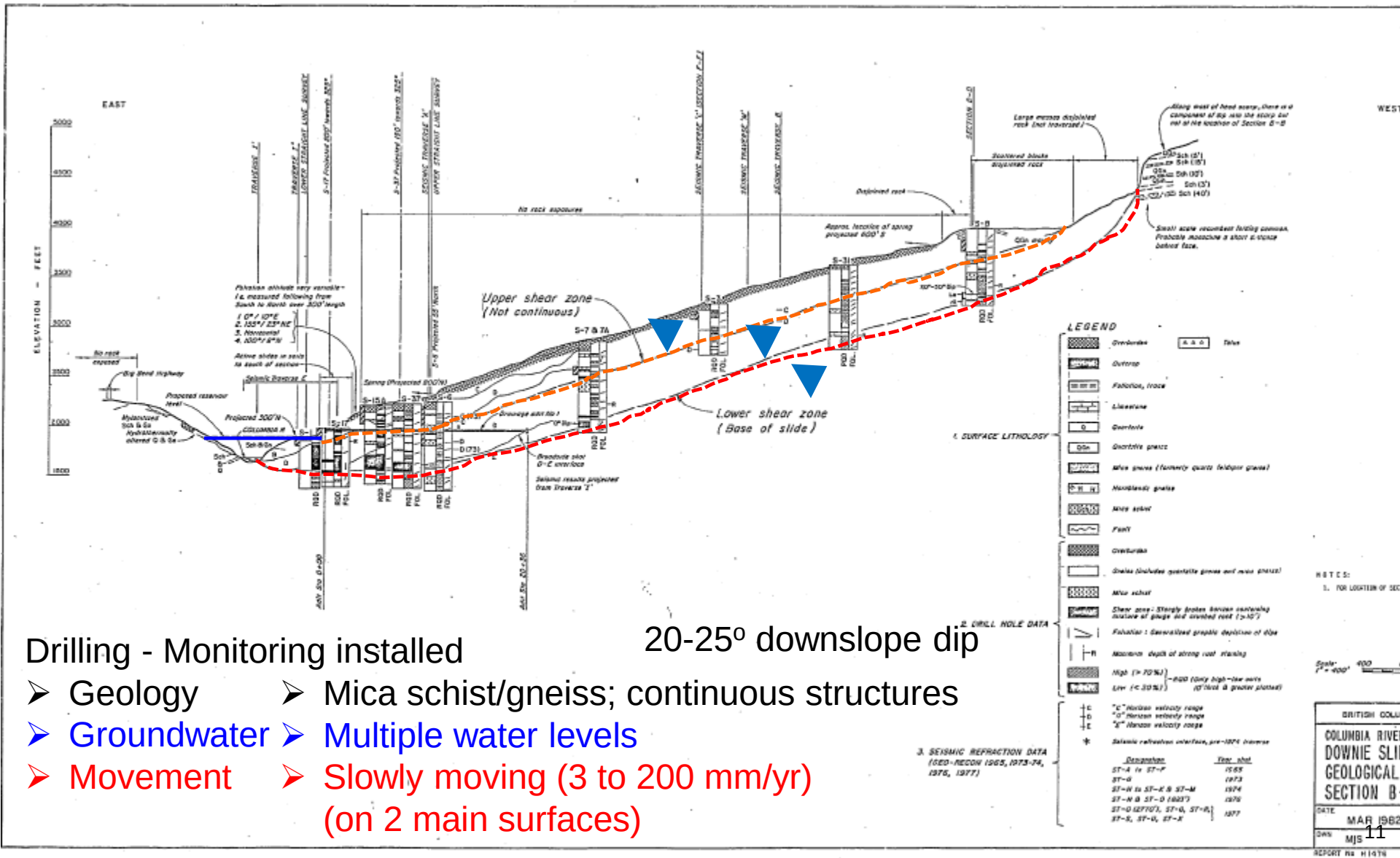
Downie Slide – Revelstoke Dam



- Dam Approval linked to Downie Stabilization
- Extensive Public Consultation and review process
- Drainage selected
- "*to more than offset filling of reservoir*"

Downie Slide – Geologic Section

- Detailed geologic model required for drainage design



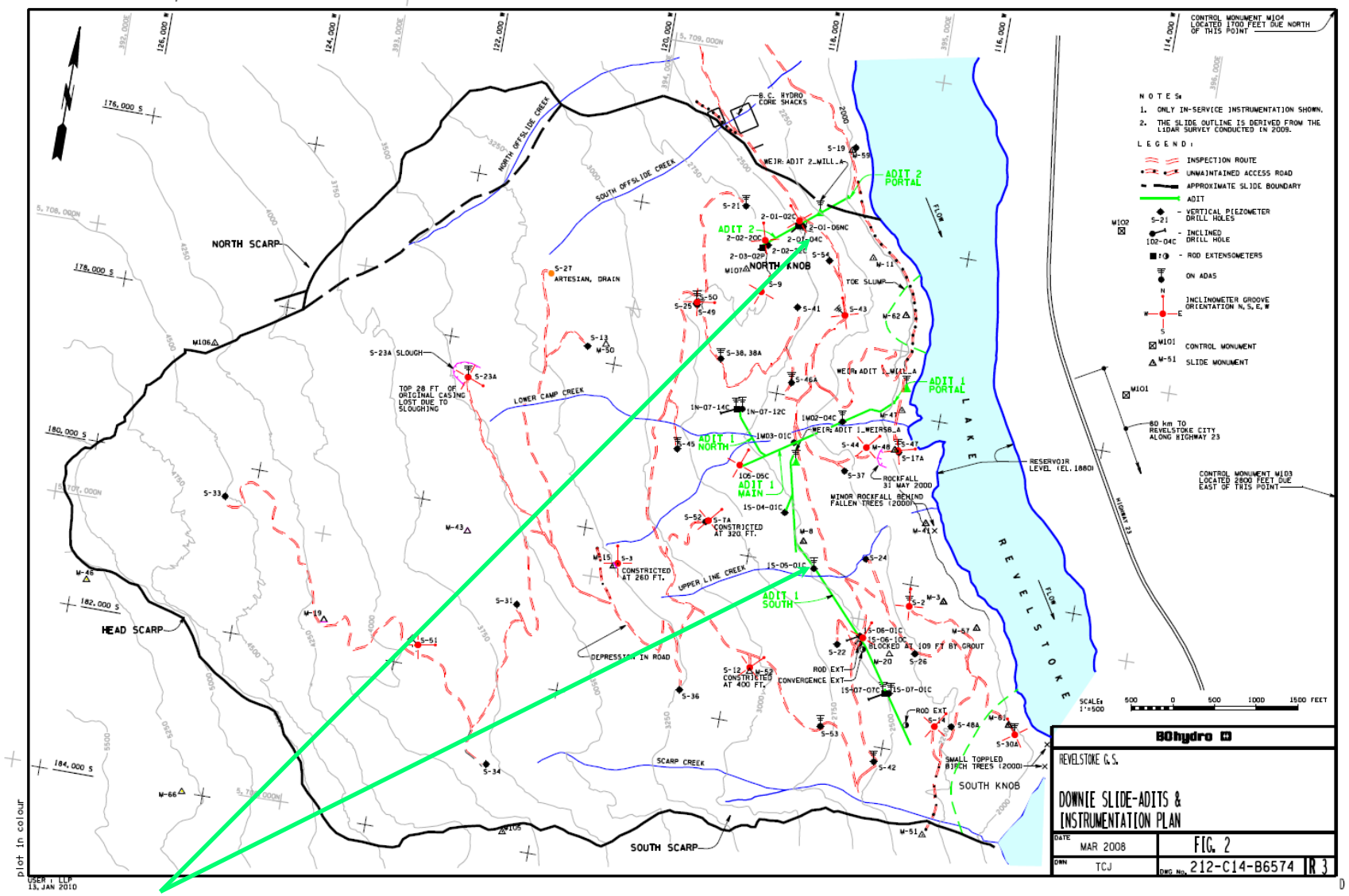
20-25° downslope dip

Drilling - Monitoring installed

- Geology
- Groundwater
- Movement

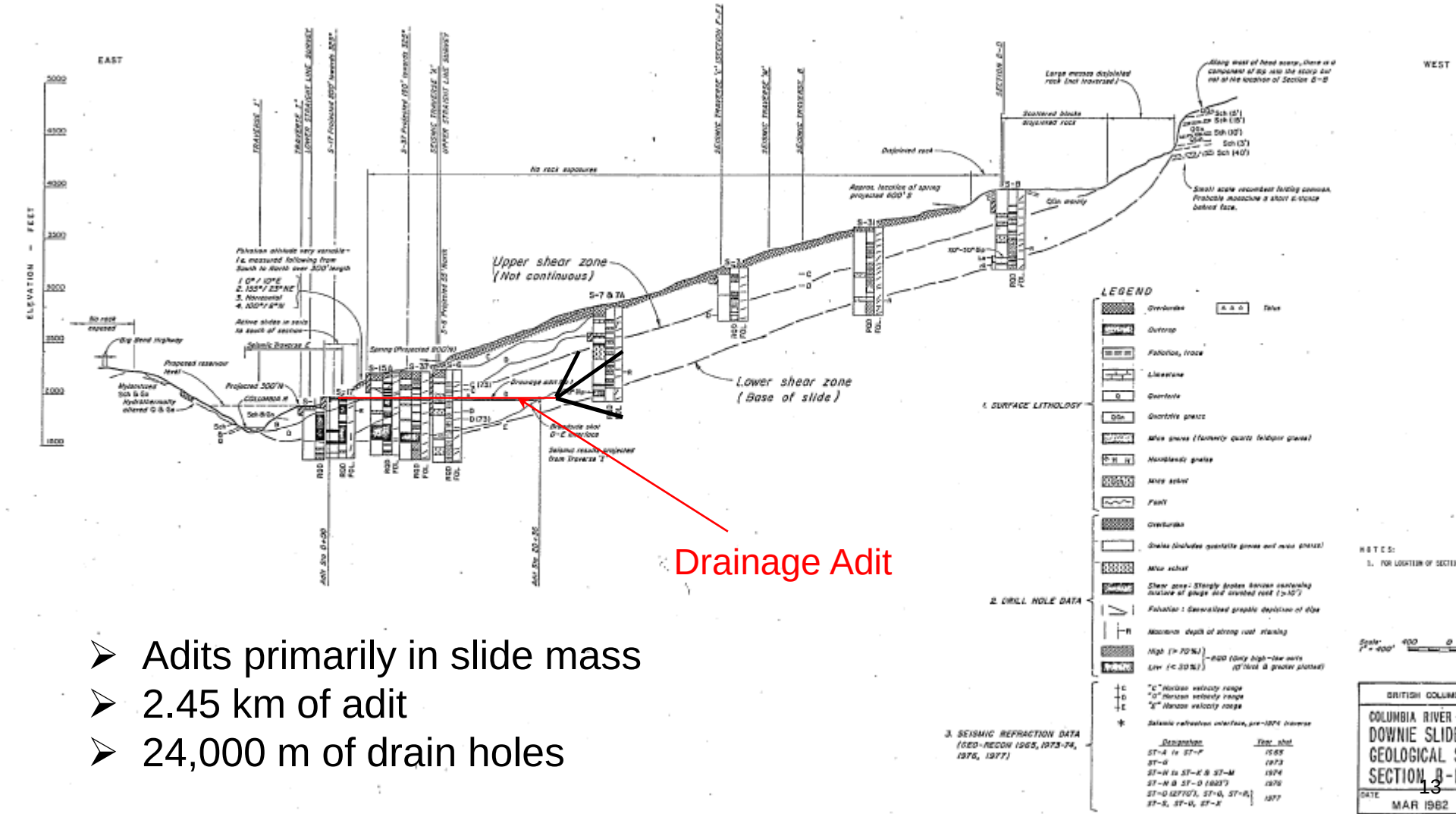
- Mica schist/gneiss; continuous structures
- Multiple water levels
- Slowly moving (3 to 200 mm/yr) (on 2 main surfaces)

Downie Slide – Drainage Program



- Adits - constructed using "Observational" approach (piezometers)
- Completed in three stages 1974-1977-1981

Downie Slide – Drainage Program

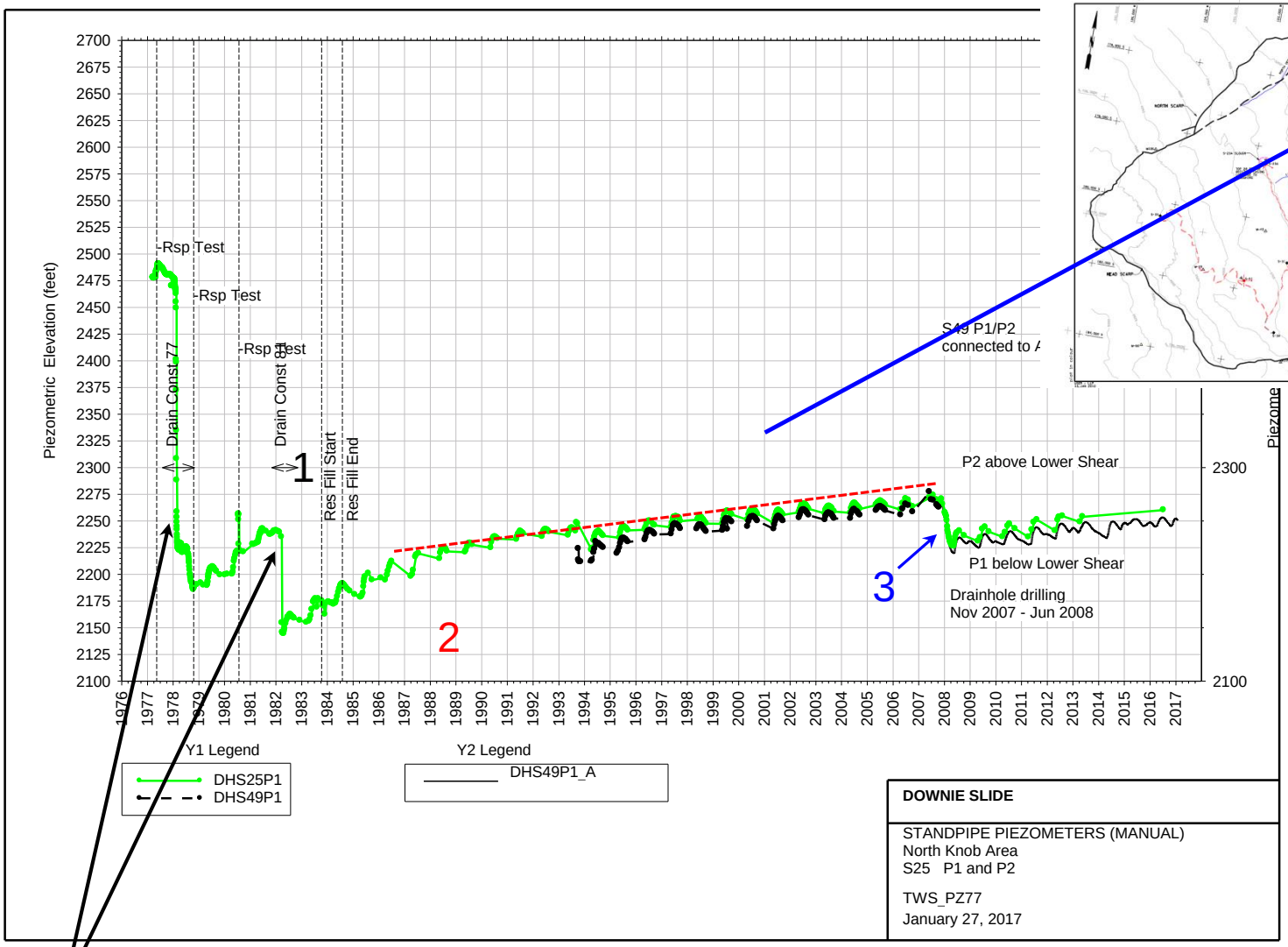


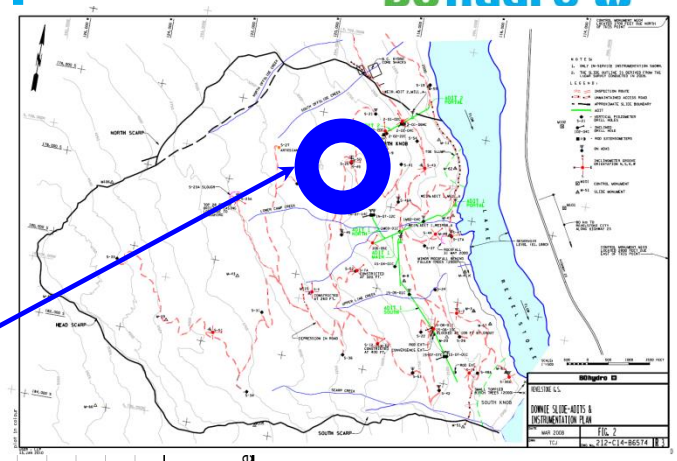
- Adits primarily in slide mass
- 2.45 km of adit
- 24,000 m of drain holes

Downie Slide – Drainage Adits

Conventional drill and blast; “horseshoe” shape; extensively supported

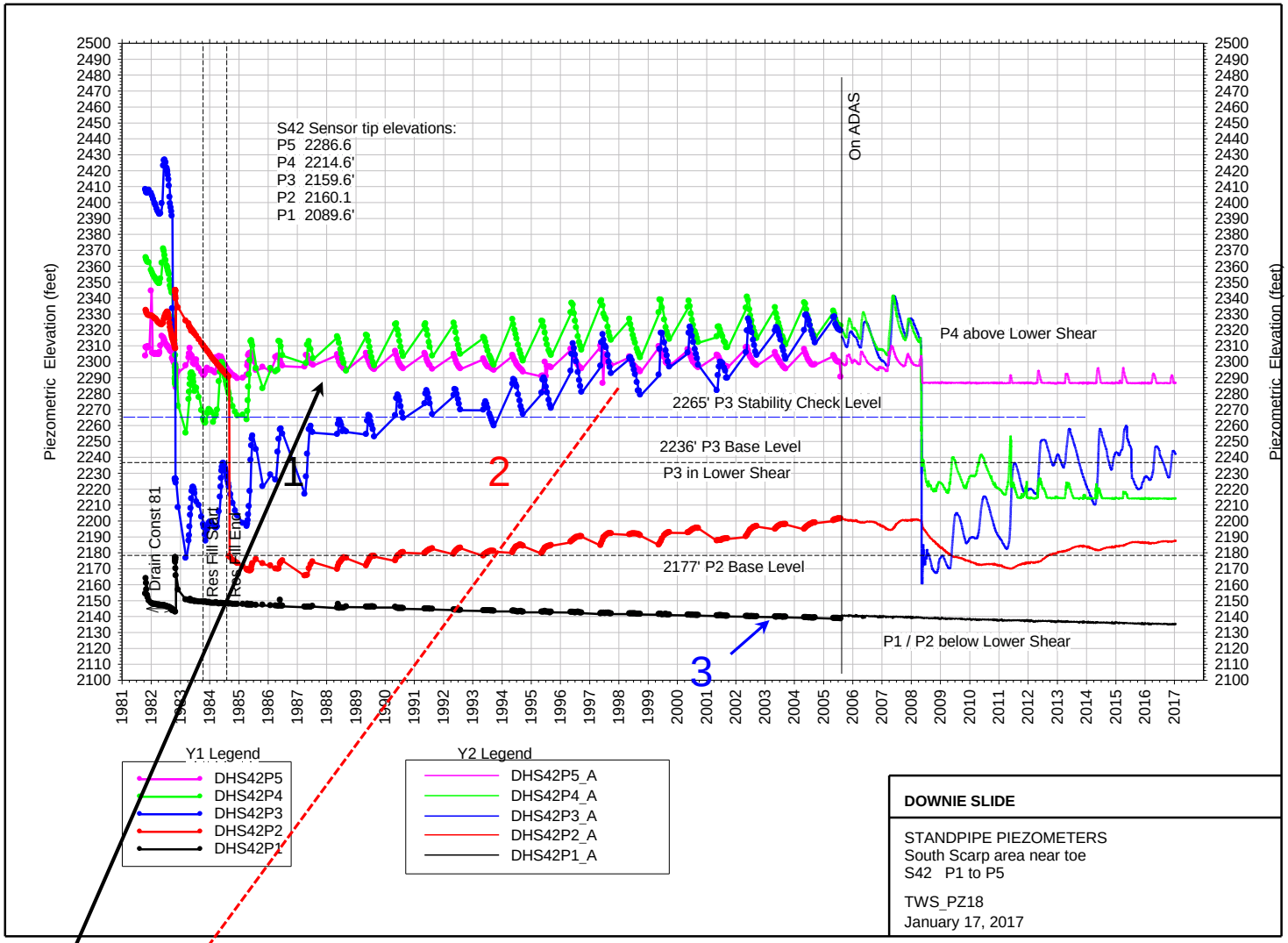
Downie Slide - Groundwater Response





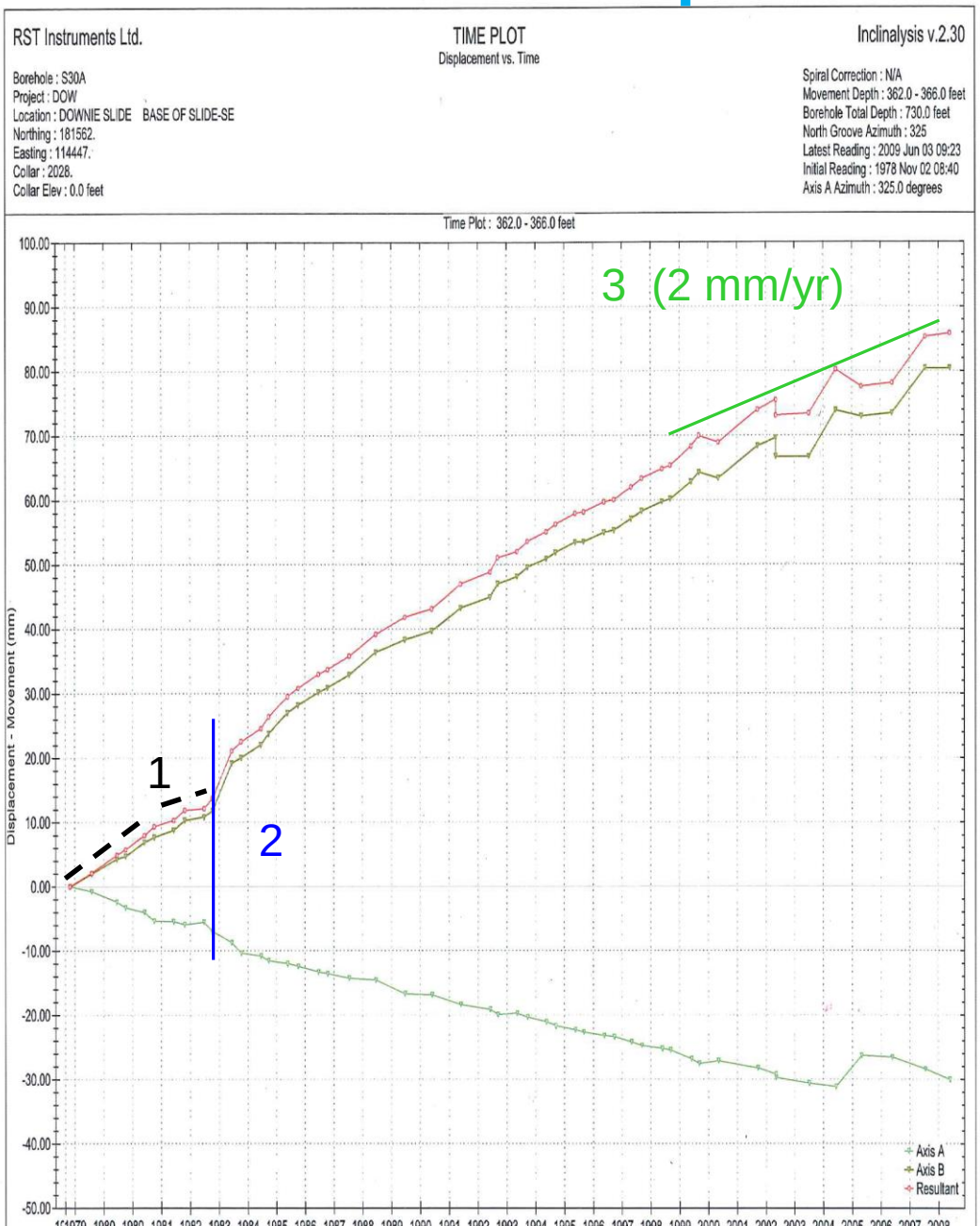
1. Significant drainage effects – up to 100 m pressure reductions
2. Met initial objective but increasing pressure trends observed
3. Additional drainage required (2007-08)

Downie Slide - Groundwater Response



1. Most piezometers encountered "perched" water levels
2. Water typically perched above the 2 active zones
3. Piezometers below slide base could indicate "dry" conditions

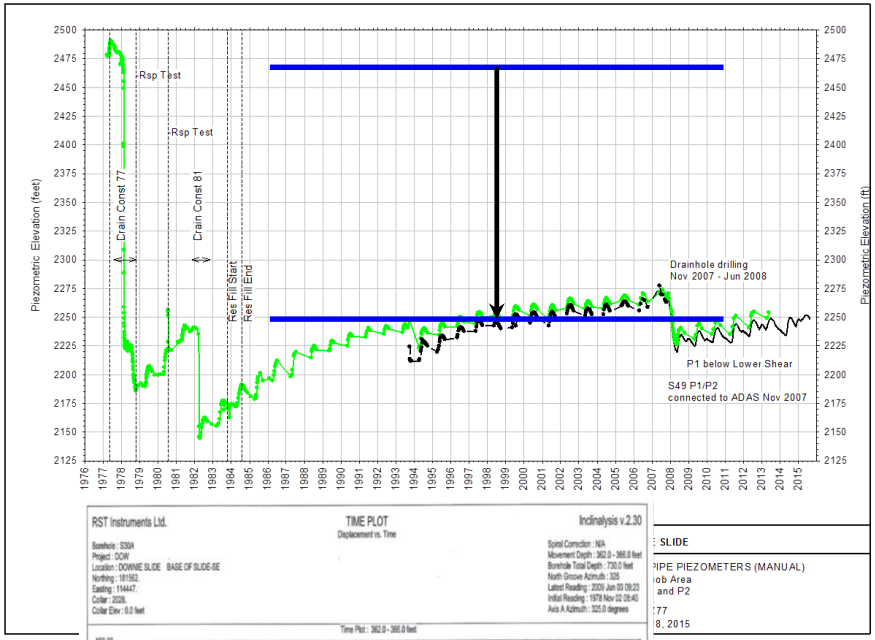
Downie Slide - Displacement



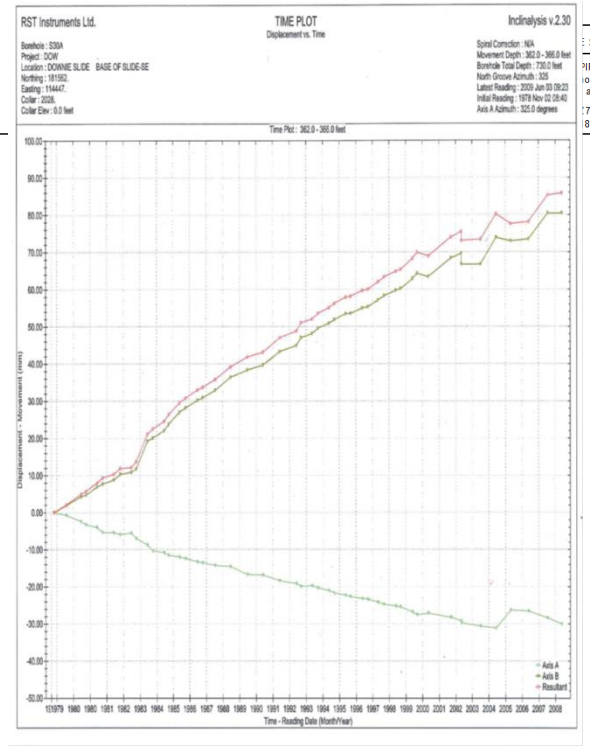
Slope displacement response to drainage, measured across lower slide plane:

1. Slight reduction following drainage (5 > 3 mm/yr)
2. Increase during reservoir filling (10 mm/yr)
3. Relatively consistent post reservoir fill (2 – 3 mm/yr)

Downie Slide – Summary



1. Groundwater levels reduced to below pre-reservoir levels



2. Displacement rates are similar or less than pre-reservoir conditions
3. Stability increased by ~ 7% (FOS)
4. *Water License Requirement – must maintain system*

BC HYDRO LANDSLIDES – Mica Dam

Mica Dam - 250 m high earthfill dam

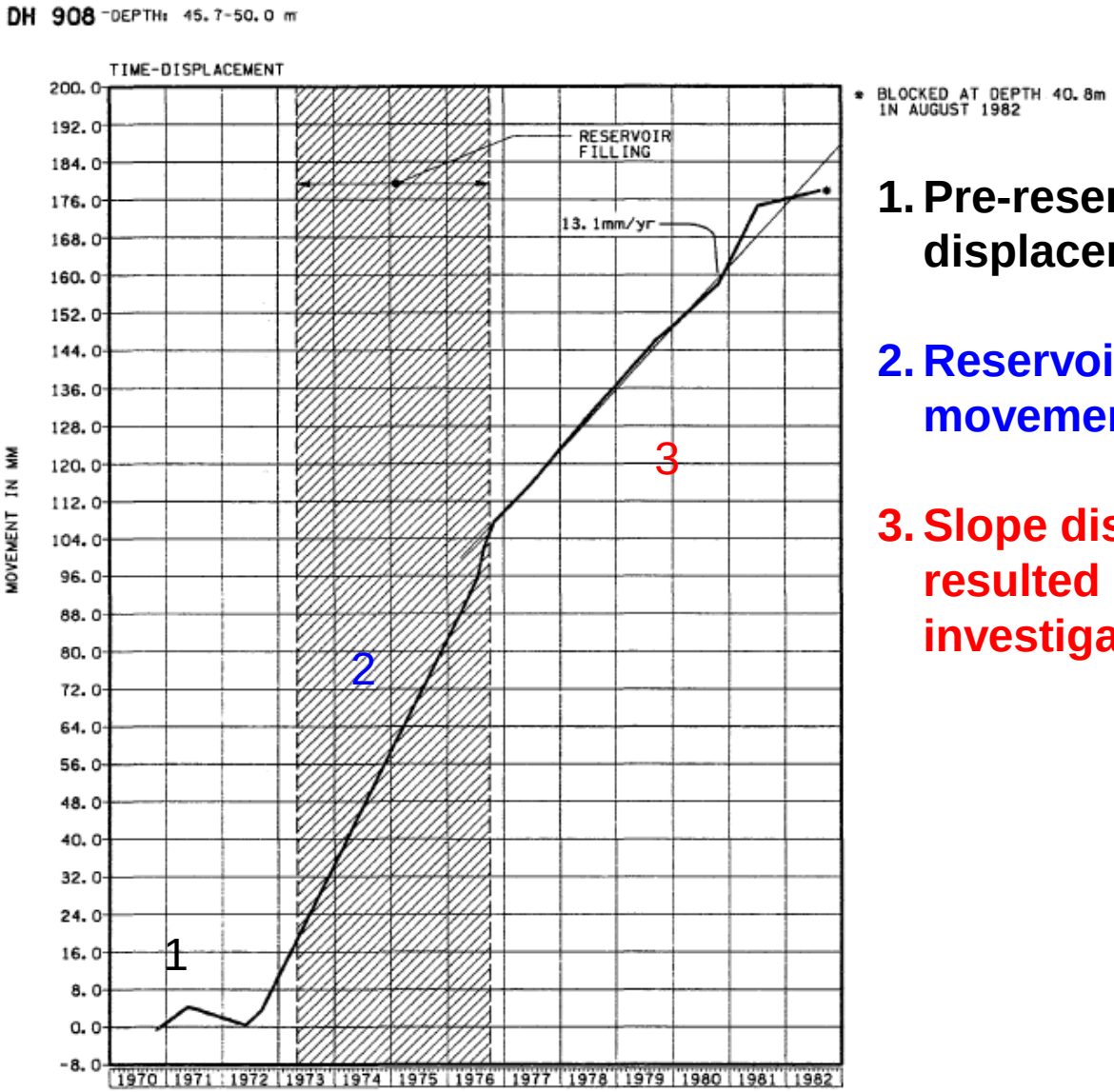
The most upstream of 14 dams on Columbia River

Major upstream landslides

Dutchman's Ridge *Potential* Slide

- Identified mid-1960's (airphotos)
- 1969 drilling
- 30 M m^3
- Physical wave model studies (50 m+ waves)
- Dam construction revised to accommodate slide waves
- Decision <u>not</u> to drain

Dutchman's Ridge - Displacement



1. **Pre-reservoir – negligible displacement detected**

2. **Reservoir filling (190 m) – initiated movements of 25 mm/yr**

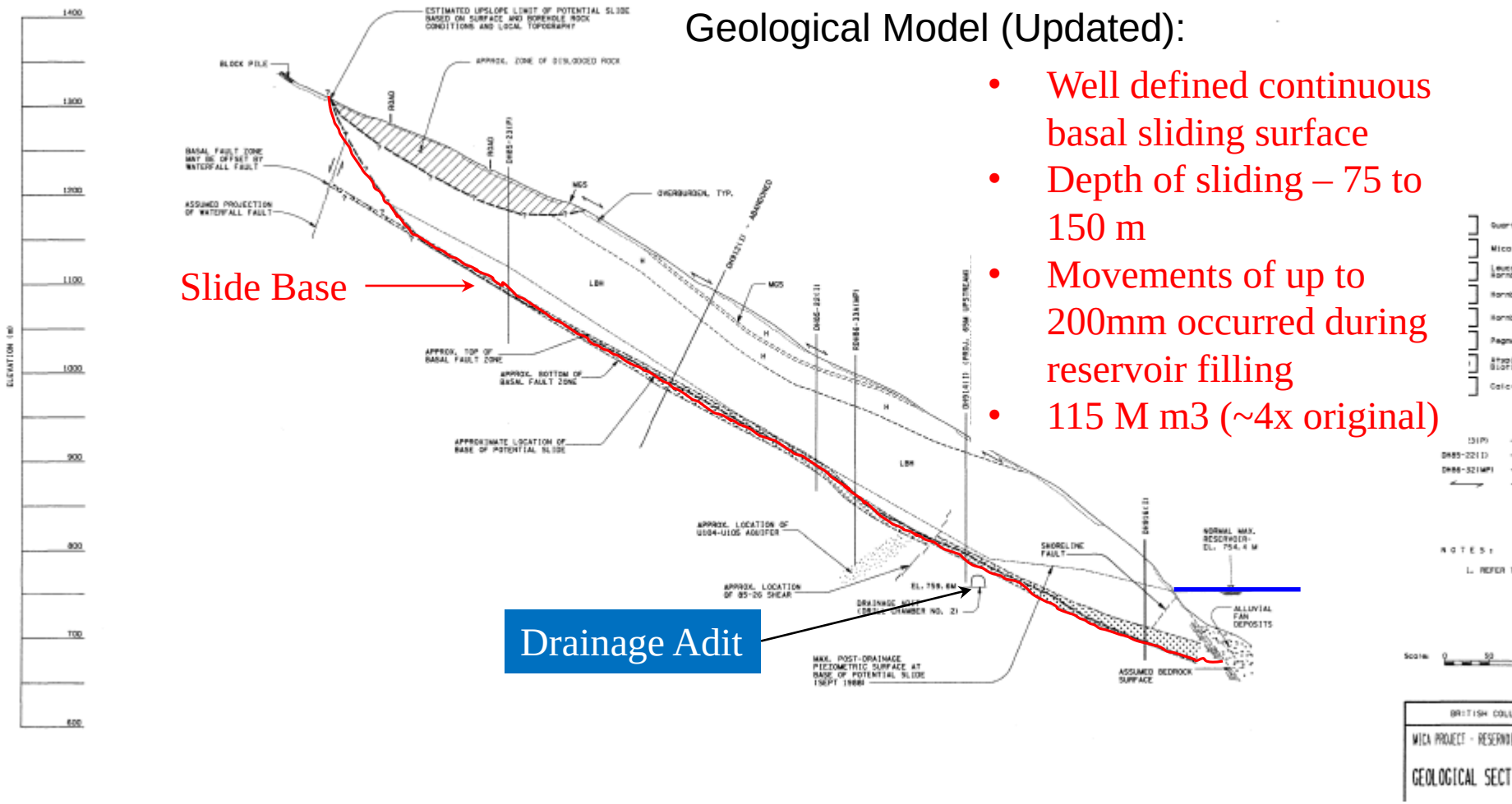
3. **Slope displacement acceleration resulted in decision to further investigate**

Slope displacement response to reservoir filling (pre-drainage)

Dutchman's Ridge – Investigations

Geological Model (Updated):

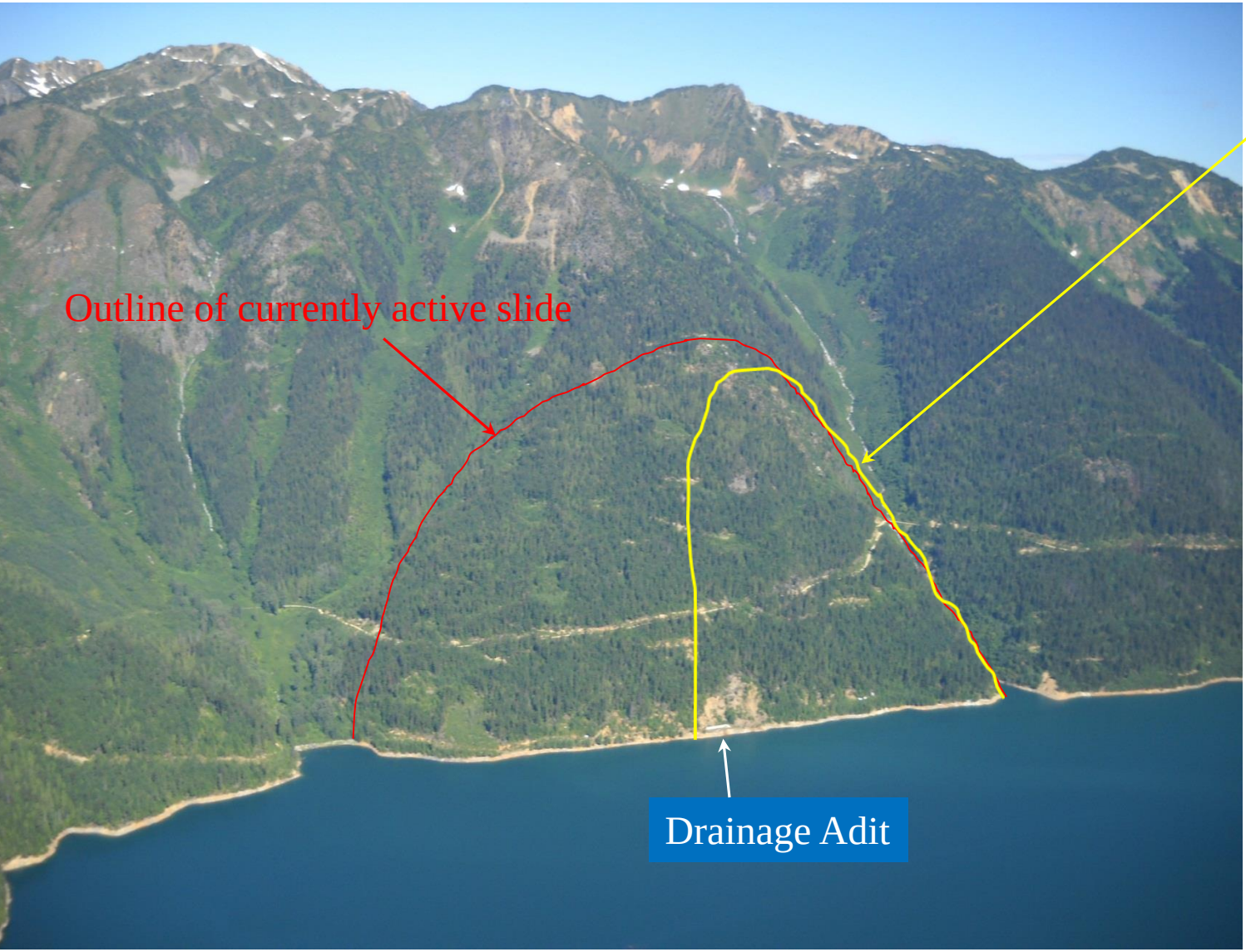
- Well defined continuous basal sliding surface
- Depth of sliding – 75 to 150 m
- Movements of up to 200mm occurred during reservoir filling
- 115 M m3 (~4x original)



Analyses concluded:

- Raising of reservoir reduced stability by ~ 10%
- Large, first time slide possible
- Remediation preferred – drainage option selected

Dutchman's Ridge Slide - Reservoir



- 1969 estimate of slide volume 30 M m^3
- Post - reservoir re-evaluation (1982)
- Slide size reassessed 115 M m^3
- Additional analyses (larger wave)
- Decision to install drainage system

Relevance of Dutchman's Ridge – Aknes

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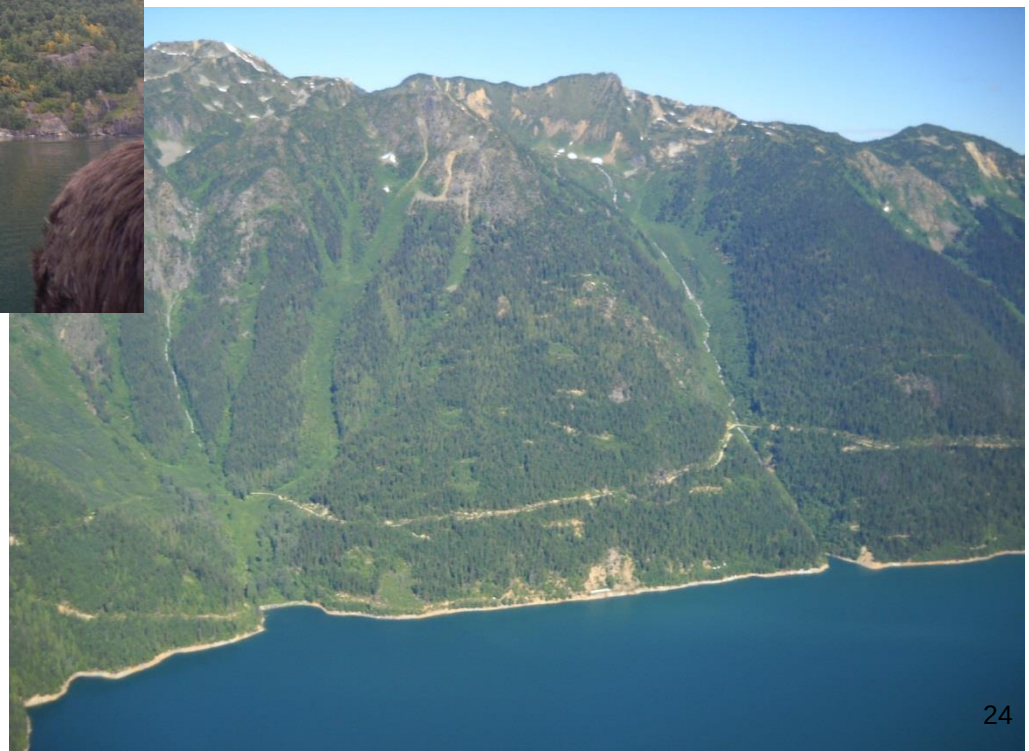
Aknes

Similarities:

- Size
- Geology
- Setting
- Landslide wave hazard

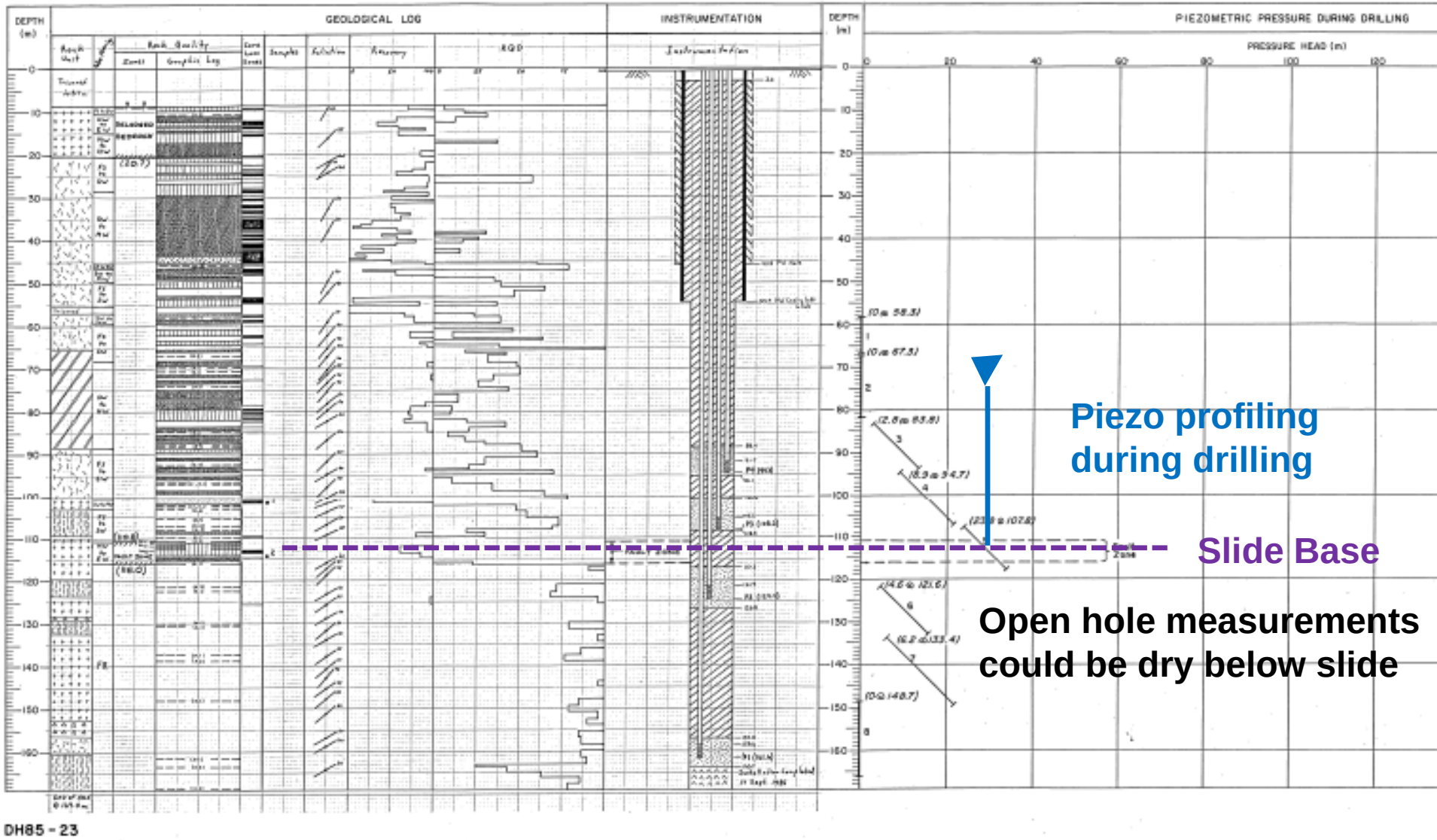


Dutchman's Ridge
British Columbia

Dutchman's Ridge – Drainage Design

- Extensive monitoring system installed (350 measurement ports):
  - To identify where water pressures could be drained
  - To evaluate effectiveness of drainage system

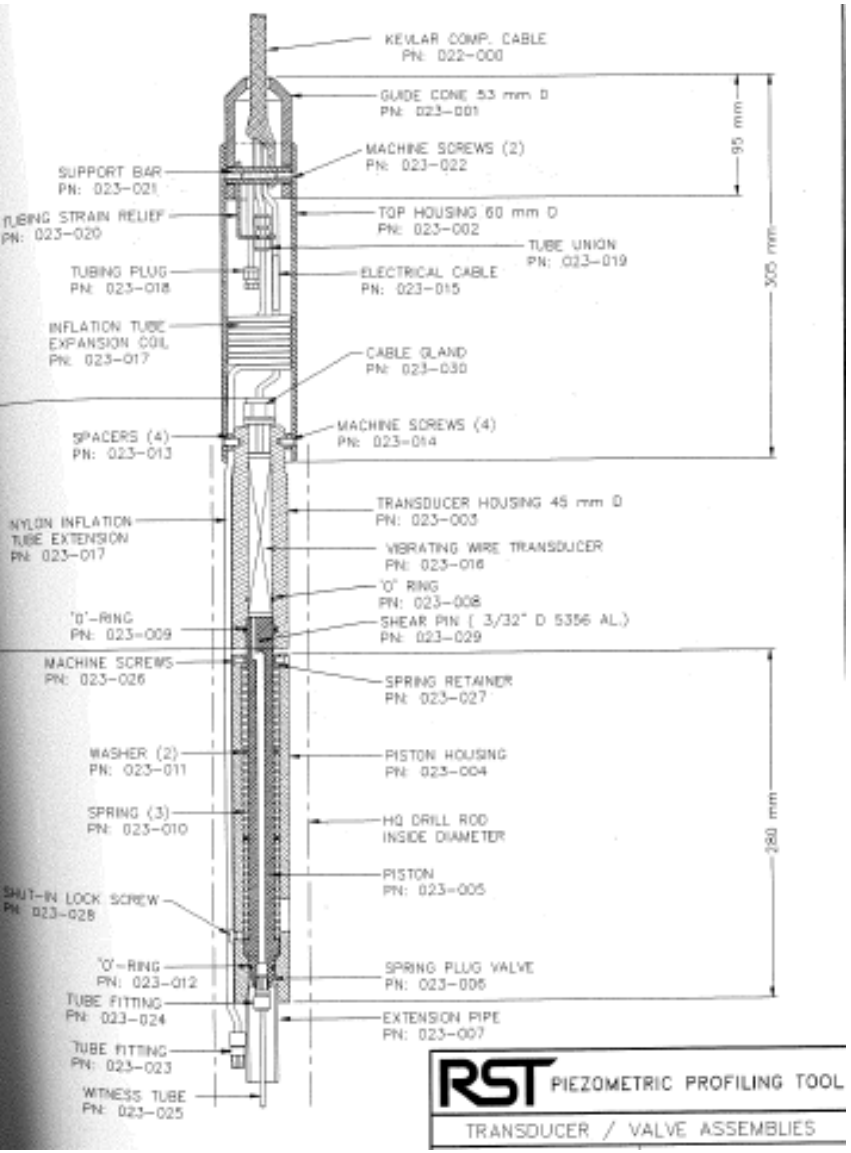
Dutchman's Ridge – Drilling Observations



Most drill holes showed "perched" water levels

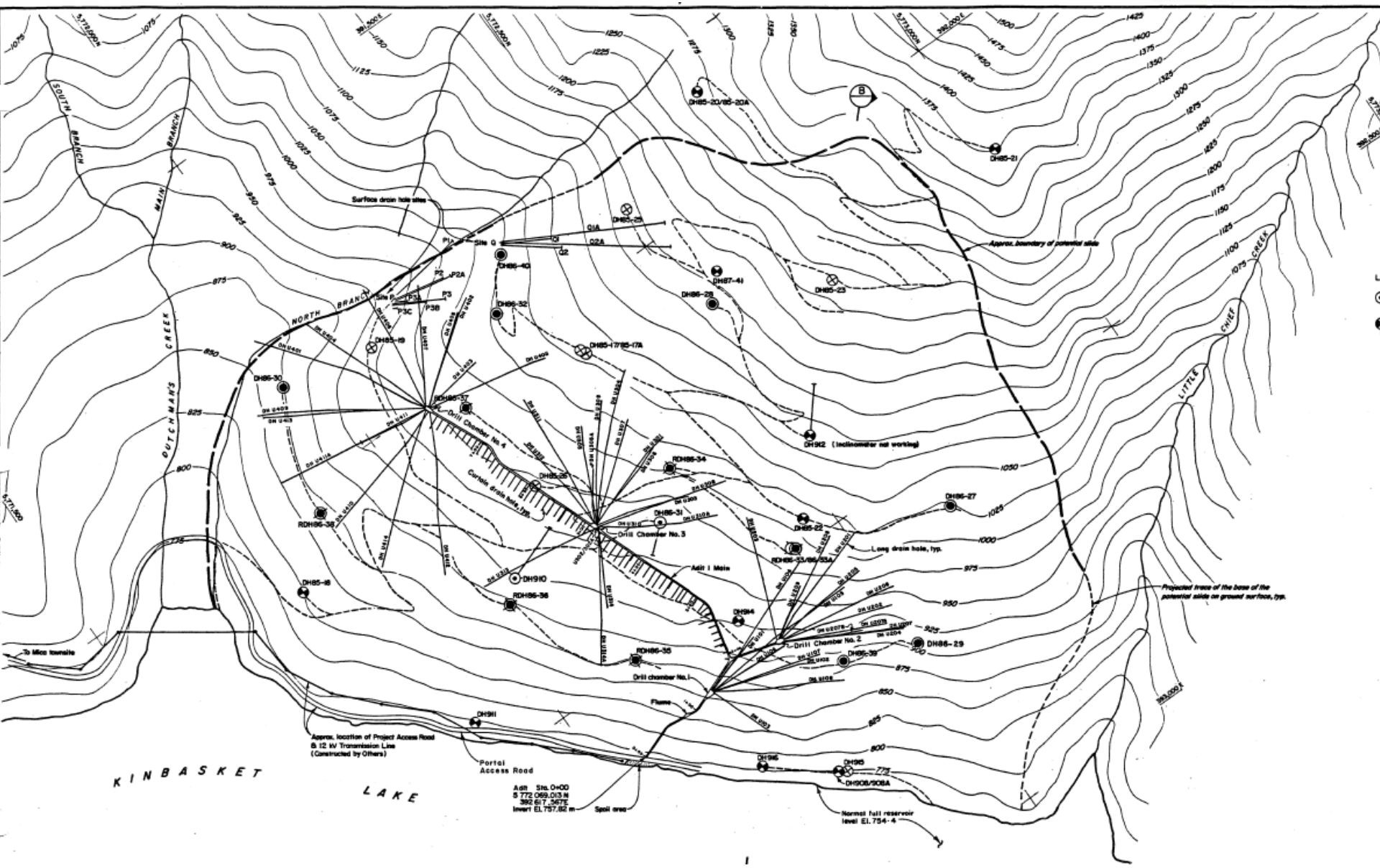
Testing allowed optimum design of piezo installation

Dutchman's Ridge – Piezo Testing



Piezometric testing during drilling
Custom "through-the-drill-string" set up
Reliable – no issues with getting stuck
Data immediately available

Dutchman's Ridge – Drainage Layout



982 m of Adit installed (1986-88) ; 20,000 m of drainholes

Dutchman' Ridge – Groundwater TH

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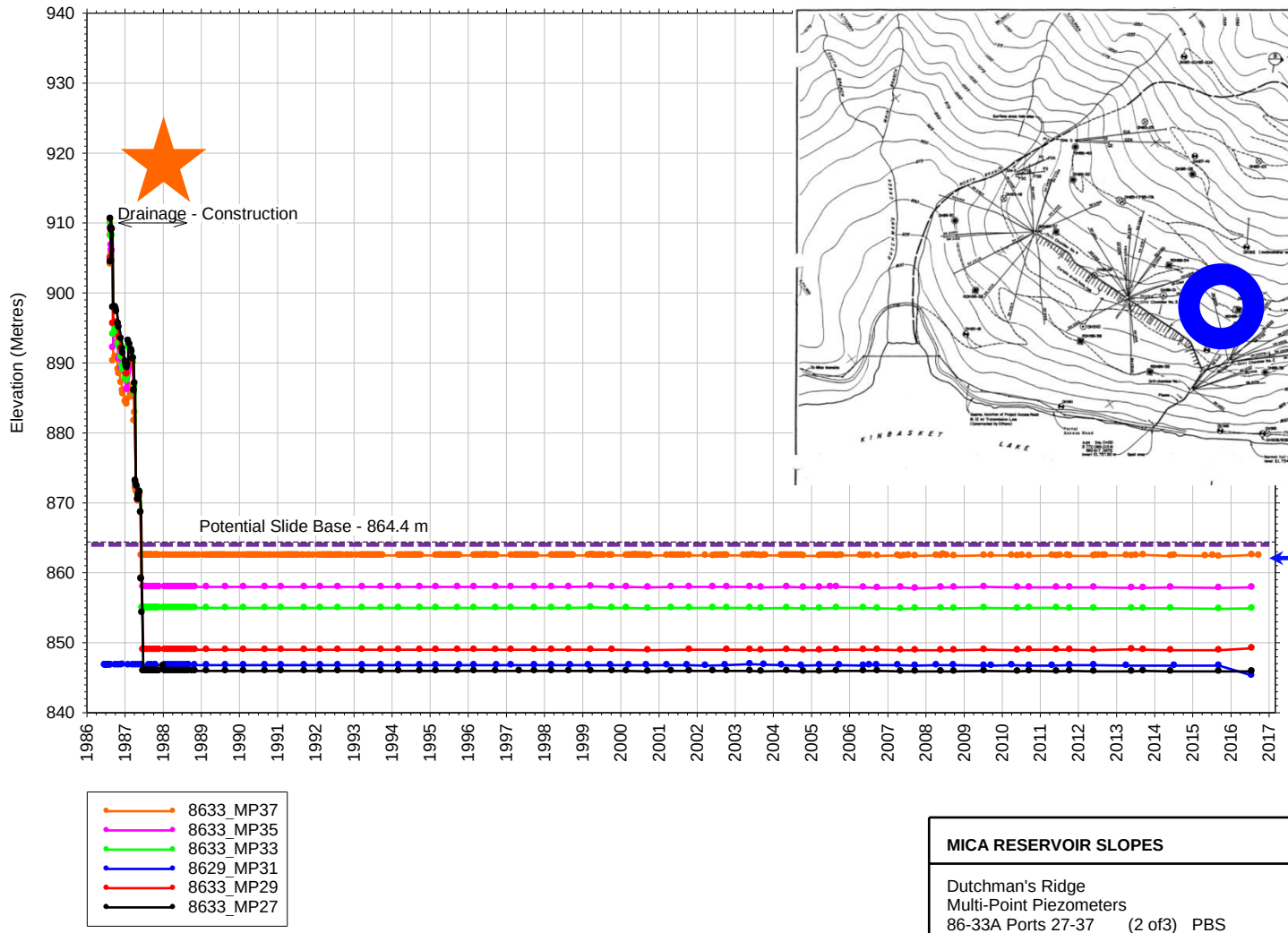

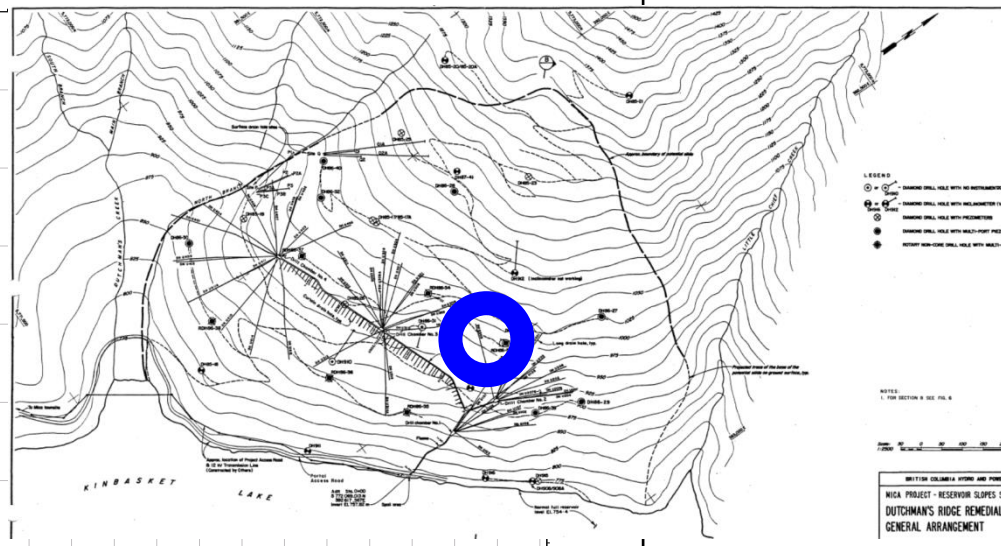

MP's dry

MICA RESERVOIR SLOPES

Dutchman's Ridge
Multi-Point Piezometers
86-33A Ports 27-37 (2 of3) PBS

DMR_PZ27
January 18, 2017

1. Large portions of potential slide fully drained.

2. Up to 100 m pressure drawdown – lasting effect

Dutchman's Ridge - Displacement

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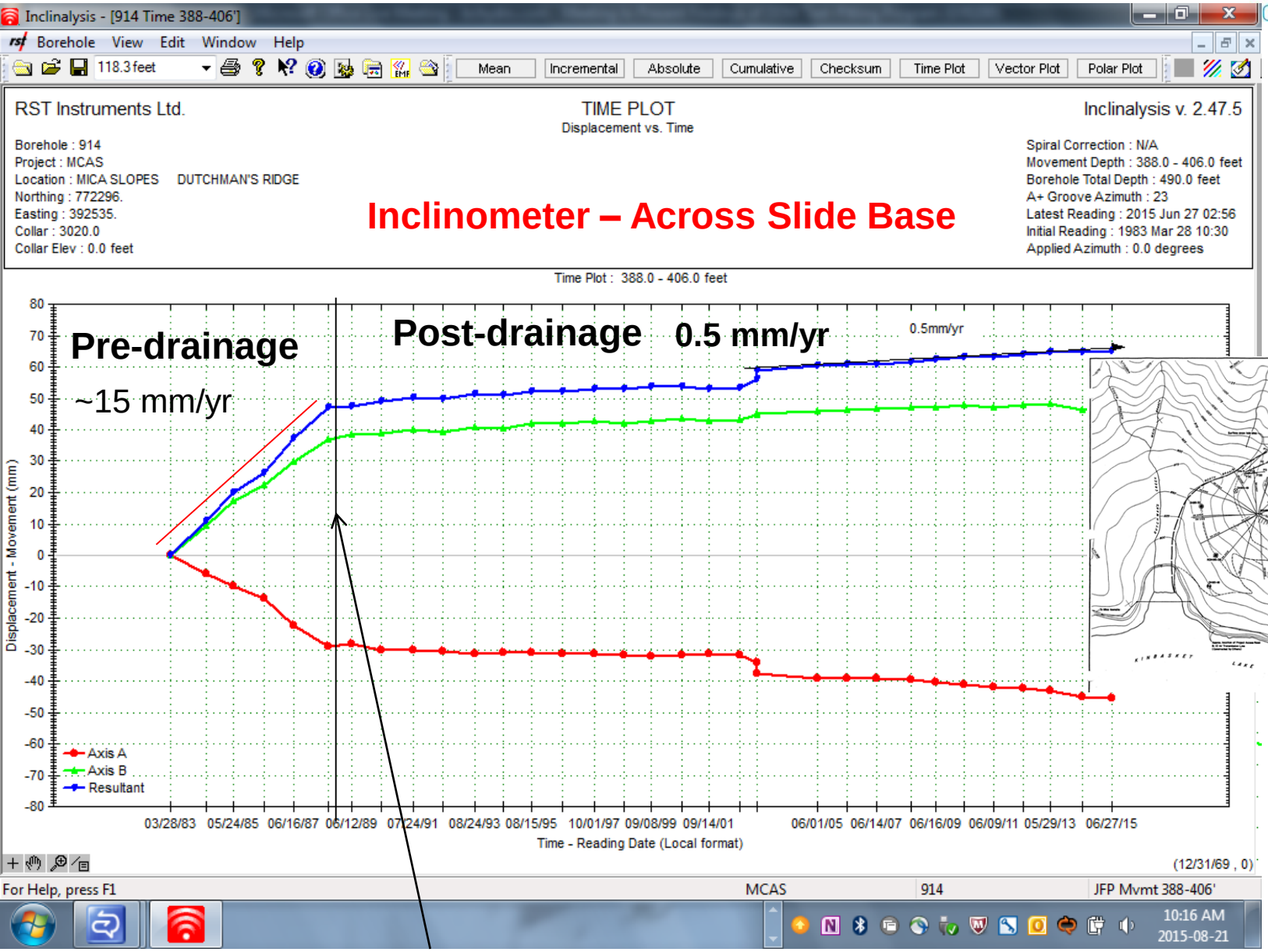

Slope displacement response to drainage - rate reduced by > order of magnitude

Dutchman's Ridge – Adit Conditions

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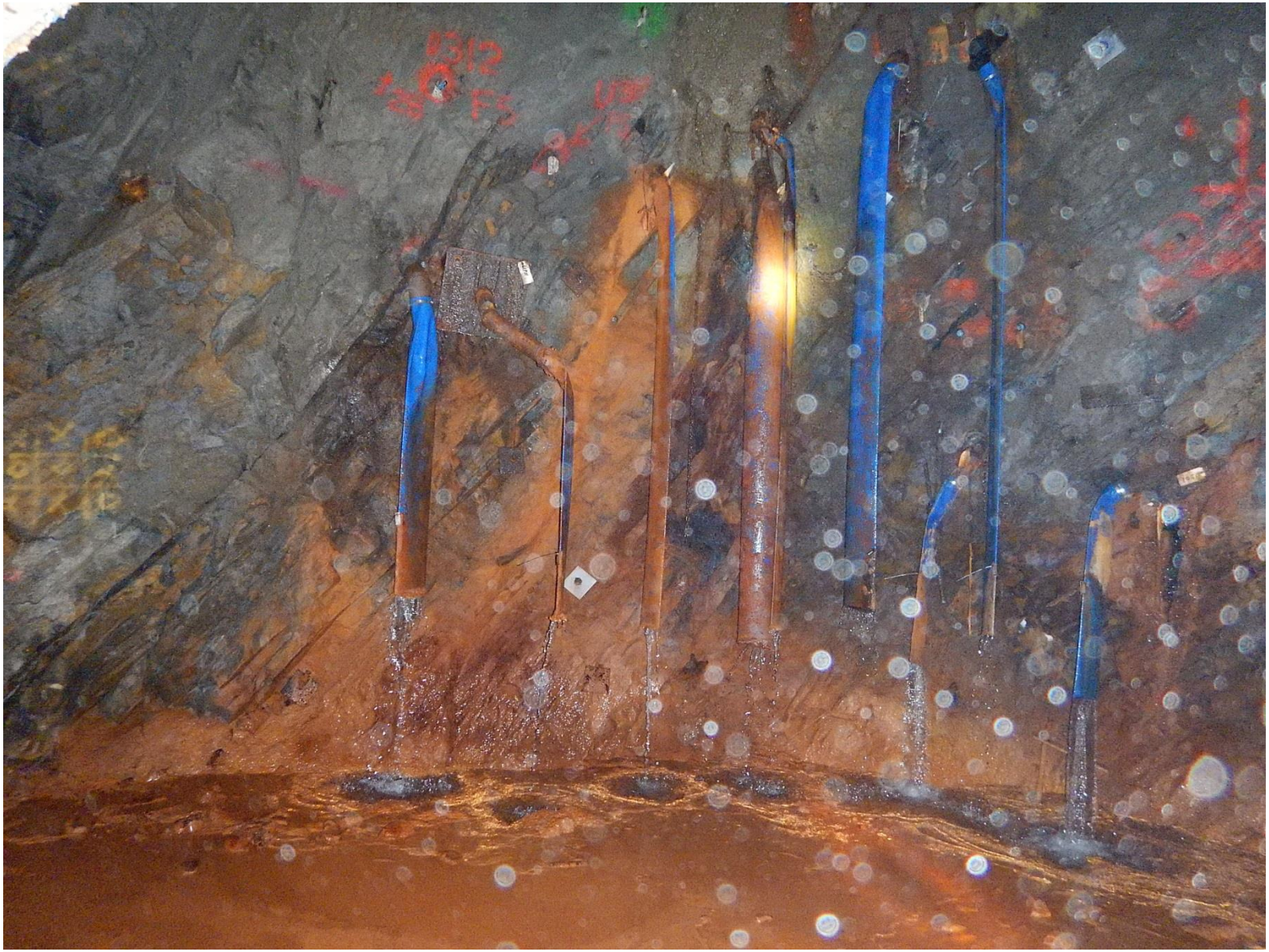
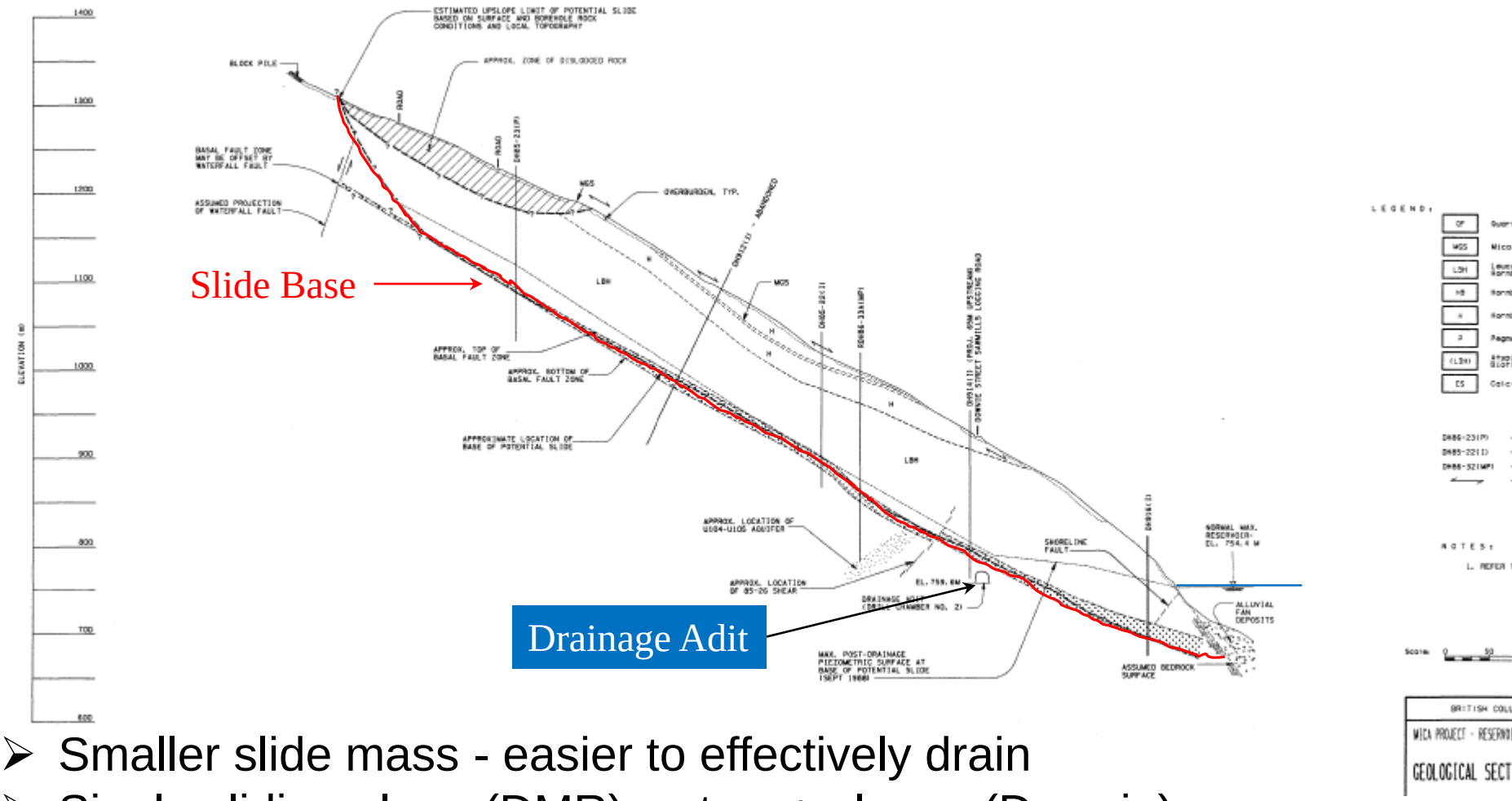


Flow rates have reduced but pressures have remained "fully drained"

Dutchman's Ridge – Compared to Downie

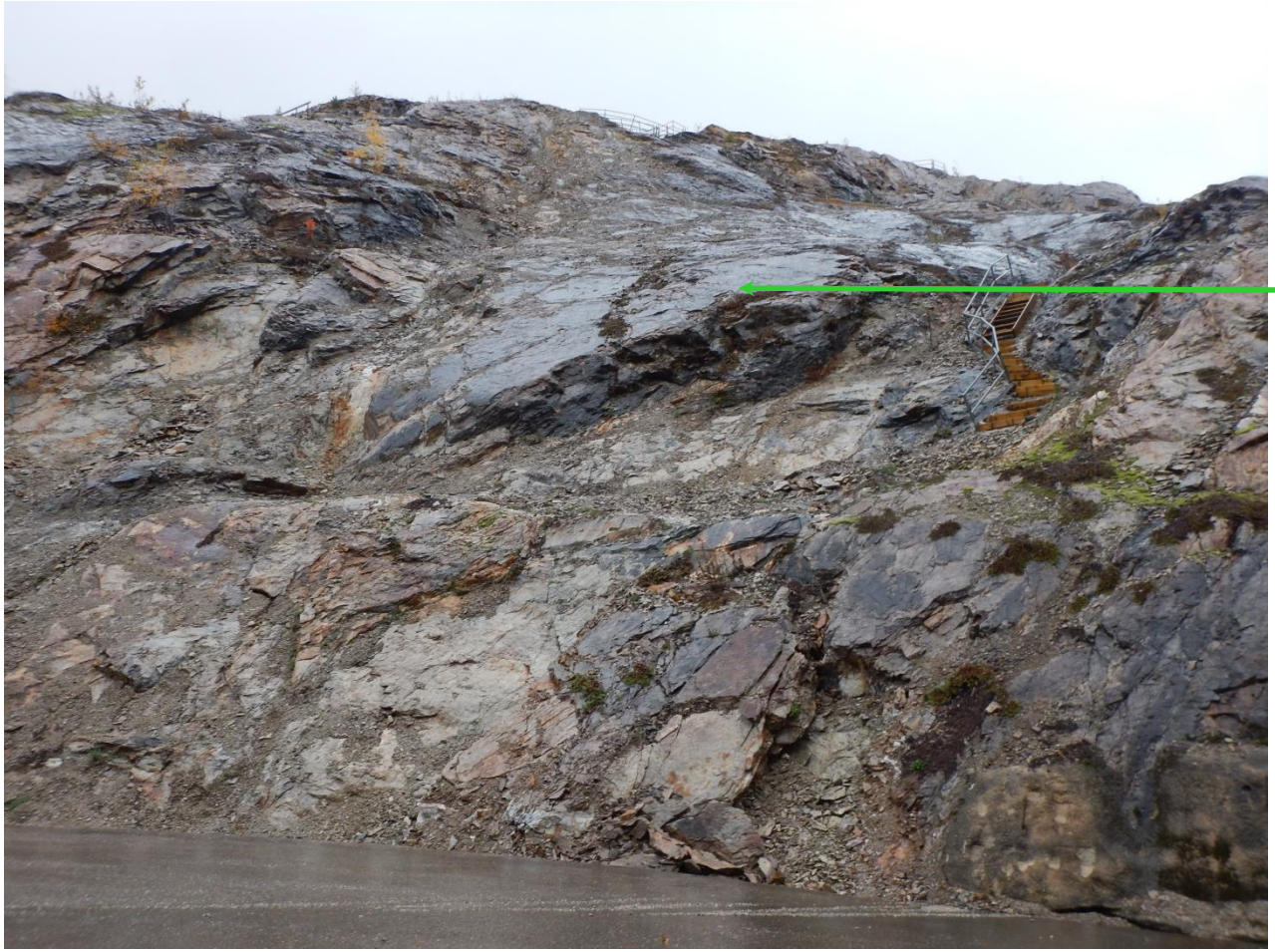


- Smaller slide mass - easier to effectively drain
- Single sliding plane (DMR) vs two + planes (Downie)
- Slightly better rock quality – less previous slide displacement
- Adit below slide in competent rock
- Nearly "fully" drained condition – effectively halted movements

Revelstoke Dam – Marble Shear Block

- 175 m high concrete gravity; with earthfill wing dam
- 1985 dam completion
- Slope instability on right bank (Marble Shear Block) 200,000 m3
- Potential to undermine spillway; block tailrace

Marble Shear Block - Geology

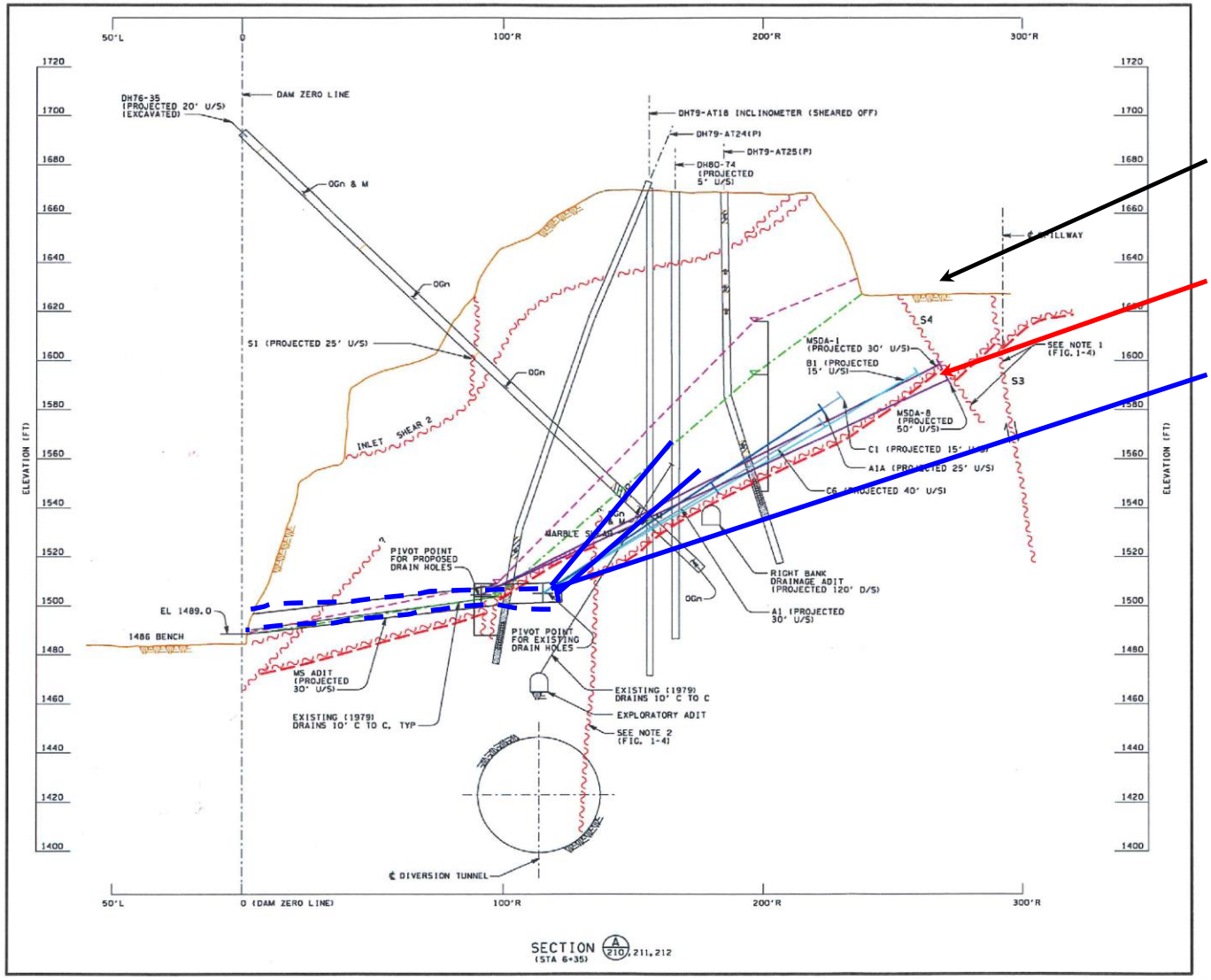


1. Quartzite / Mica Gneiss
2. Persistent planes of weakness (foliation / shears) dipping down slope
3. Considerable groundwater

Risk Management

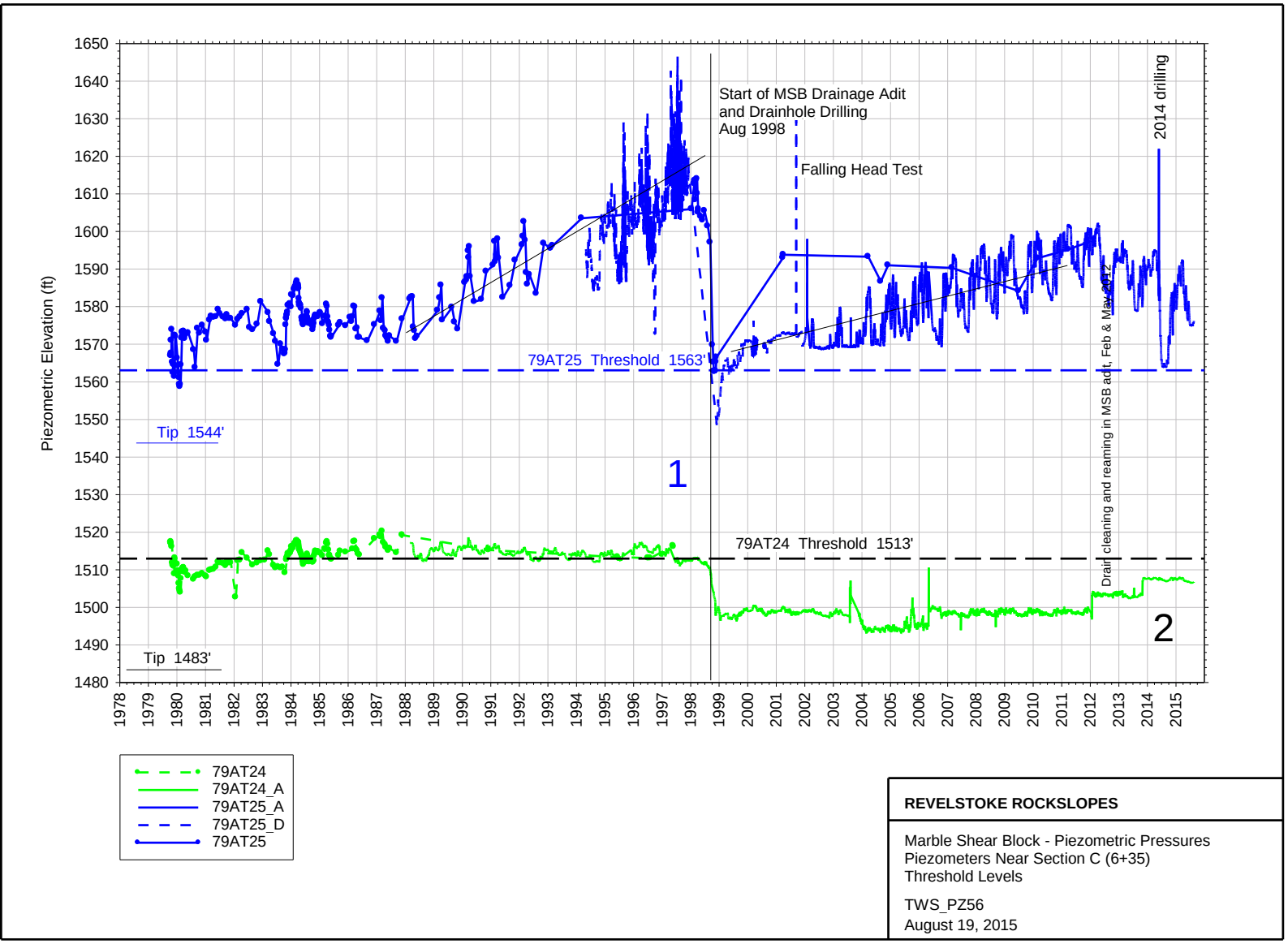
1. Risk to spillway / discharge facilities considered unacceptable
2. Drainage selected as remedial option

Marble Shear Block – Drainage



1. Spillway Structure
2. Sliding Plane
3. Adit (40 m long)
4. With ~1000 m of drainholes

Marble Shear Block – Groundwater TH



1. Significant pressure reductions (up to 15 m) from drainage

2. Remedial effects are persisting over 15 years – lasting results

Marble Shear Block - Displacement

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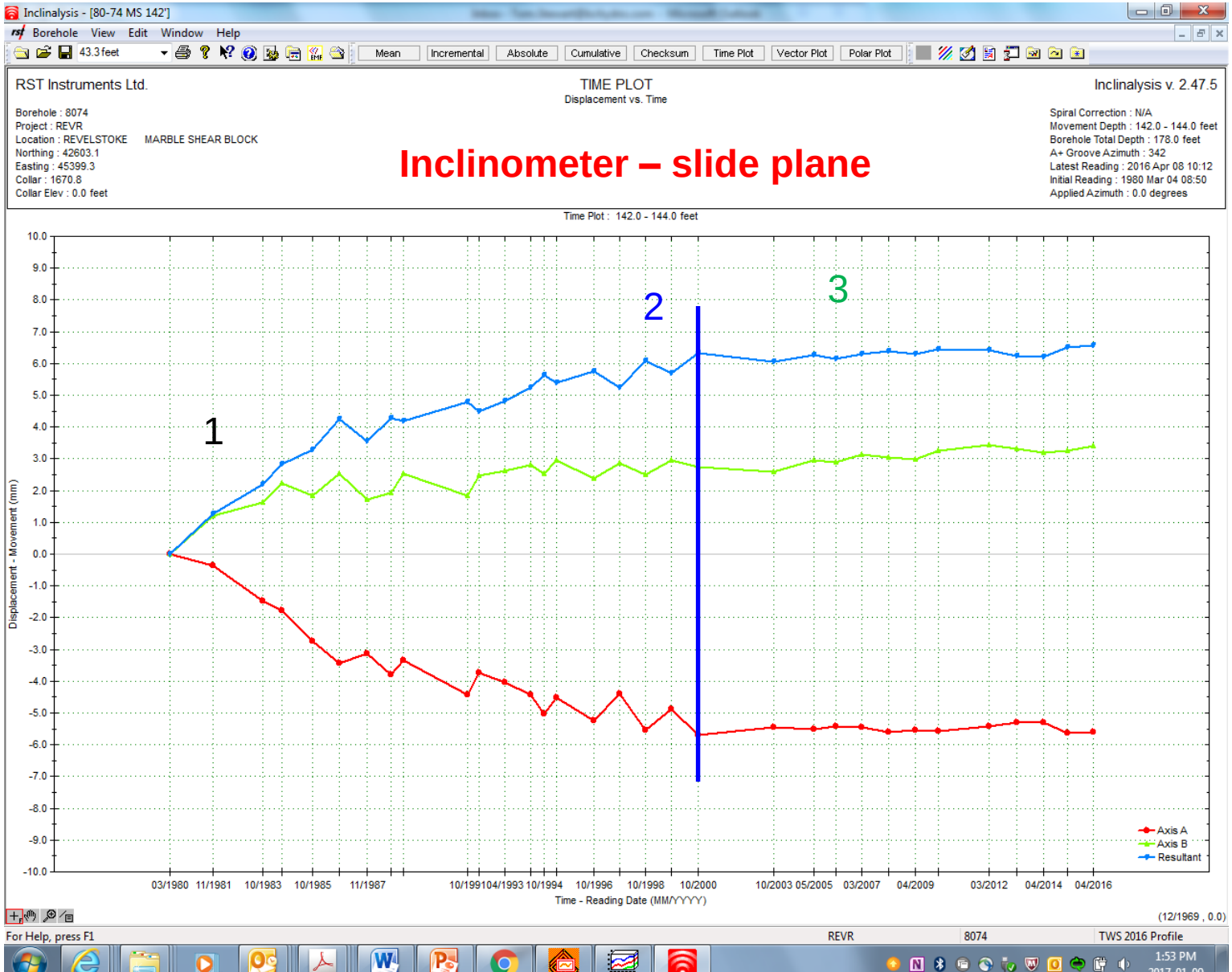


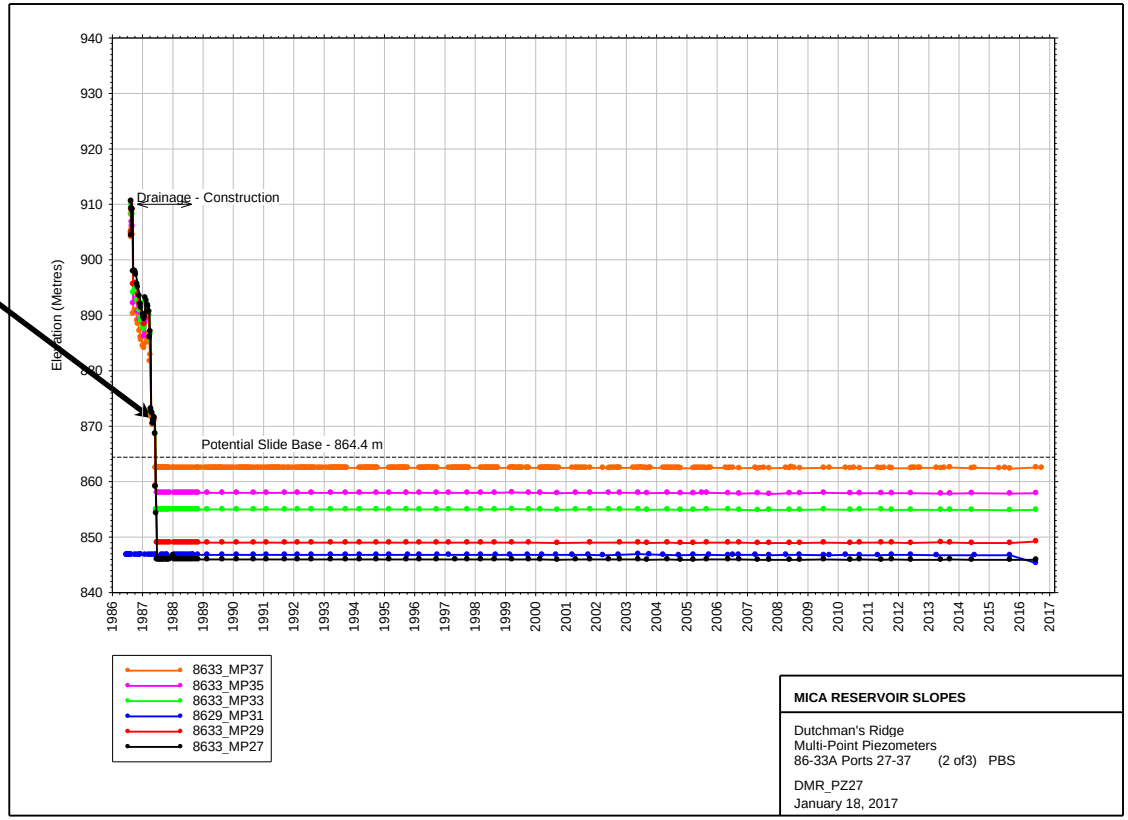
1. Minor displacement prior to drainage installation (2mm/yr)
2. Drainage 1998-99
3. Slope displacement effectively stopped following drainage

LANDSLIDE REMEDIATION THROUGH DRAINAGE

Lessons Learned – Summary:

1. Drainage has been effective – objectives achieved

- **Dewatering /depressurizing**
- **Displacement reduced/stopped**
- **Improved stability (5-10% FOS)**



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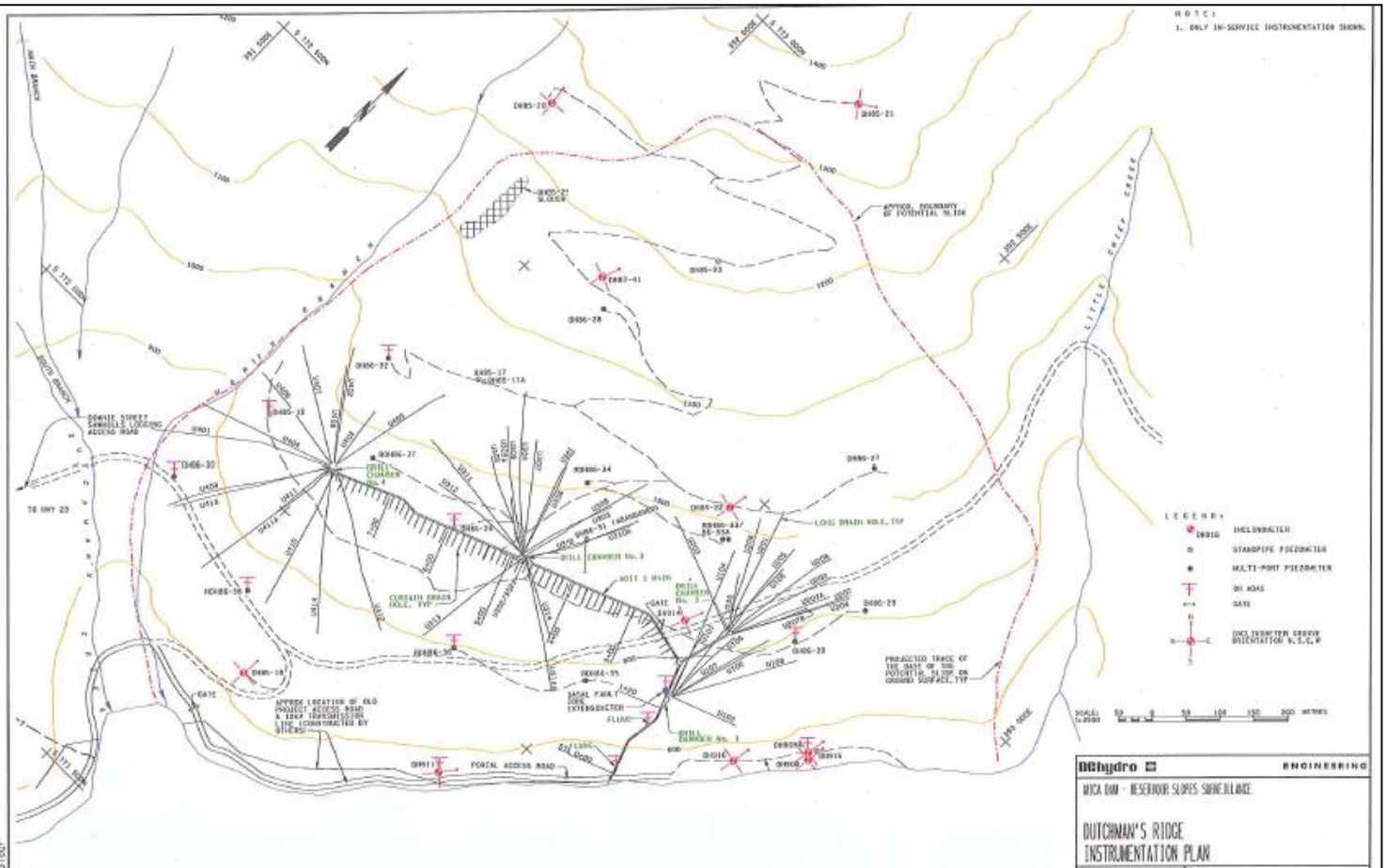
Tom Stewart, January 2017

LANDSLIDE REMEDIATION THROUGH DRAINAGE

Lessons Learned – Summary:

2. Well positioned monitoring system required (plan/evaluate)

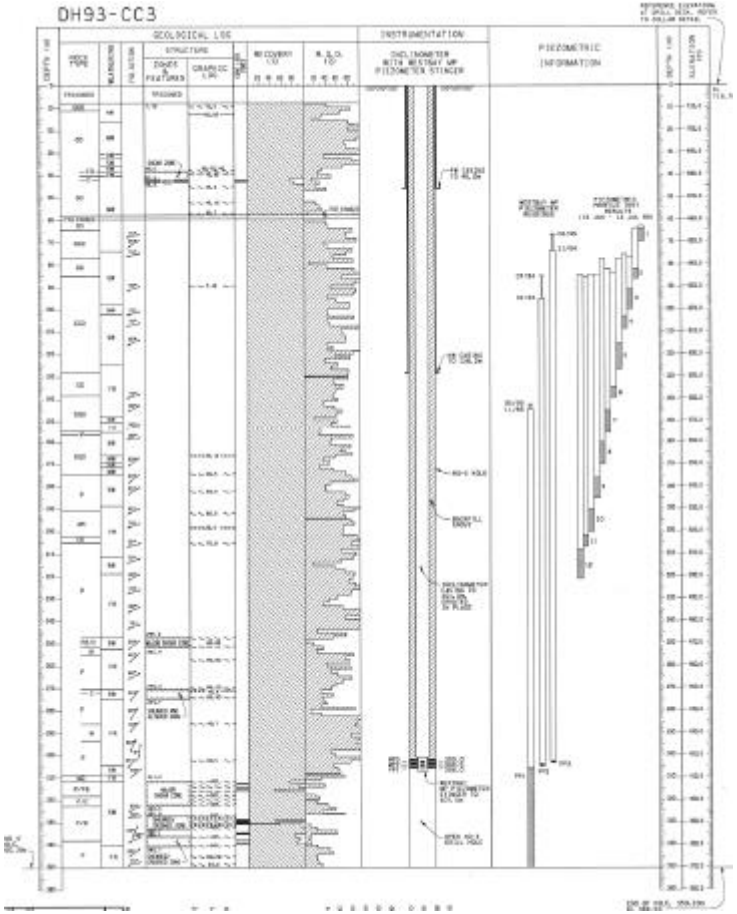


Need to understand where water is located
Detailed site investigation and monitoring required
Needs to be installed before drainage

LANDSLIDE REMEDIATION THROUGH DRAINAGE

Lessons Learned – Summary:

3. Well positioned monitoring system required (plan/evaluate)

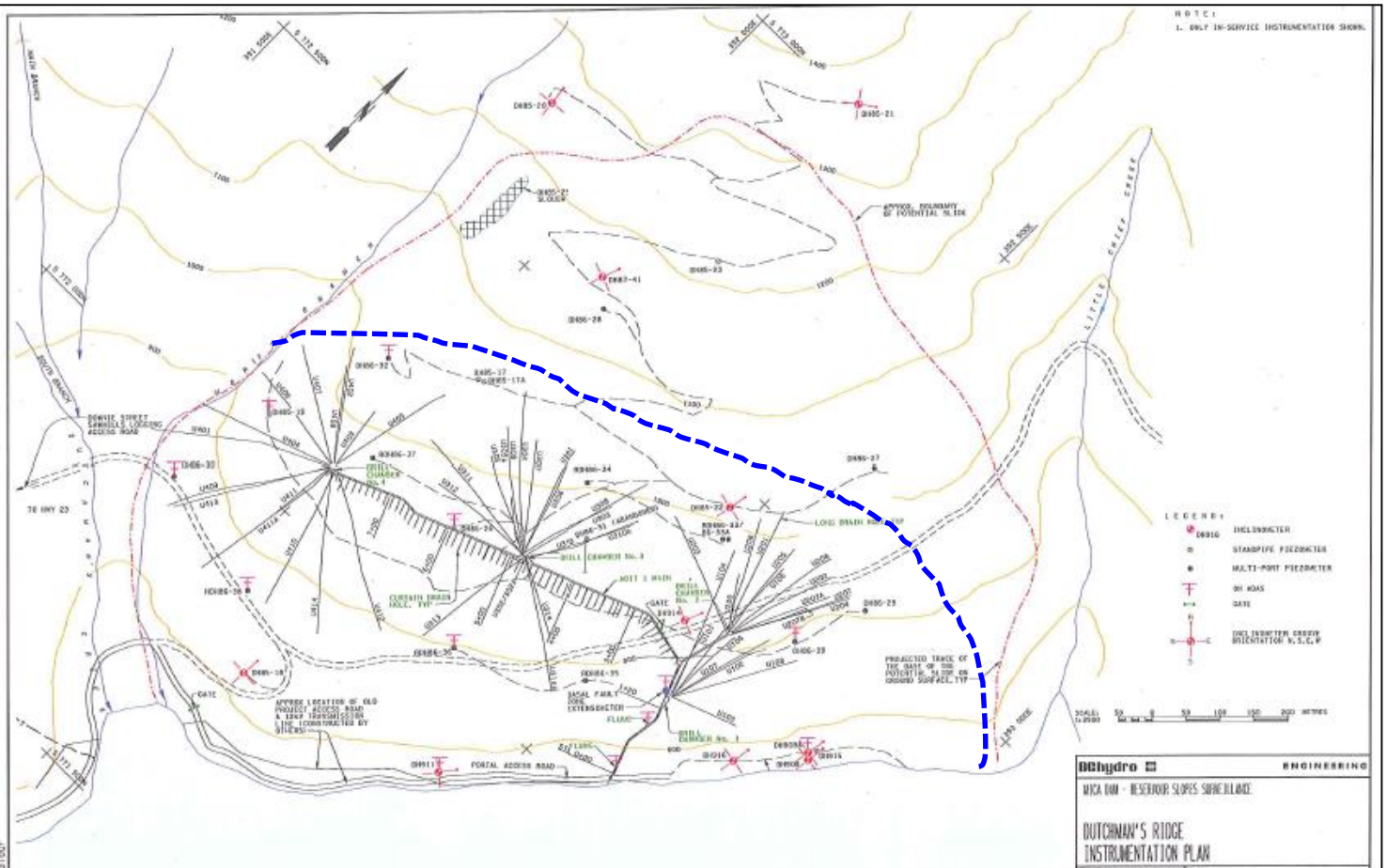


1. Need to conduct *in situ* testing during drilling to understand where water is located –
2. Identifies perched zones and downhole gradients that are otherwise missed
3. Allows planning for permanent piezometric monitoring.
4. Use of multi-port type piezometers highly effective (i.e. “Westbay” type).

LANDSLIDE REMEDIATION THROUGH DRAINAGE

Lessons Learned – Summary:

4. Drainage response typically confined to treated area only

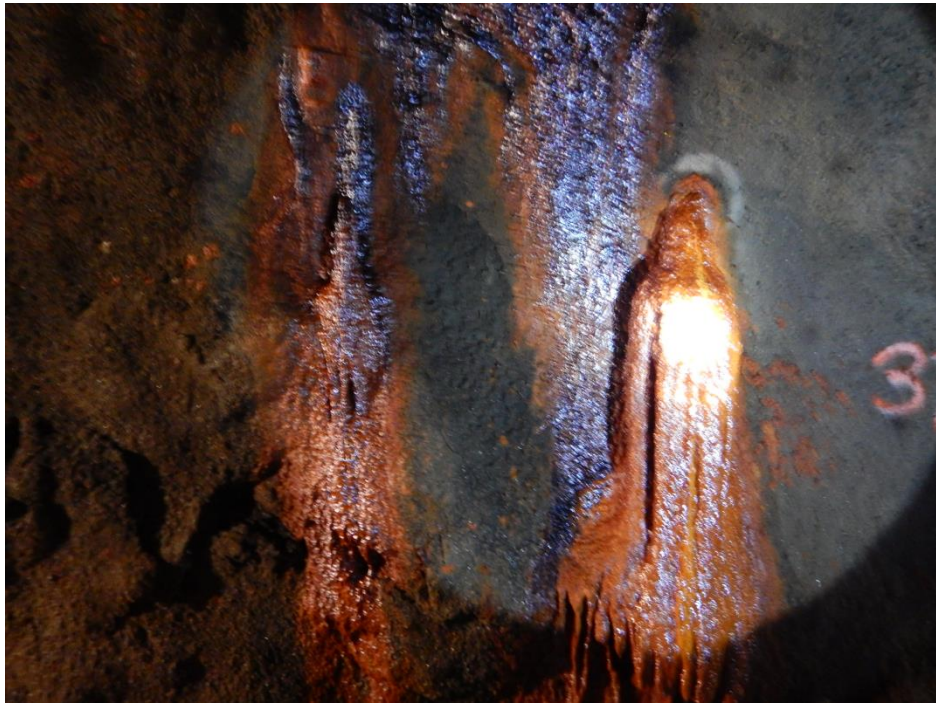


LANDSLIDE REMEDIATION THROUGH DRAINAGE

Lessons Learned – Summary:

5. Plan for maintenance – successful results come from long-term commitment

- **Lighting, ventilation, power supply**
- **Drainhole replacement (cleaning ineffective)**
- **Requirement to install additional monitoring**
- **Rock support**



BC hydro
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LANDSLIDE REMEDIATION THROUGH DRAINAGE

Questions / Discussion ?

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BRITISH COLUMBIA – NORWEGIAN CONTEXT

BC hydro
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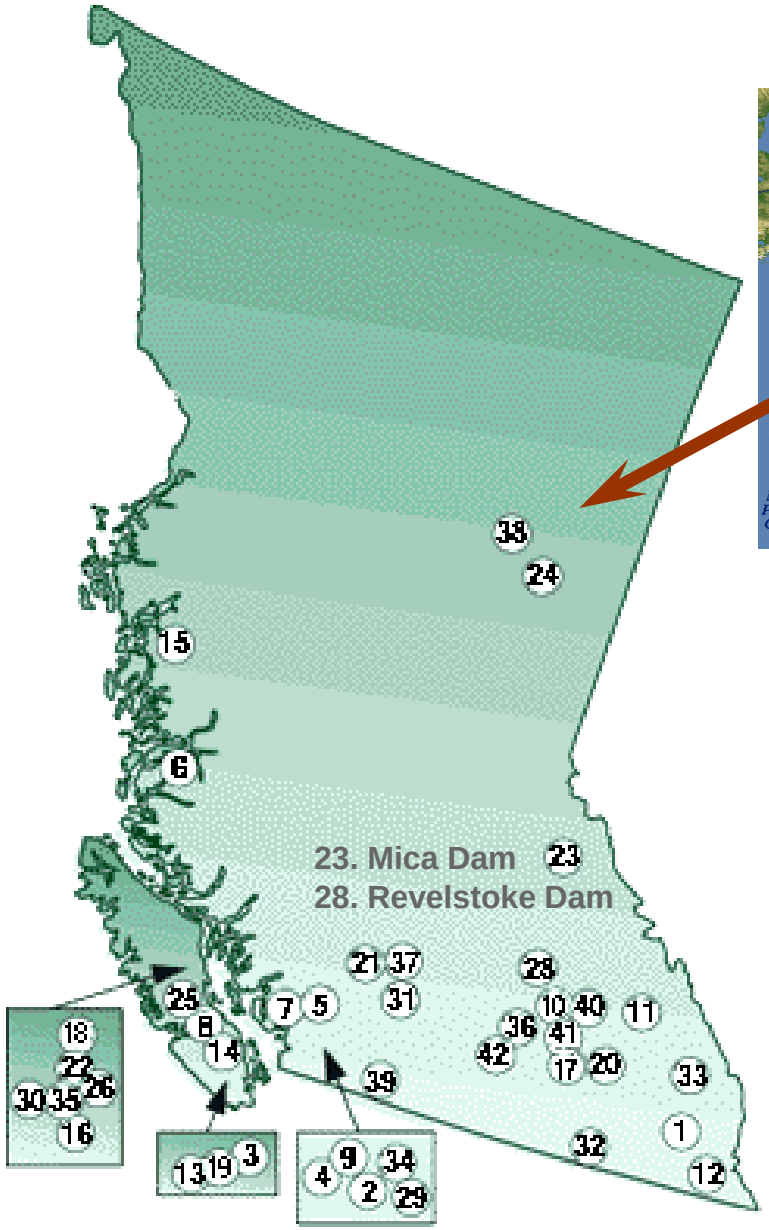

British Columbia	Norway
944,735 sq. km	304,282 sq. km
1900 km long	1347 km long
505 km wide	304 km wide
Mountainous	Mountainous
Lots of snow	Lots of snow
Lots of fjords	Lots of fjords

3% of population of Norwegian descent