Two-Phase Continuum Models for Geophysical Particle-Fluid Flows

Seminar: 21 March - 15 April 2016

Sediment gravity flows in Quesnel Lake caused by the catastrophic Mount Polley mine tailings dam failure

Ray Kostaschuk

Simon Fraser University

Outline

- The Tailings Dam Failure and Subaerial Debris Flows in Hazeltine Creek
- Subaqueous Gravity Flows in Quesnel Lake
- Erosion by Subaqueous Debris Flows in Quesnel Lake
  - Preliminary Results From the Iverson (2012) Entrainment Model
- Geoflo19: Modelling Debris Flow Deposition in Quesnel Lake

Date	Location	Parent company	Ore type	Type of Incident	Release	Impacts
2015, Nov. 21	Hpakant, Kachin state, Myanmar	?	jade	waste heap failure	?	at least 113 people killed
2015, Nov. 5	Germano mine, Bento Rodrigues, distrito de Mariana, Região Central, Minas Gerais, Brazil	Samarco Mineração S.A. (50% BHP Billiton, 50% Vale)	iron	failure of two tailings dams holding a combined 62 million m^3 (apparently, the Fundão dam broke first, releasing tailings into the Santarém dam, which failed then as well)	32 million m^3 Video of the flow slide	slurry wave flooded town of Bento Rodrigues, destroying 158 homes, at least 17 persons killed and 2 reported missing; slurry pollutes North Gualaxo River, Carmel River and Rio Doce over 663 km, destroying 15 square kilometers of land along the rivers and cutting residents off from potable water supply
2014, Sep. 10	Herculano mine, Itabirito, Região Central, Minas Gerais, Brazil	Herculano Mineração Ltda.	iron	tailings dam failure	?	two workers killed and one missing
2014, Aug. 7	Buenavista del Cobre mine, Cananea, Sonora, Mexico	Southern Copper Corp. (Grupo México)	copper	tailings dam failure	40,000 m^3 of copper sulphate	flow into the 420km-long Bacanuchi river waterway, a tributary of the Sonora River, directly affecting 800,000 people
2014, Aug. 4	Mount Polley mine, near Likely, British Columbia, Canada	Imperial Metals Corp.	copper, gold	tailings dam failure due to foundation failure (**view details**)	7.3 million m^3 of tailings, 10.6 million m^3 of water, and 6.5 million m^3 of interstitial water	tailings flowing into adjacent Polley Lake and, through Hazeltine Creek, into Quesnel Lake (Mitchell Bay)


British
Columbia
500 km
Vancouver

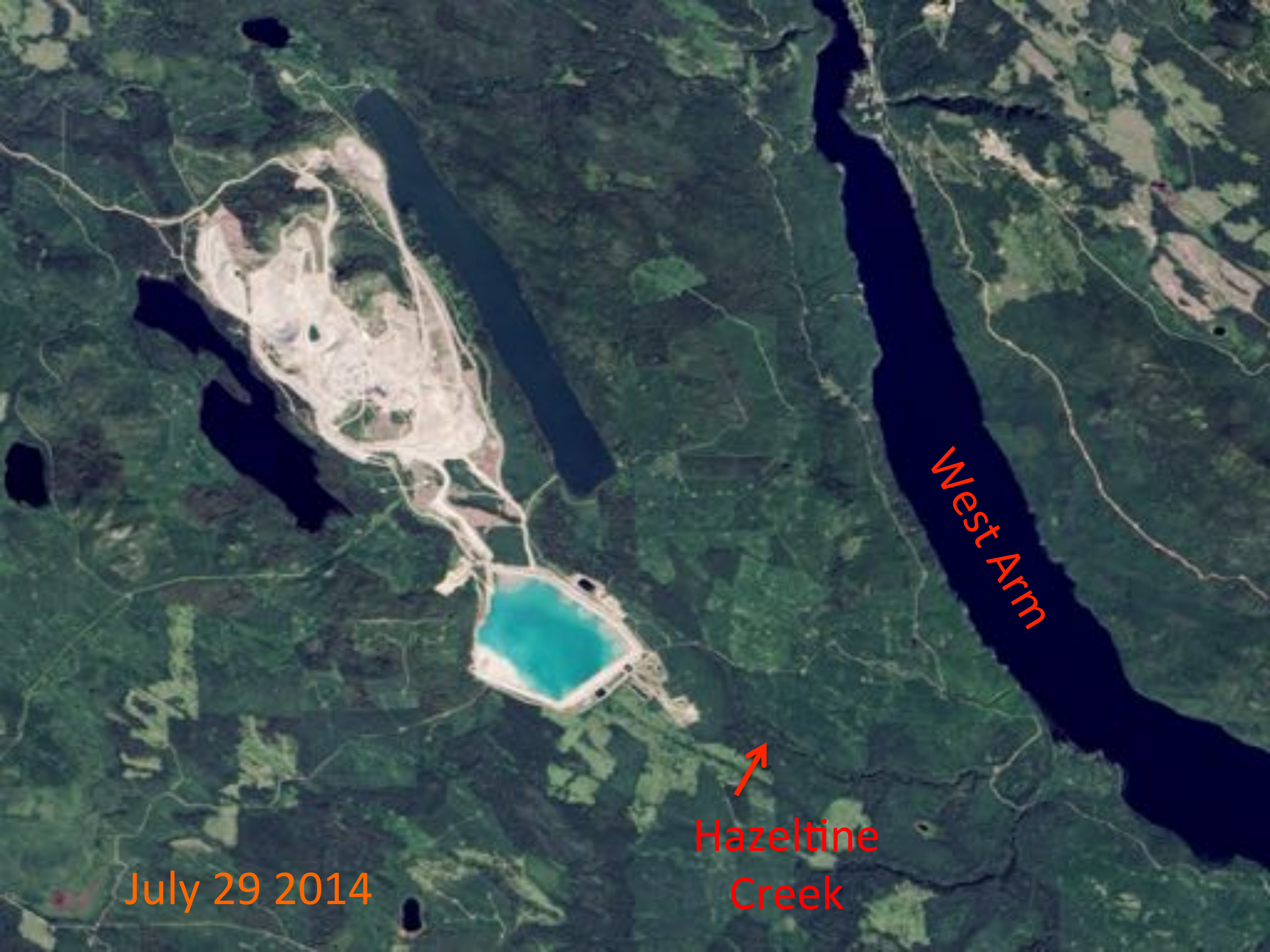

West Arm
Mt Polley
Mine
Quesnel Lake
20 km


ECOTOURS BC

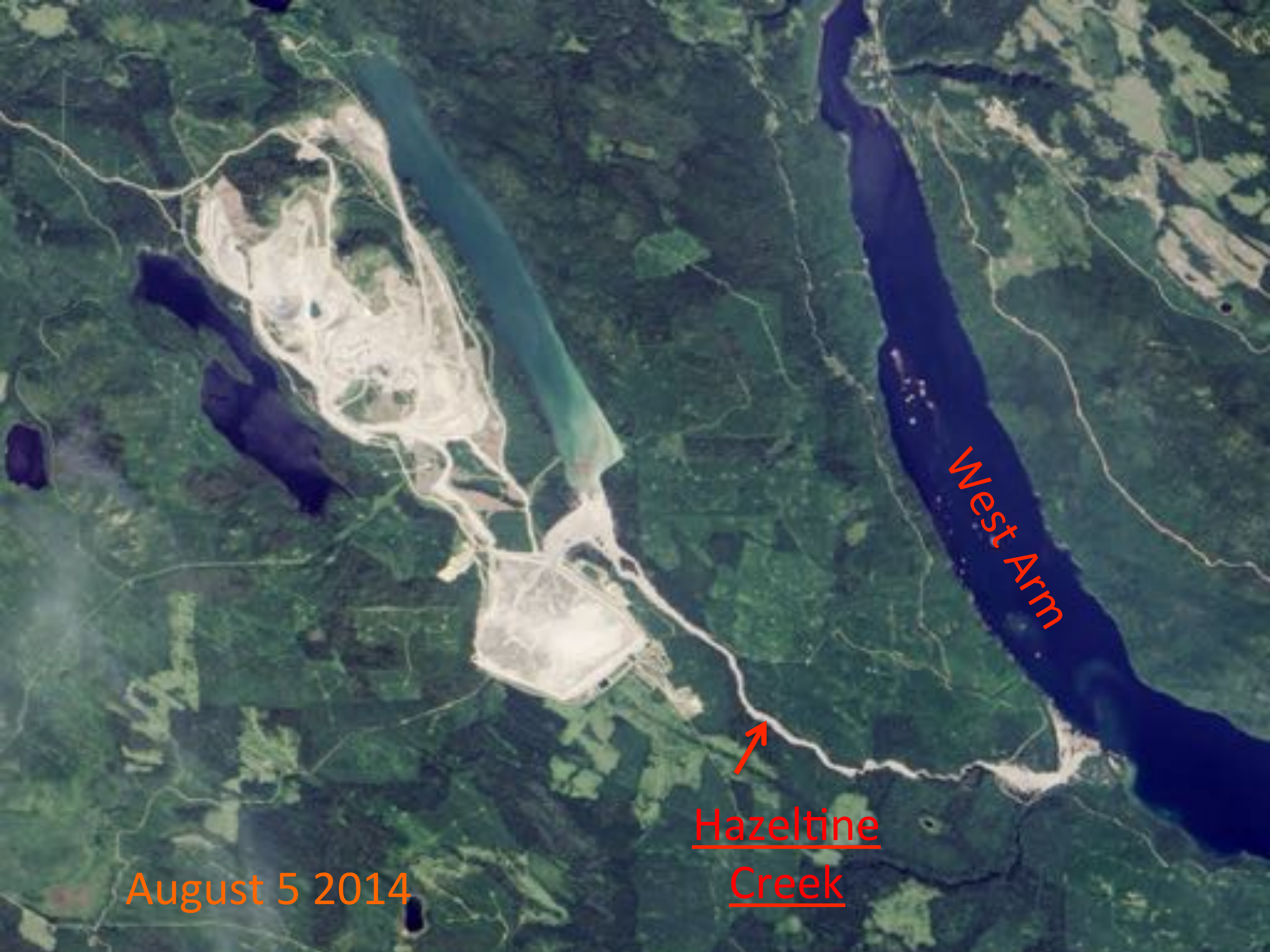
The Tailings Dam Failure and Subaerial Debris Flows in Hazeltine Creek

- Early on August 4, 2014, a tailings dam failure occurred at the Mount Polley Mine causing water and toxic tailings to be released to Polley Lake, Hazeltine Creek and Quesnel Lake
- The failure of the dam was caused by a combination of poor design, poor maintenance, and inadequate inspection by the British Columbia government

https://www.youtube.com/watch?v=VYYwzAvQIF8



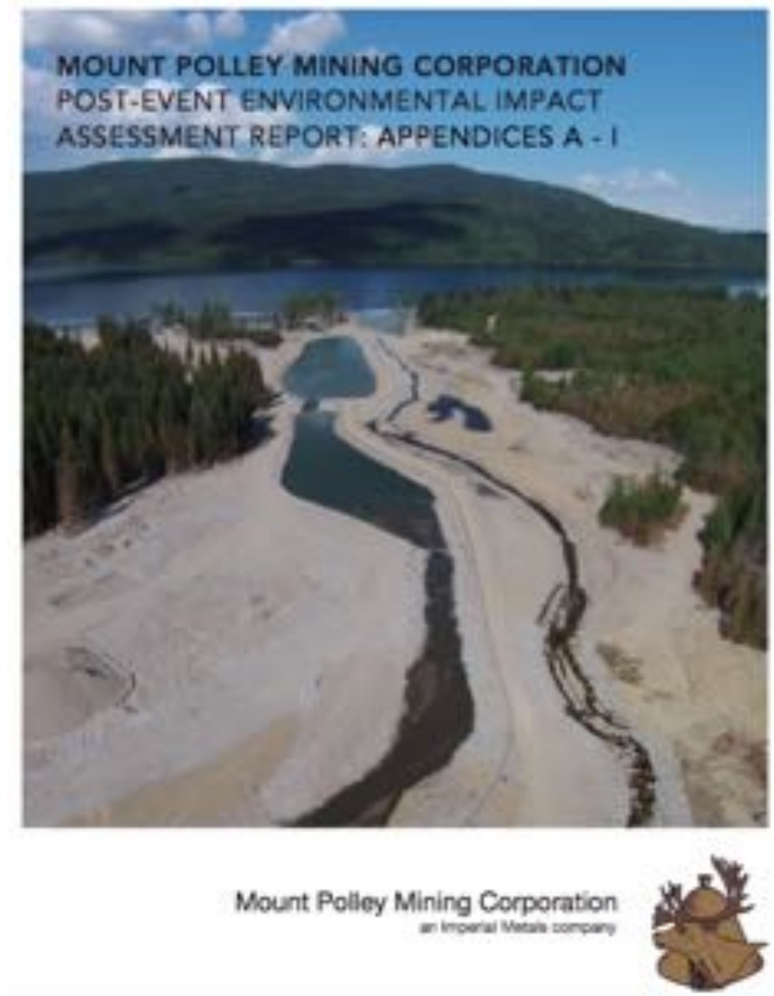
West Arm
Hazeltine
Creek
July 29 2014



West Arm
Hazeltine
Creek
August 5 2014

JUNE 5, 2015


MOUNT POLLEY MINING CORPORATION
POST-EVENT ENVIRONMENTAL IMPACT
ASSESSMENT REPORT – KEY FINDINGS REPORT
Mount Polley Mining Corporation
an Imperial Metals company

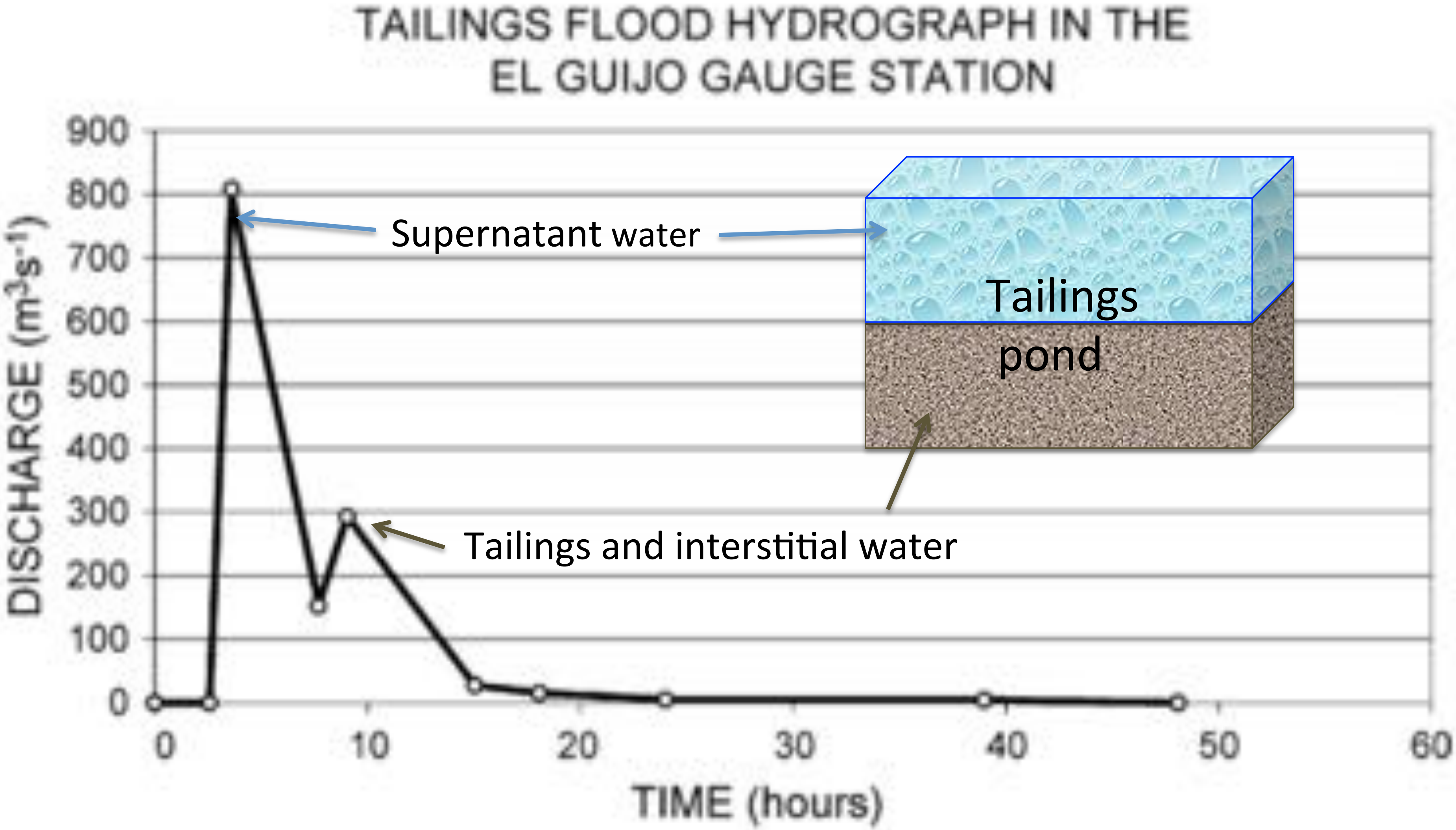

MOUNT POLLEY MINING CORPORATION
POST-EVENT ENVIRONMENTAL IMPACT
ASSESSMENT REPORT: APPENDICES A - I
Mount Polley Mining Corporation
an Imperial Metals company

https://www.youtube.com/watch?v=xAItFxc8bME


grey layer of
fine material
red layer of
sandy material
topsoil

Volume estimates for tailings dam failure

Volume Estimation	Total
Supernatant water (Mm^3)	10.6
Tailings solids (Mm^3)	7.3
Interstitial water (Mm^3)	6.5
Construction materials (Mm^3)	0.6
Total outflow volume (Mm^3)	25.0
Net volume of eroded material (Mm^3)	0.6 To 1.7
Total volume of the event (Mm^3)[3]	25.6 To 26.7

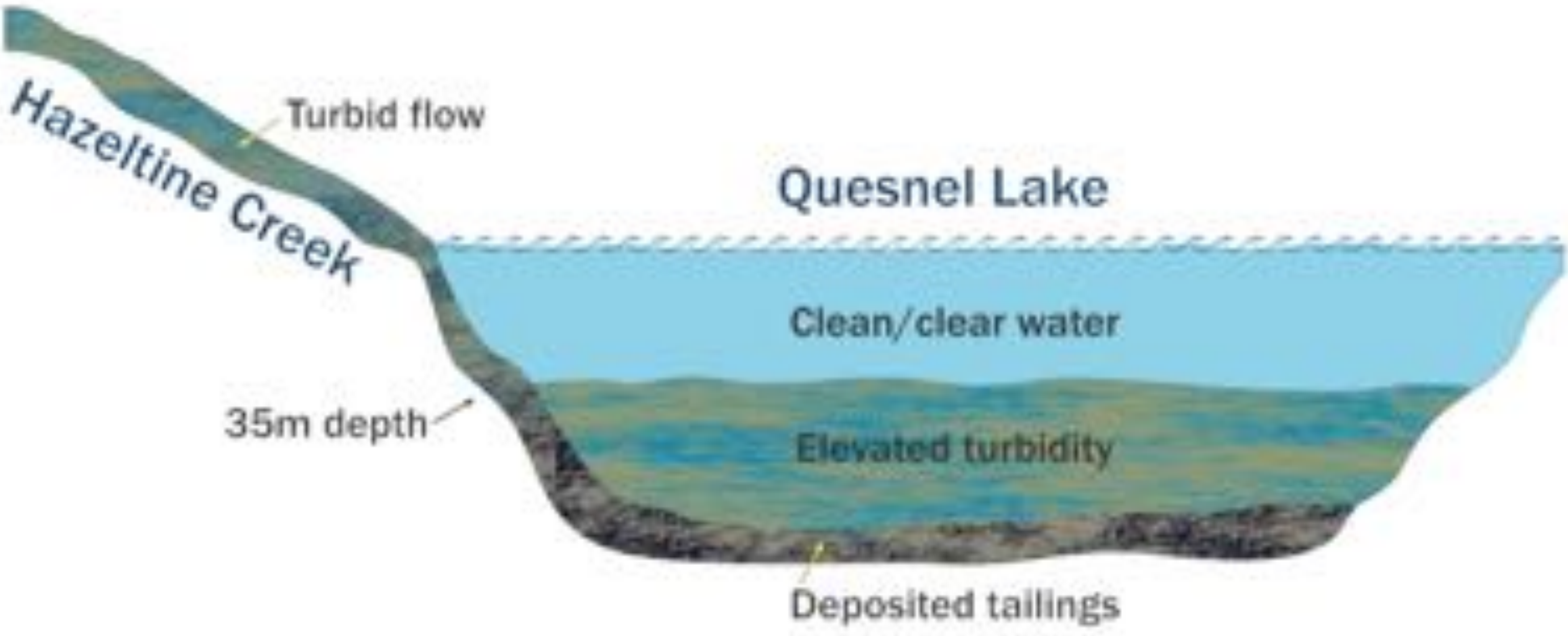


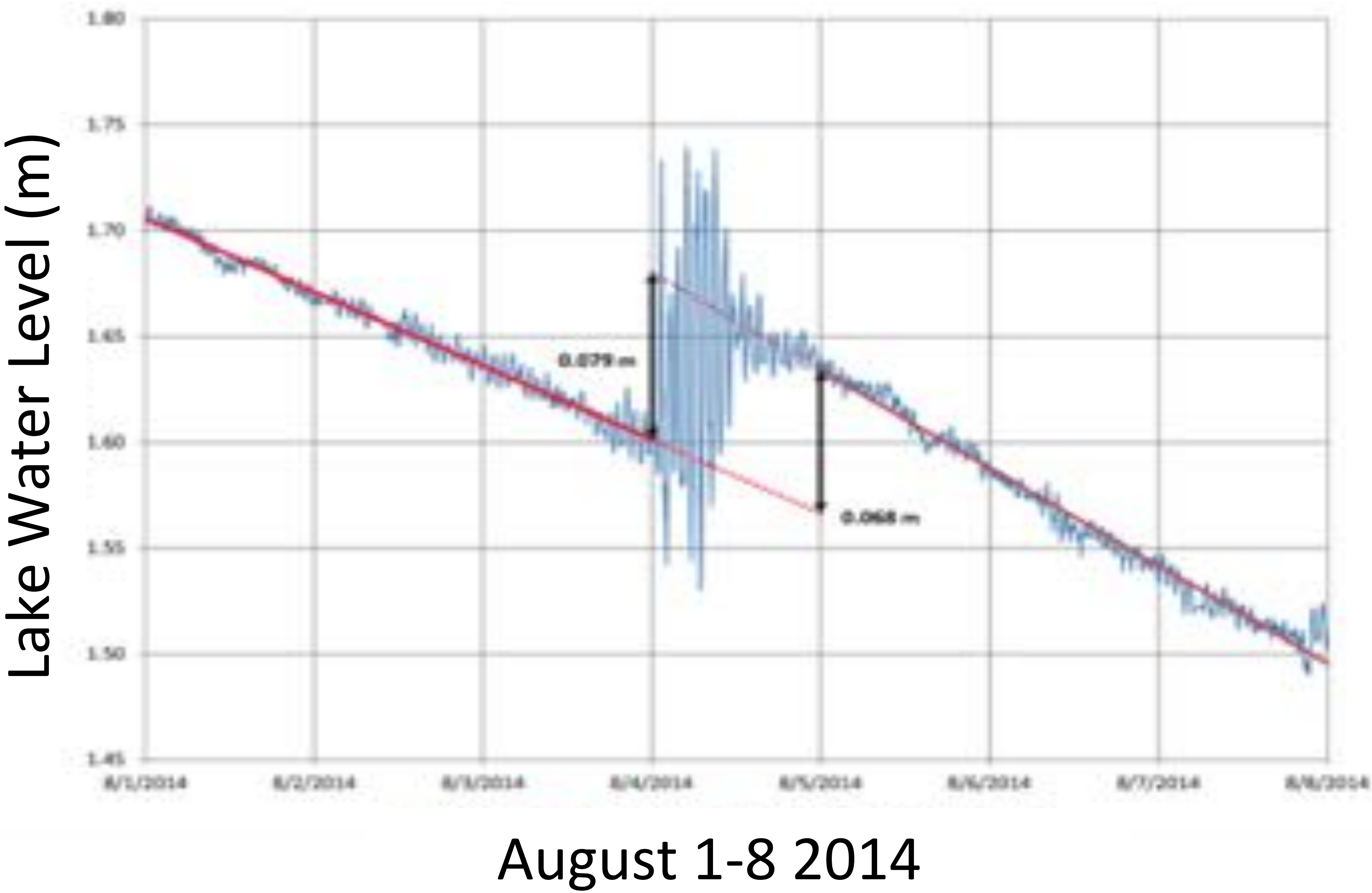
Rico et al. 2008, Journal of Hazardous Materials

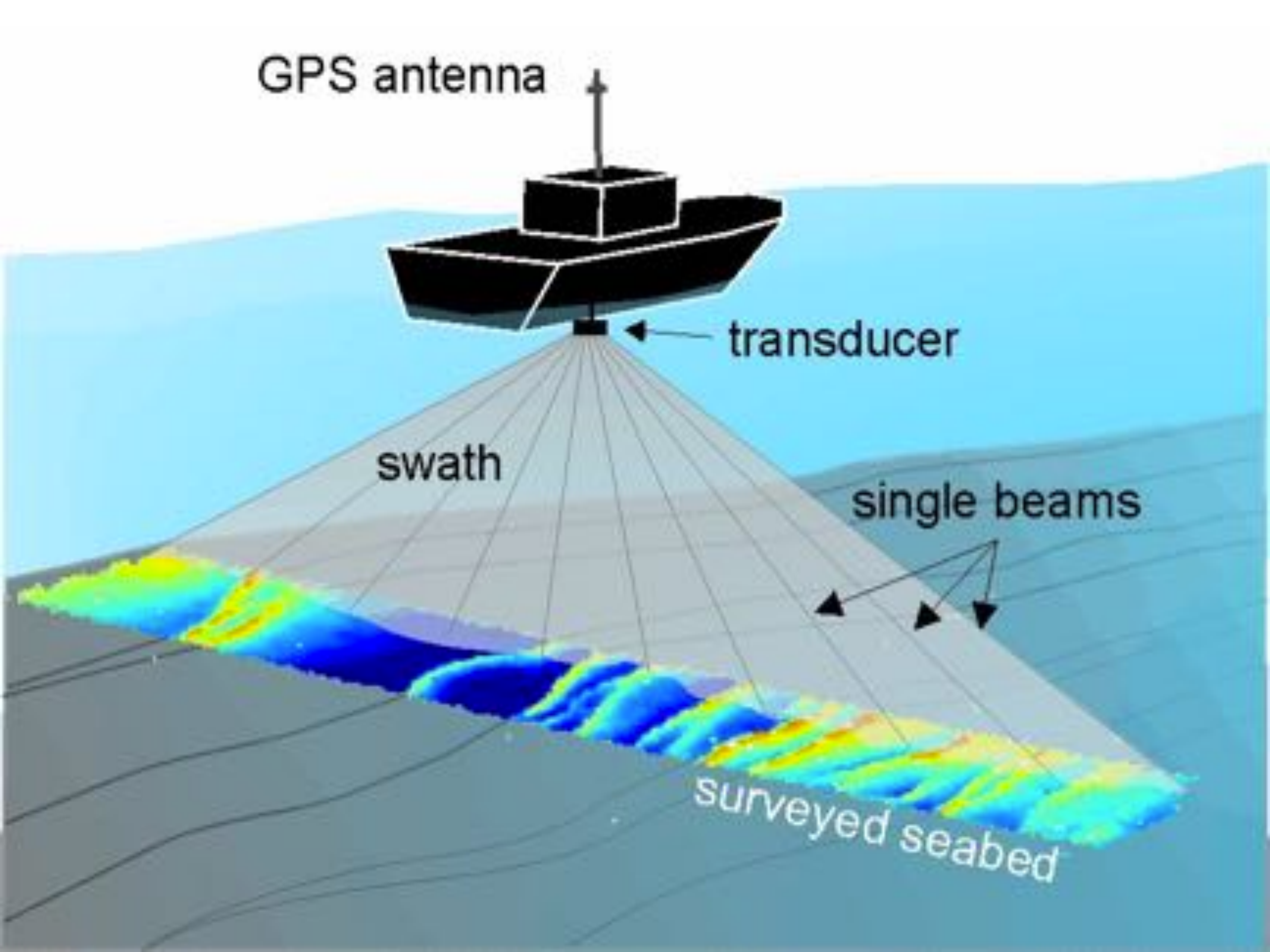

low-energy
debris flow
high-energy
debris flow

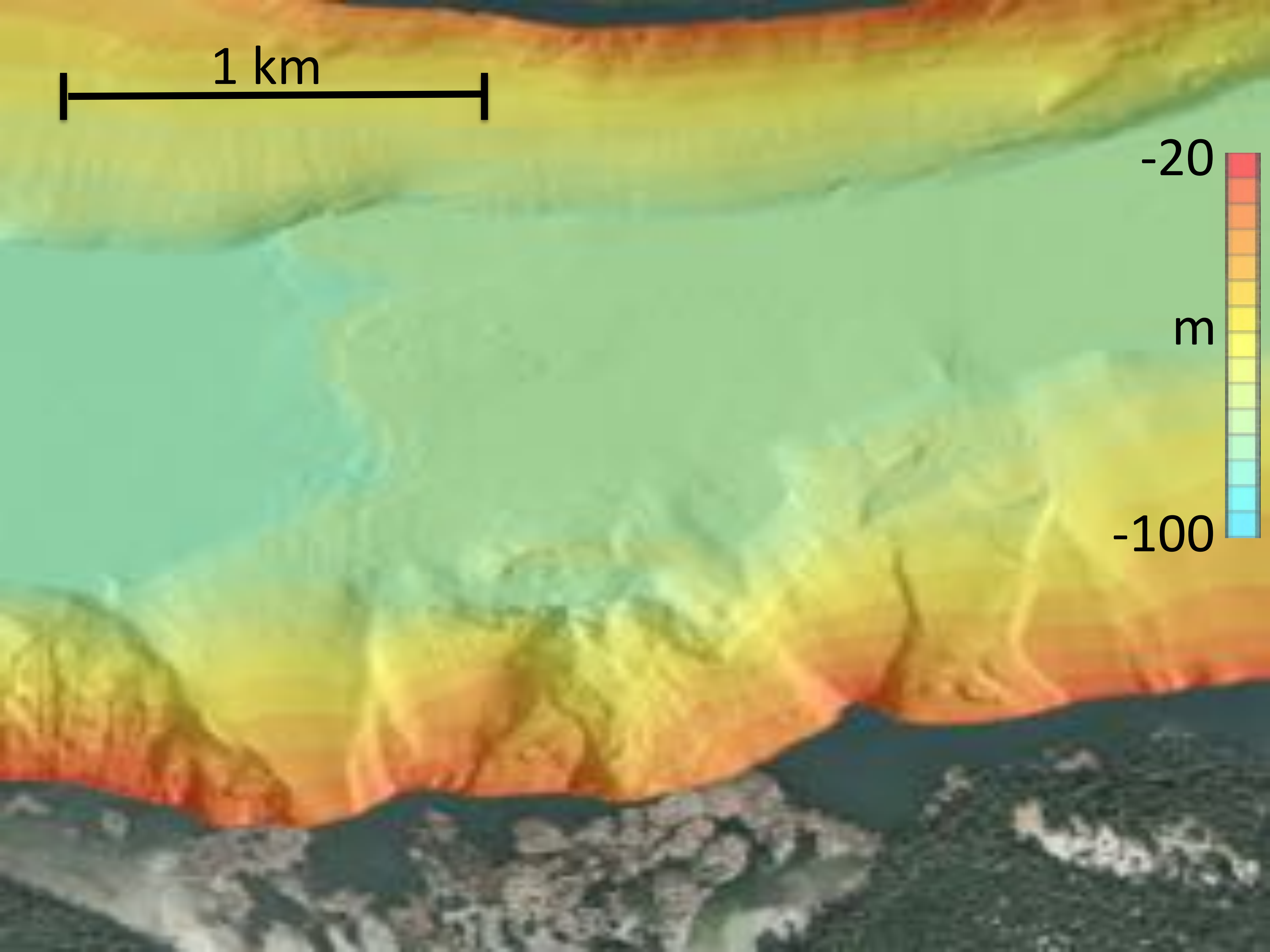
https://www.youtube.com/watch?v=YJqDJZQU8E4

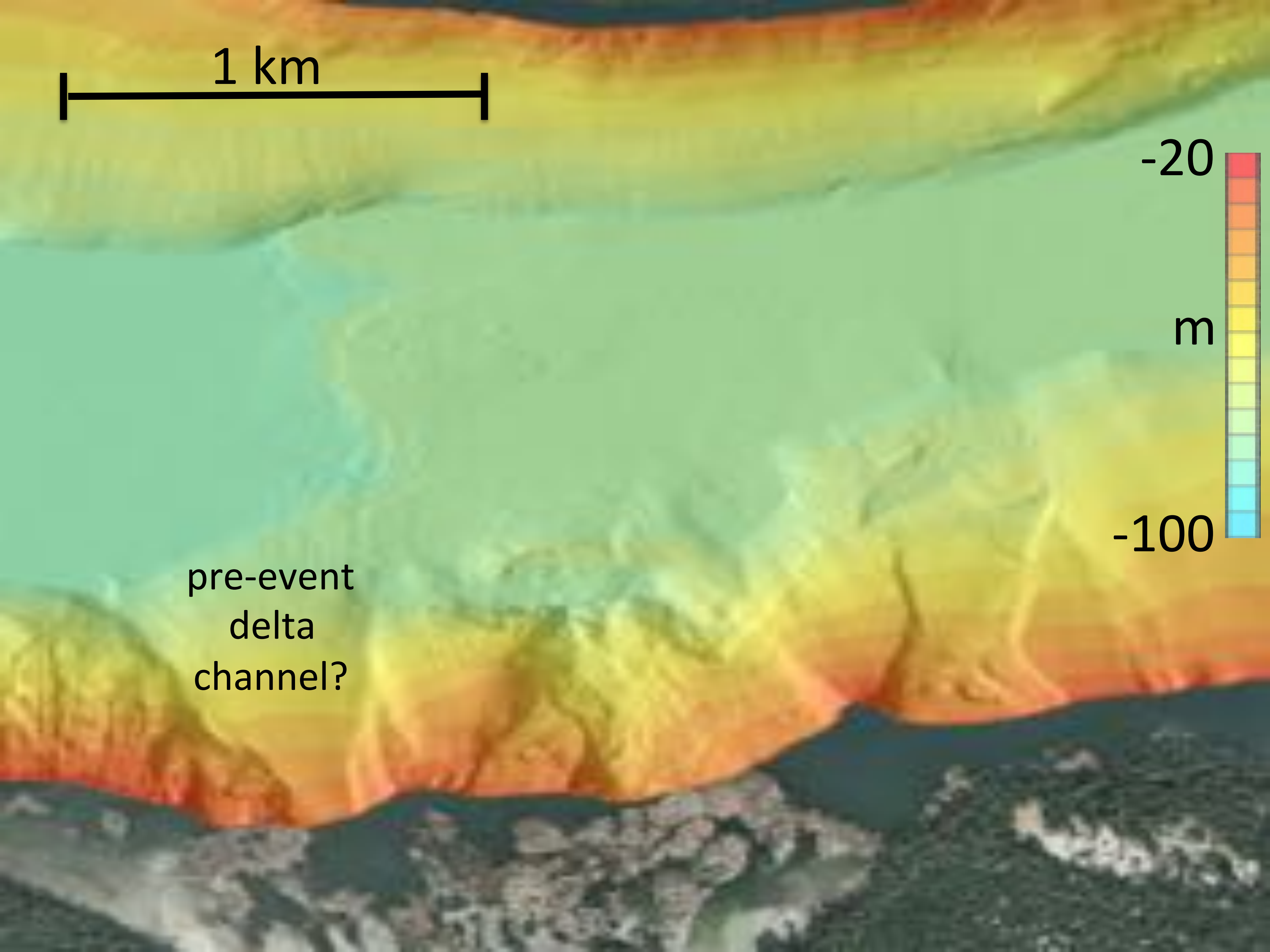
Subaqueous Gravity Flows in Quesnel Lake

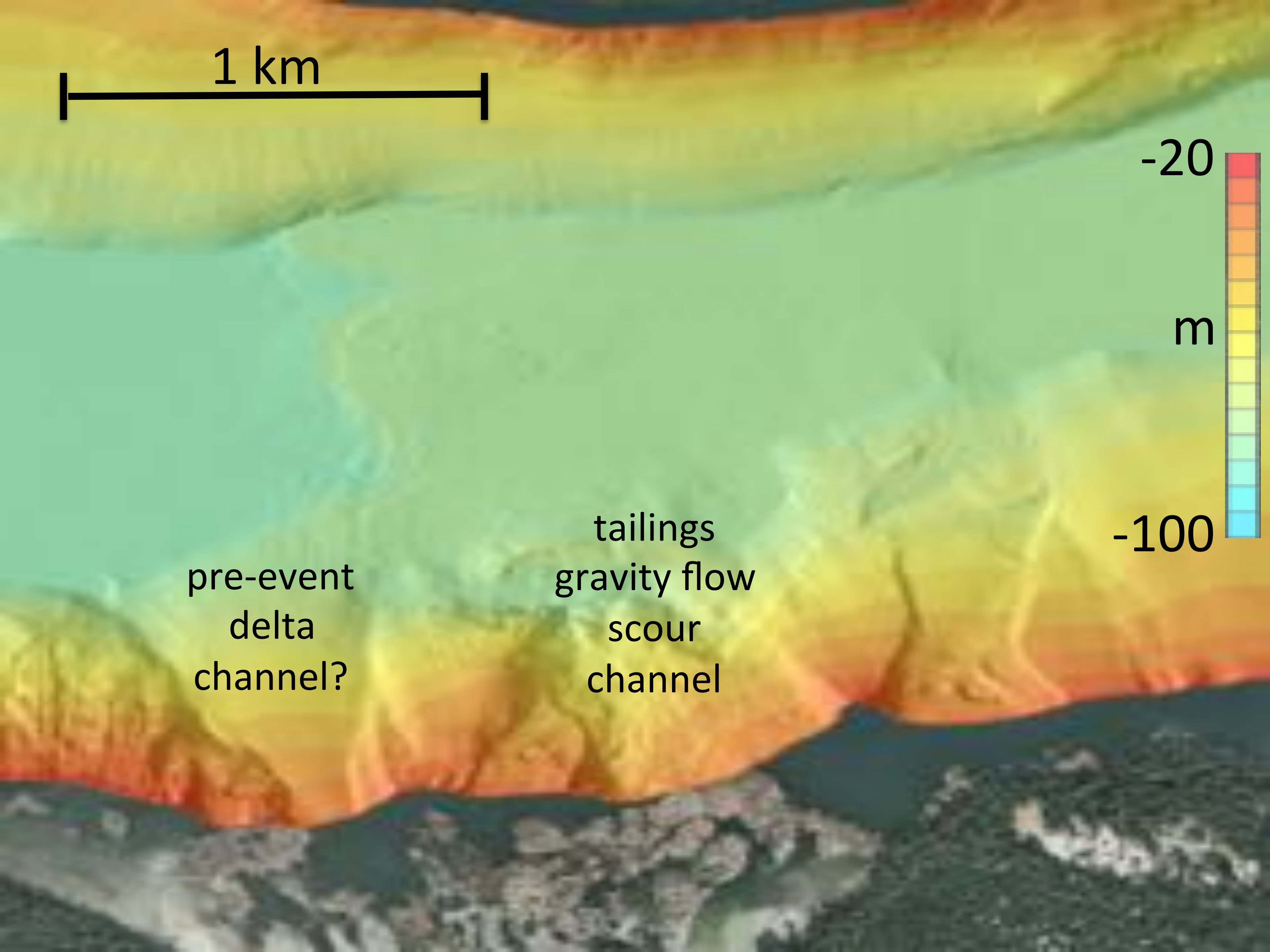


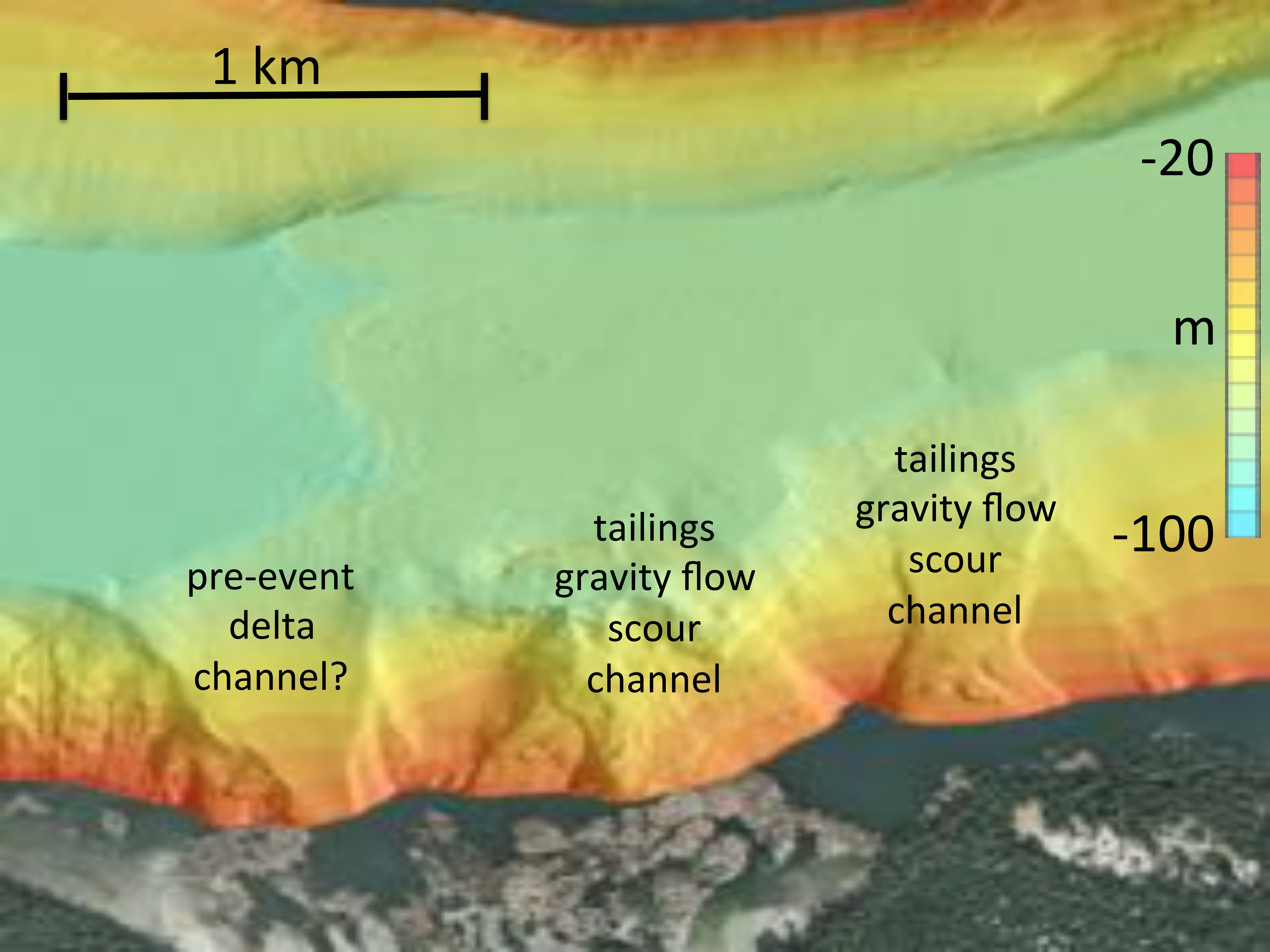

Lake Water Level (m)
1.80
1.75
1.70
1.65
1.60
1.55
1.50
1.45
0.079 m
0.068 m
8/1/2014
8/2/2014
8/3/2014
8/4/2014
8/5/2014
8/6/2014
8/7/2014
8/8/2014
August 1-8 2014

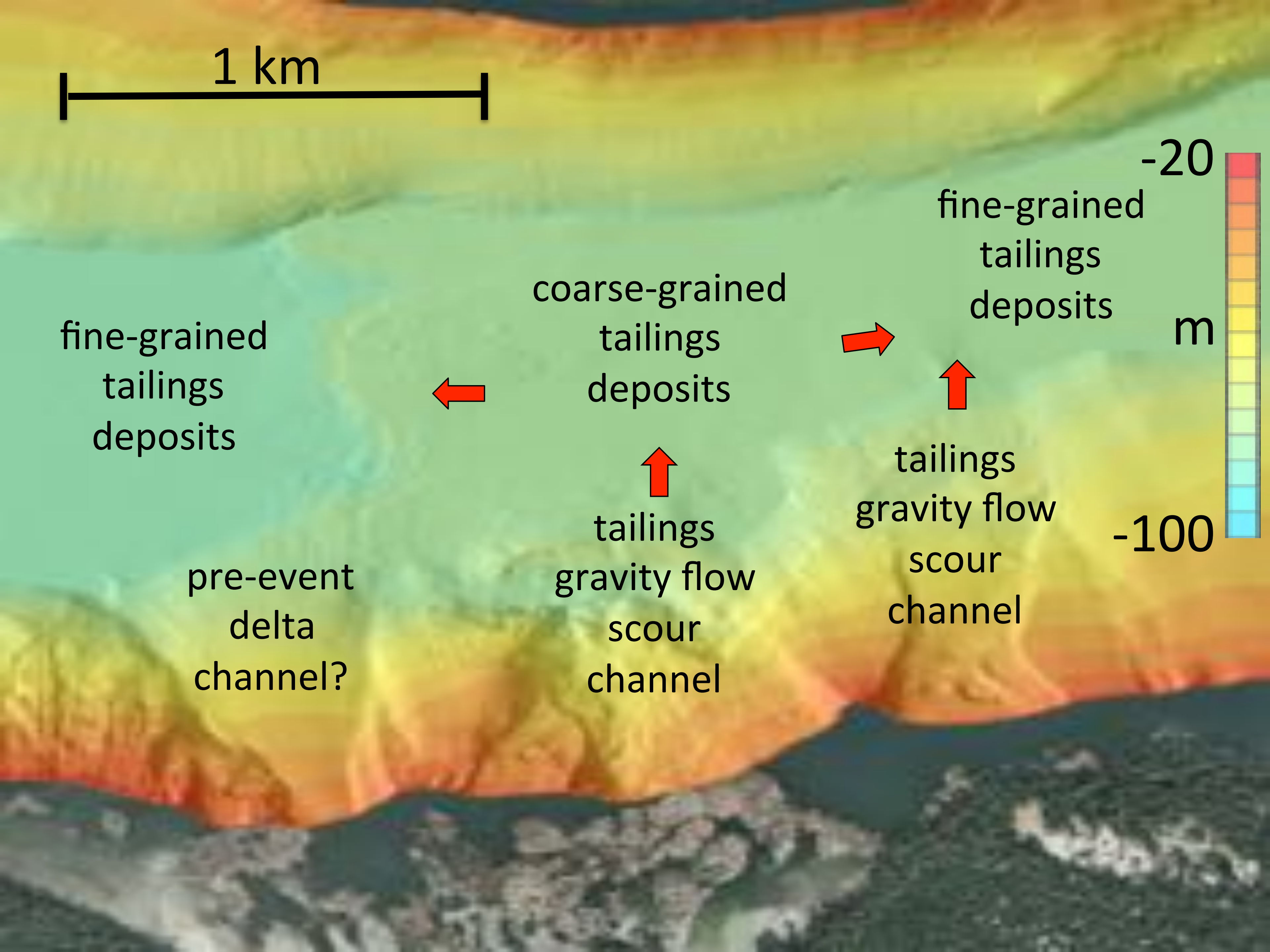

GPS antenna
transducer
swath
single beams
surveyed seabed

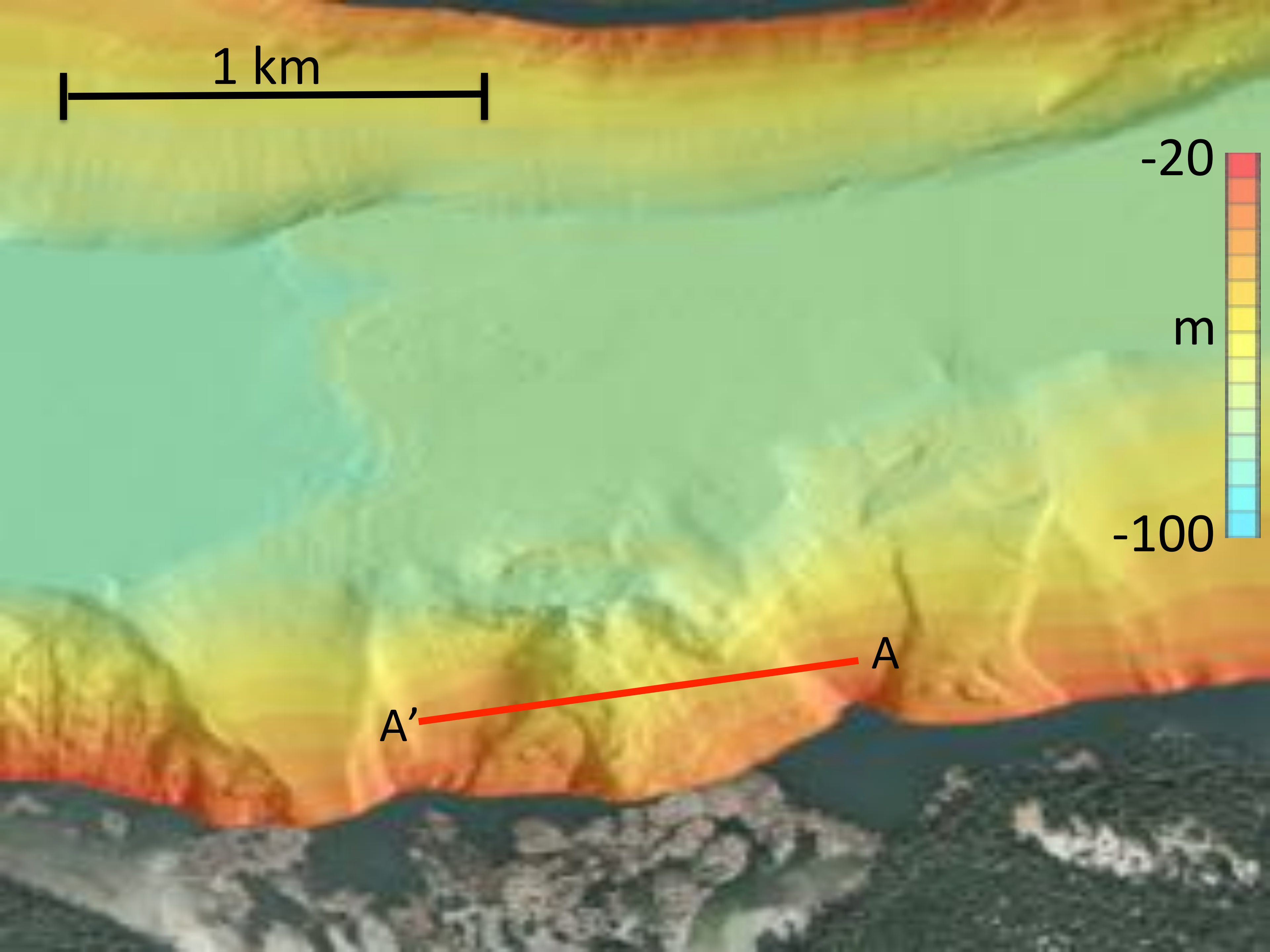

1 km
-20
m
-100


1 km
-20
m
-100
pre-event
delta
channel?

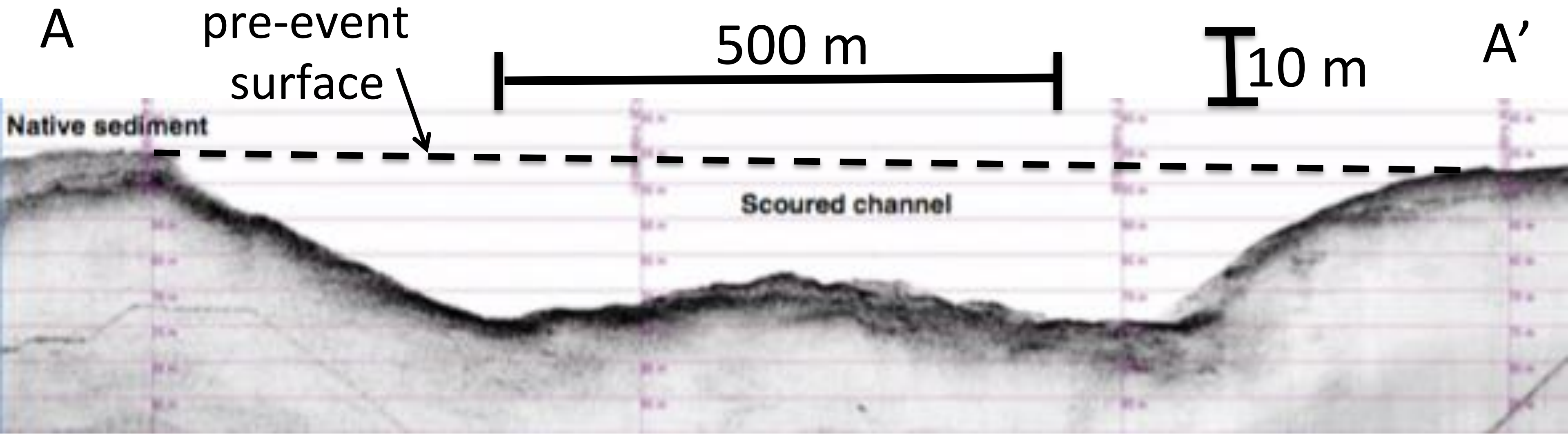

1 km
-20
m
-100
tailings
gravity flow
scour
channel
pre-event
delta
channel?


1 km
-20
m
-100
pre-event
delta
channel?
tailings
gravity flow
scour
channel
tailings
gravity flow
scour
channel

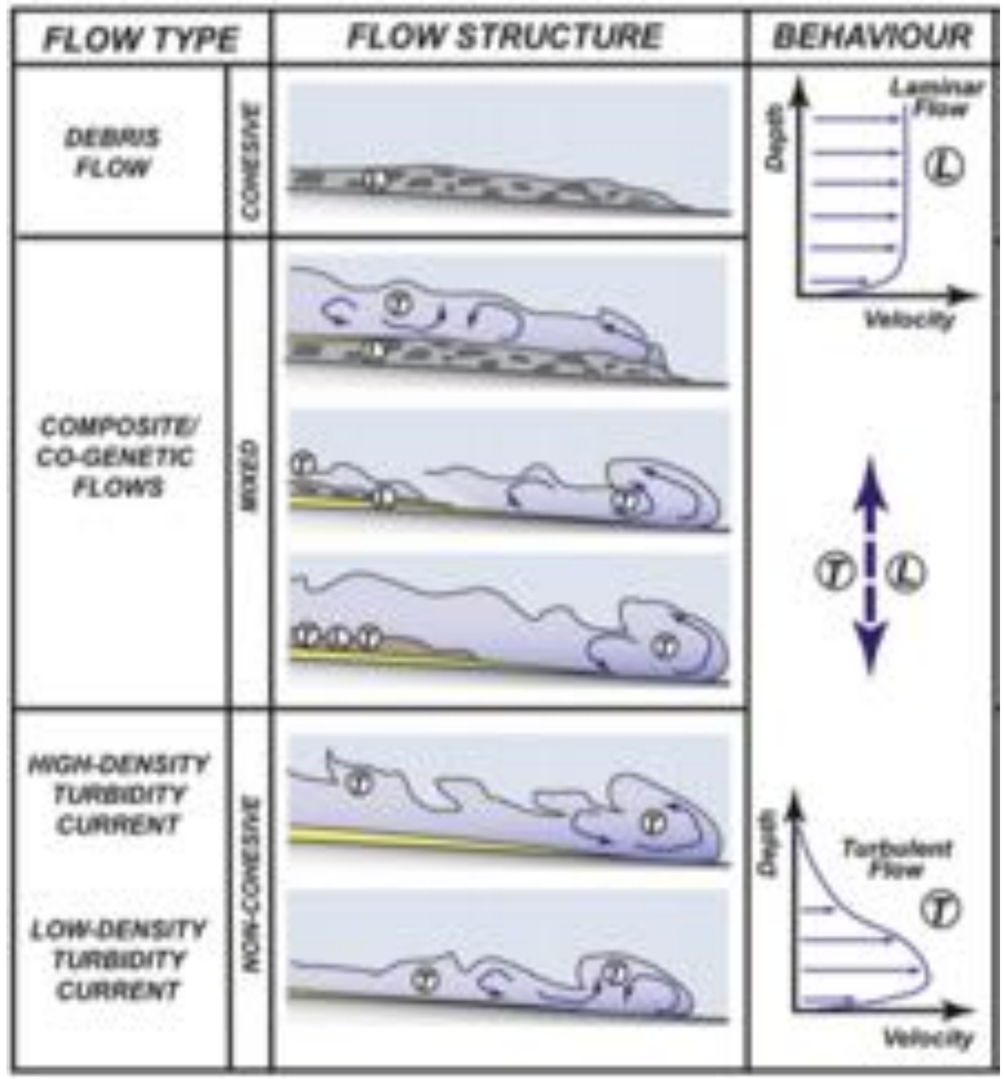

1 km
-20
m
-100
fine-grained tailings deposits
coarse-grained tailings deposits
fine-grained tailings deposits
tailings gravity flow scour channel
tailings gravity flow scour channel
pre-event delta channel?


1 km
-20
m
-100
A
A’

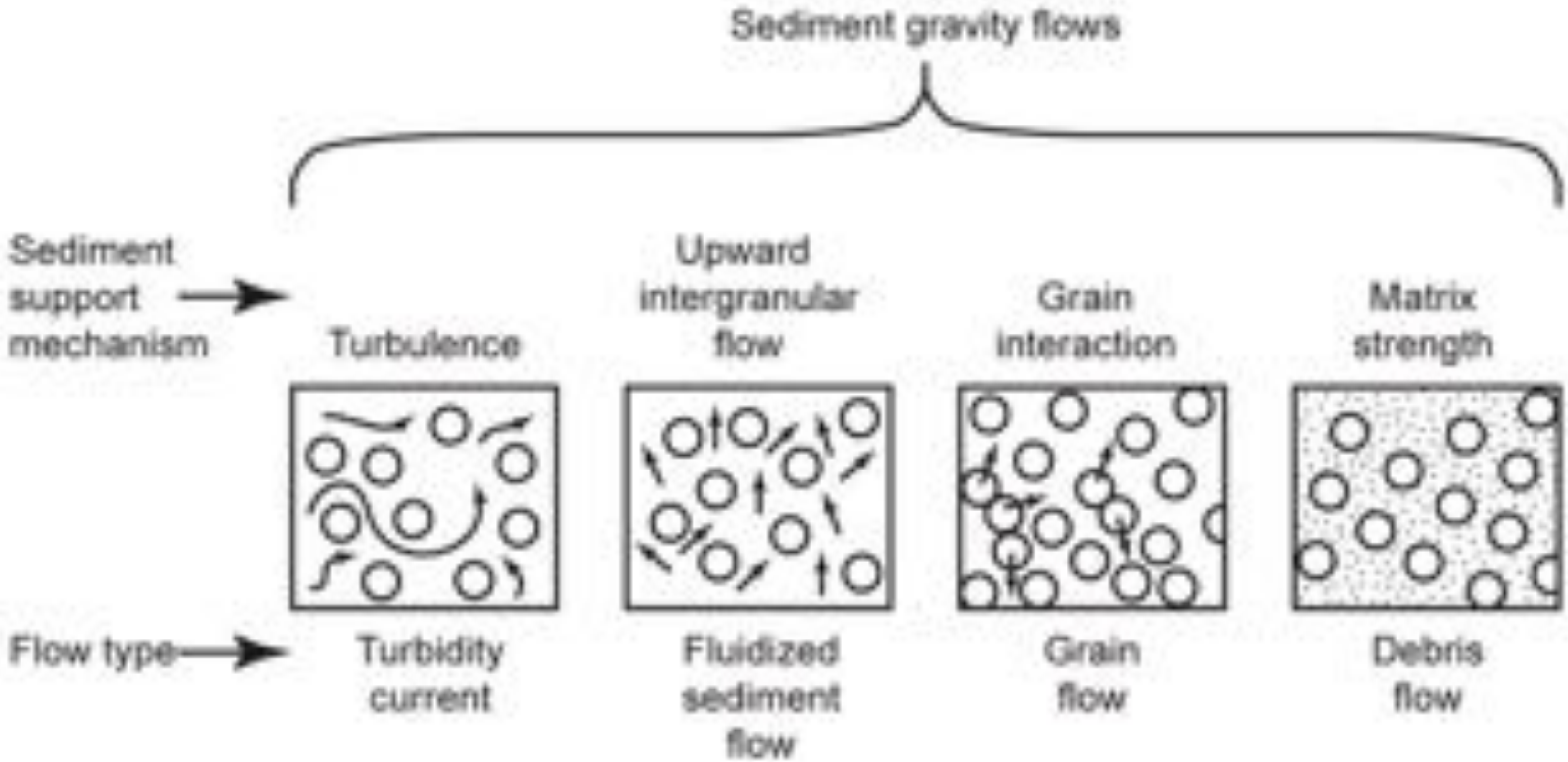
Erosion by Subaqueous Debris Flows in Quesnel Lake



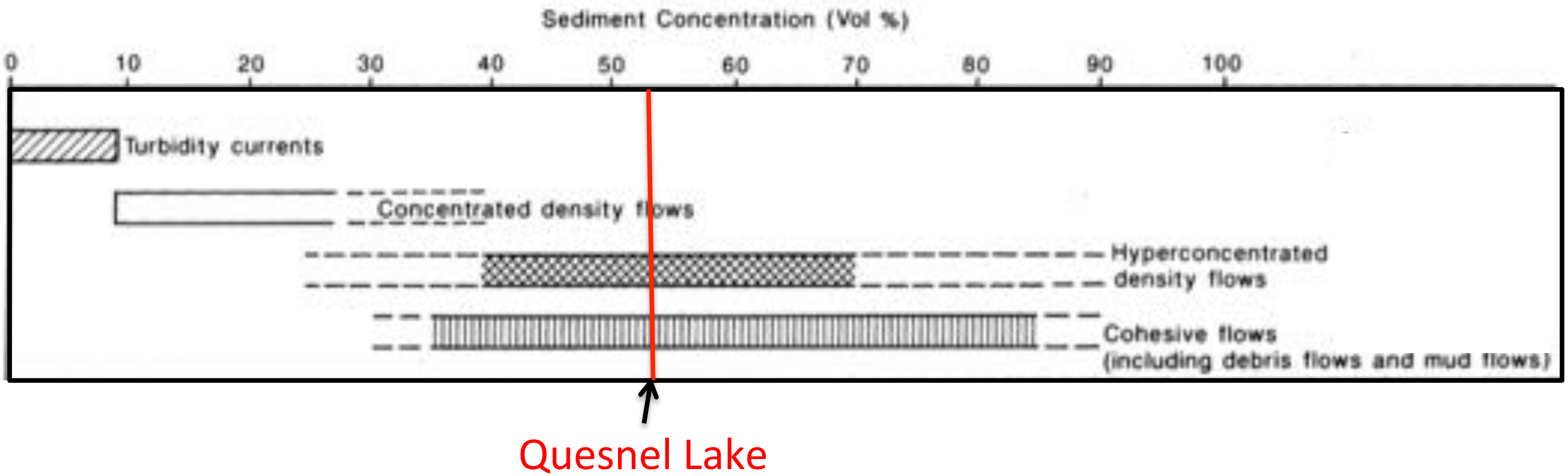
Classification



Haughton et al. 2009, Marine and Petroleum Geology



Haughton et al. 2009, Marine and Petroleum Geology



Mulder et al. 2001, Sedimentology

Erosion

- Up to 20 m vertical incision and $1.5x10^6$ m^3 scoured in small cobbles and gravel on Hazeltine Creek fan-delta

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, F03006, doi:10.1029/2011JF002189, 2012

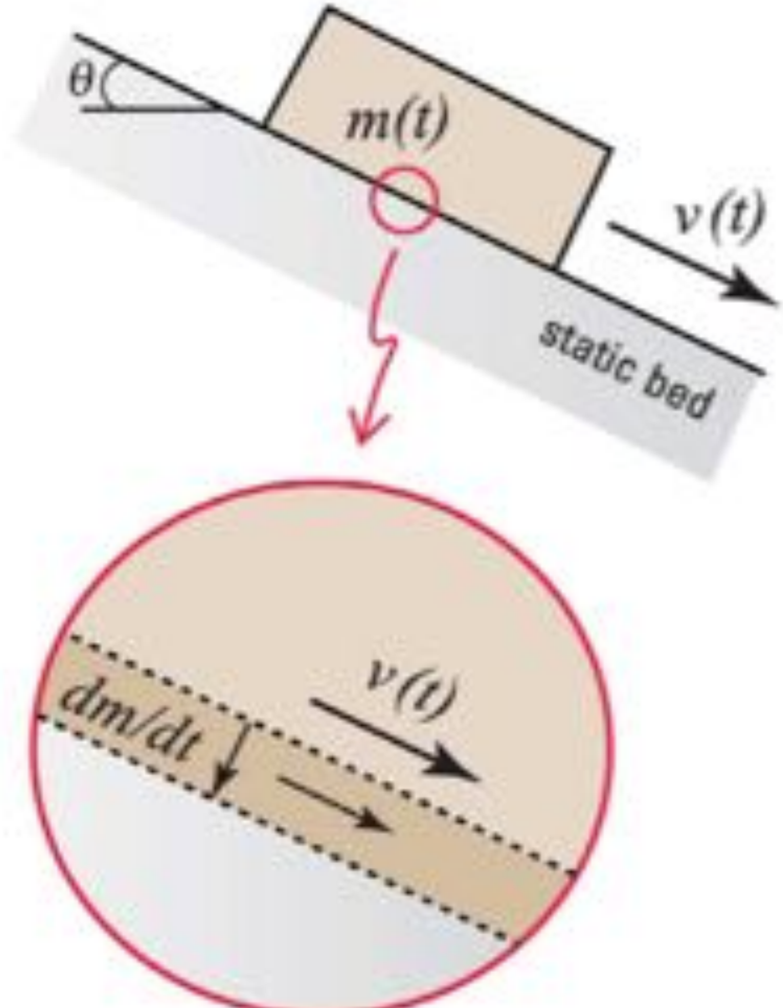
Elementary theory of bed-sediment entrainment by debris flows and avalanches

Richard M. Iverson[1]

The Bare Bones of the Iverson model

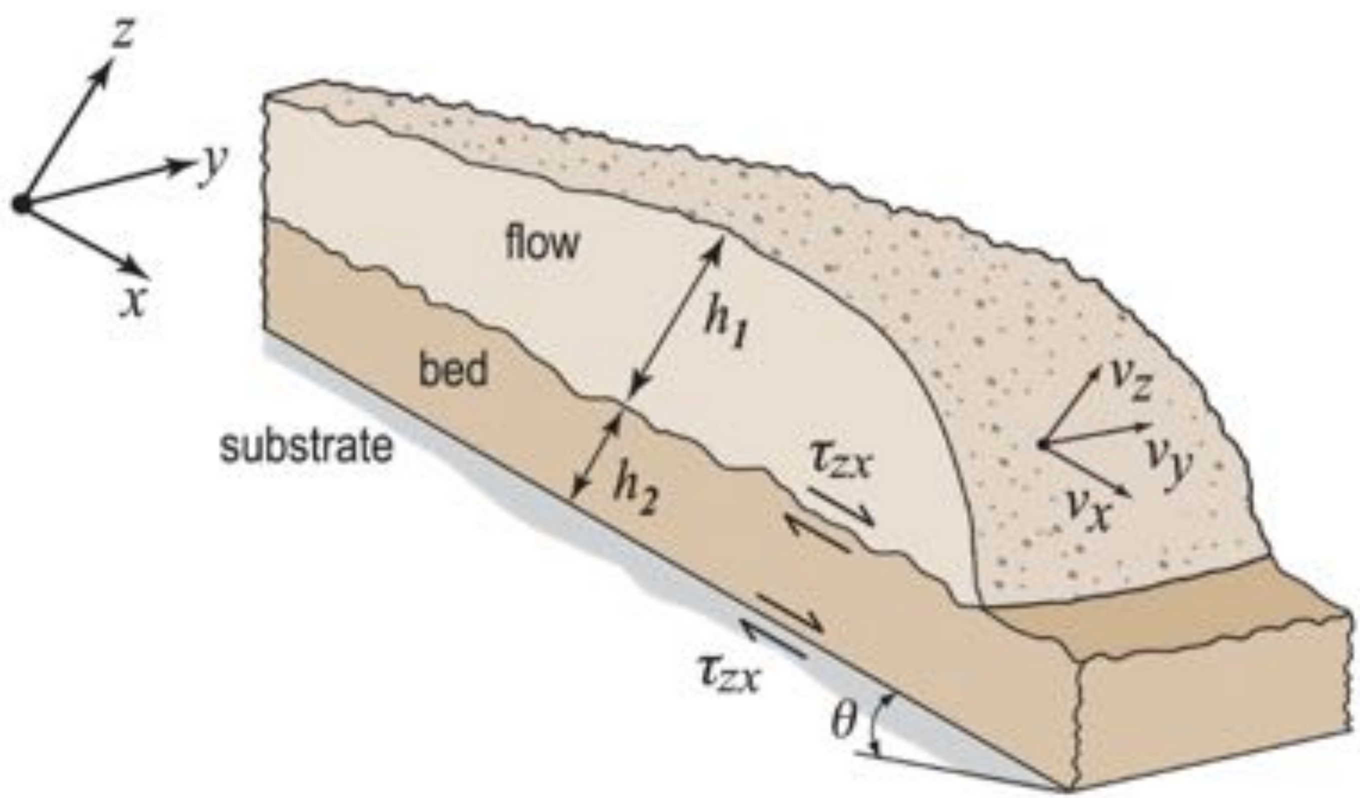
Part 1:

- Coulomb slide block of mass *m(t)* and velocity *v(t)* descending a plane inclined at the angle θ

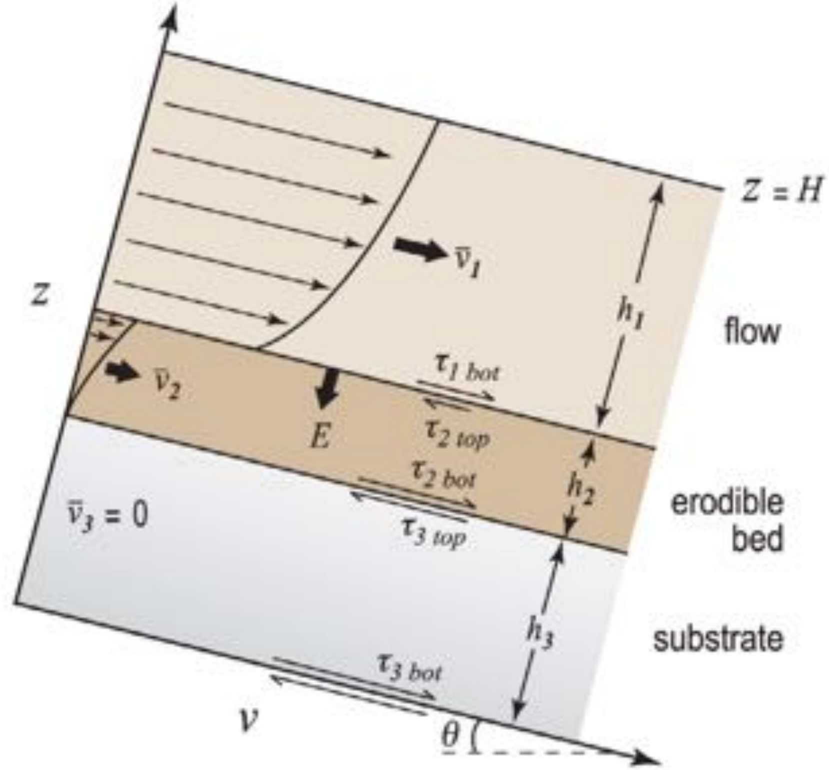


Part 2:

- Three-layer, depth- integrated, continuum-mechanical model of mass and momentum exchange between a flow, an erodible bed, and a stable substrate.



- Part 2 model identifies mechanical controls on entrainment efficiency at the bed boundary
- Explicit predictions of the entrainment rate E result from making reasonable assumptions about flow velocity profiles and boundary shear tractions



$$E = \frac{\tau_{1bot} - \tau_{2top}}{\rho[(1 - s_1)\bar{v}_1 - v_{2top}]}. \tag{34}$$

where: τ is shear stress, ρ is the bulk density of the flow, s_1 is a fitting parameter for the velocity profile in the flow, v is velocity

- Boundary shear tractions τ_{1bot} and τ_{2top} obey a Coulomb friction rule $\tau = \mu\sigma'_{zz}$ where μ is the Coulomb friction coefficient, σ' is effective normal stress:

$$\sigma'_{zz} = \sigma_{zz} - p, \tag{36}$$

- Boundary shear tractions that satisfy $\tau = \mu\sigma'_{zz}$

$$\tau_{1bot} = \mu_1(\sigma_{zz\,1bot} - p_{1bot}) = \mu_1(\rho g h_1 \cos\theta - p_{1bot}), \tag{37}$$

$$\tau_{2top} = \mu_2(\sigma_{zz\,2top} - p_{2top}) = \mu_2(\rho g h_1 \cos\theta - p_{2top}), \tag{38}$$

where p is fluid pore pressure

- By incorporating (37) and (38), (34) becomes:

$$E = \frac{\rho g h_1 (\mu_1 - \mu_2) \cos\theta + \mu_2 p_{2\,top} - \mu_1 p_{1\,bot}}{(1 - s_1)\rho \bar{v}_1}. \qquad (39)$$

- Contrasts in boundary pore fluid pressure can also promote entrainment
- If the top of the bed sediment becomes completely liquefied by high pore pressures (i.e., $p_{2top} = \rho g h_1 \cos\theta$) and the value $s_1 = ½$ is adopted to describe the flow velocity profile, then (39) reduces to:

$$E = \frac{2\mu_1 g h_1 \cos\,\theta(1-\lambda_1)}{\bar{v}_1}, \tag{41}$$

where θ is the slope angle, μ_1 is the flow's Coulomb friction coefficient, h_1 is its thickness, v_1 is its depth-averaged velocity, and λ_1 is its degree of liquefaction:

$$\lambda_1 = p_{1bot}/\rho g h_1 \cos\,\theta \tag{42}$$

$$E = \frac{2\mu_1 g h_1 \cos\theta(1-\lambda_1)}{\bar{v}_1}, \quad (41)$$

where θ is the slope angle, μ_1 is the flow's Coulomb friction coefficient, h_1 is its thickness, v_1 is its depth-averaged velocity, and λ_1 is its degree of liquefaction:

$$\lambda_1 = p_{1bot}/\rho g h_1 \cos\theta \quad (42)$$

- Is there anything counterintuitive about (41)?

$$E = \frac{2\mu_1 g h_1 \cos\theta(1-\lambda_1)}{\bar{v}_1}, \quad (41)$$

where θ is the slope angle, μ_1 is the flow's Coulomb friction coefficient, h_1 is its thickness, v_1 is its depth-averaged velocity, and λ_1 is its degree of liquefaction:

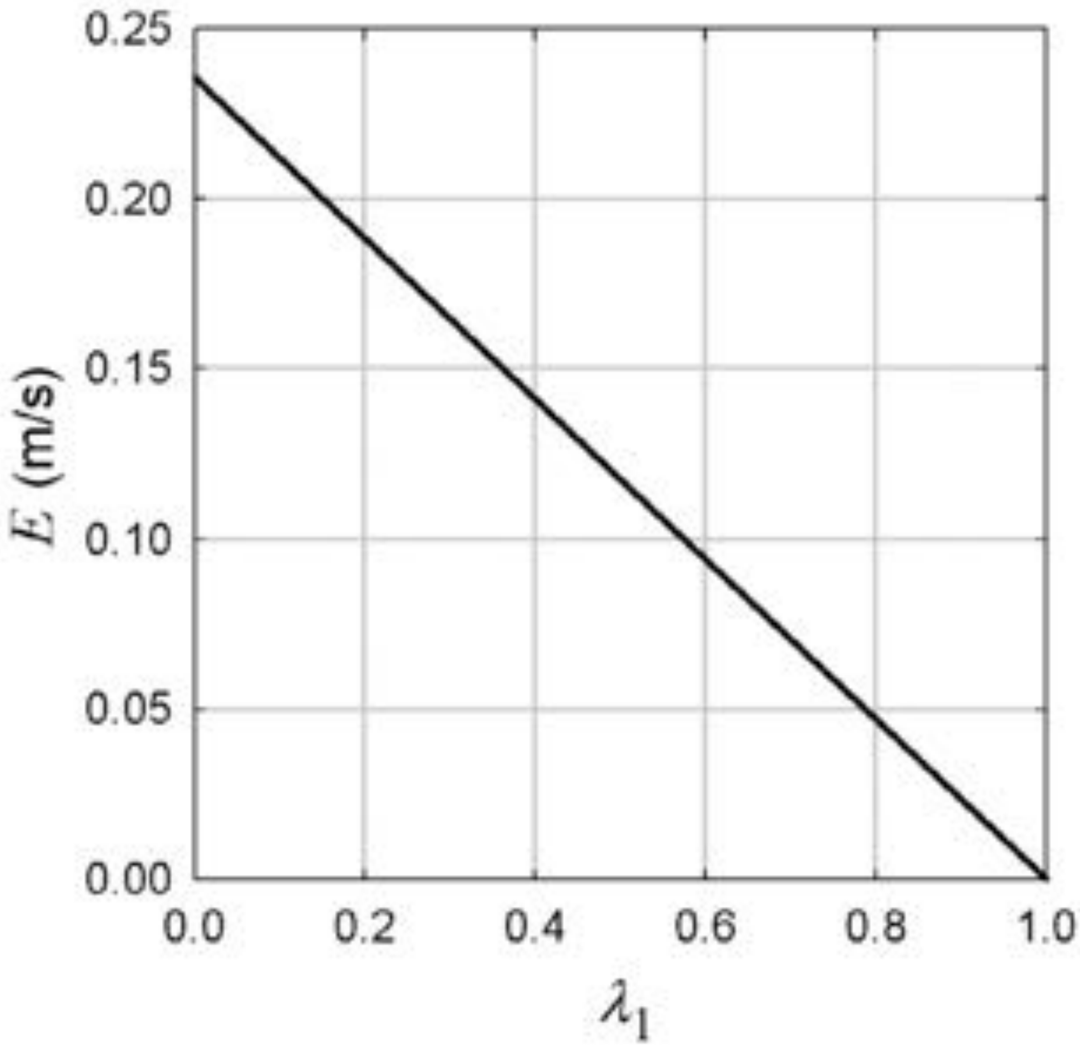
$$\lambda_1 = p_{1bot}/\rho g h_1 \cos\theta \quad (42)$$

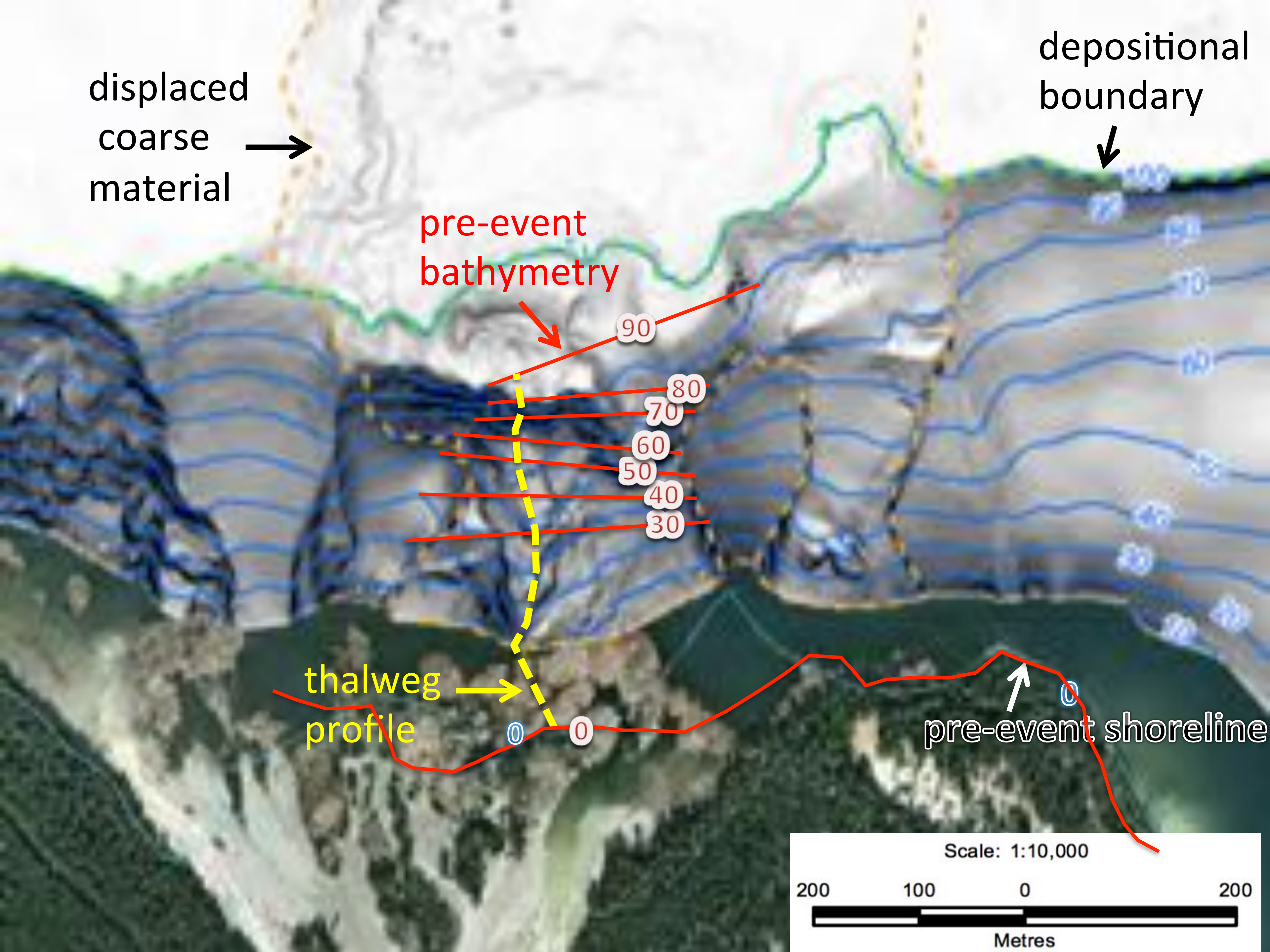
- Is there anything counterintuitive about (41)?

$$E \propto 1/v_{1bot}$$

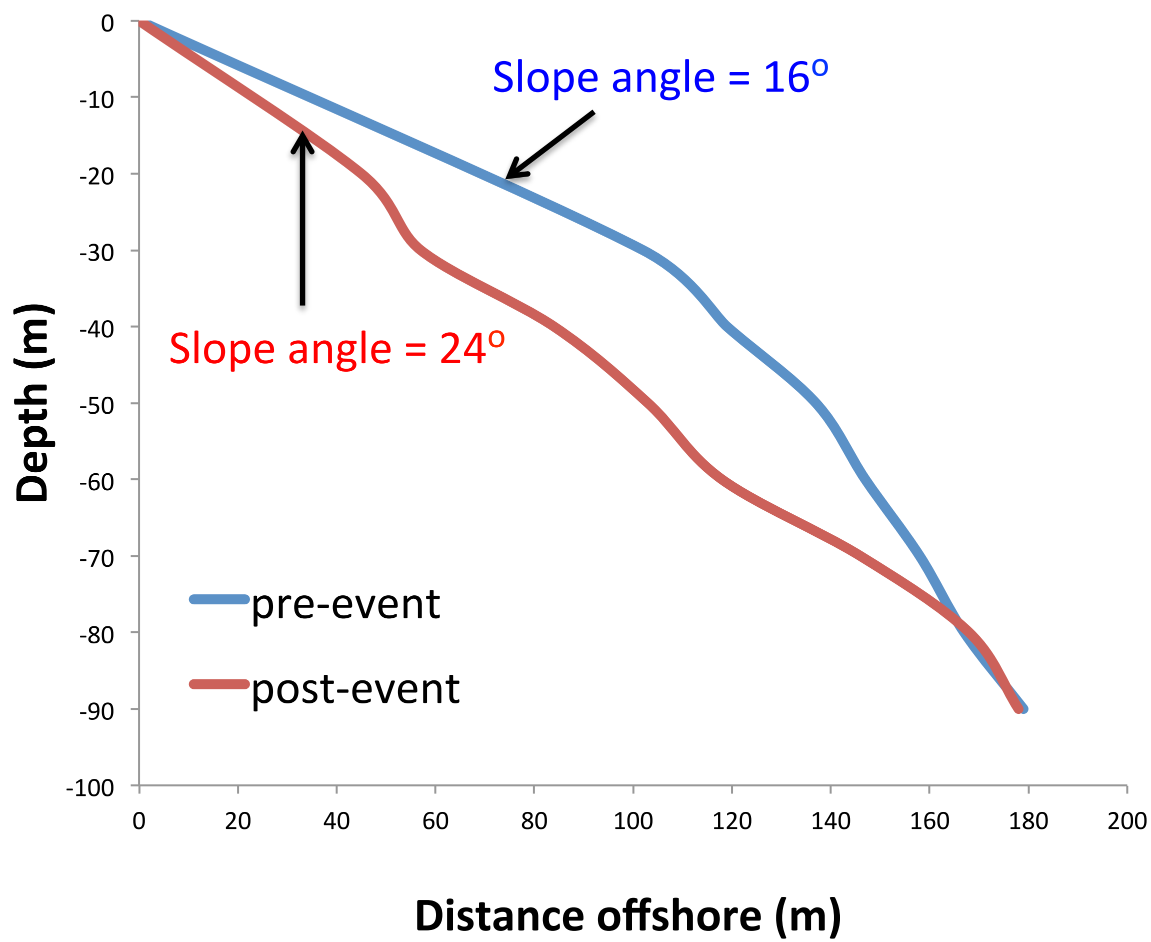

Duff
BEER
Duff
BEER

- Flow liquefaction likely plays a critical role in bed entrainment



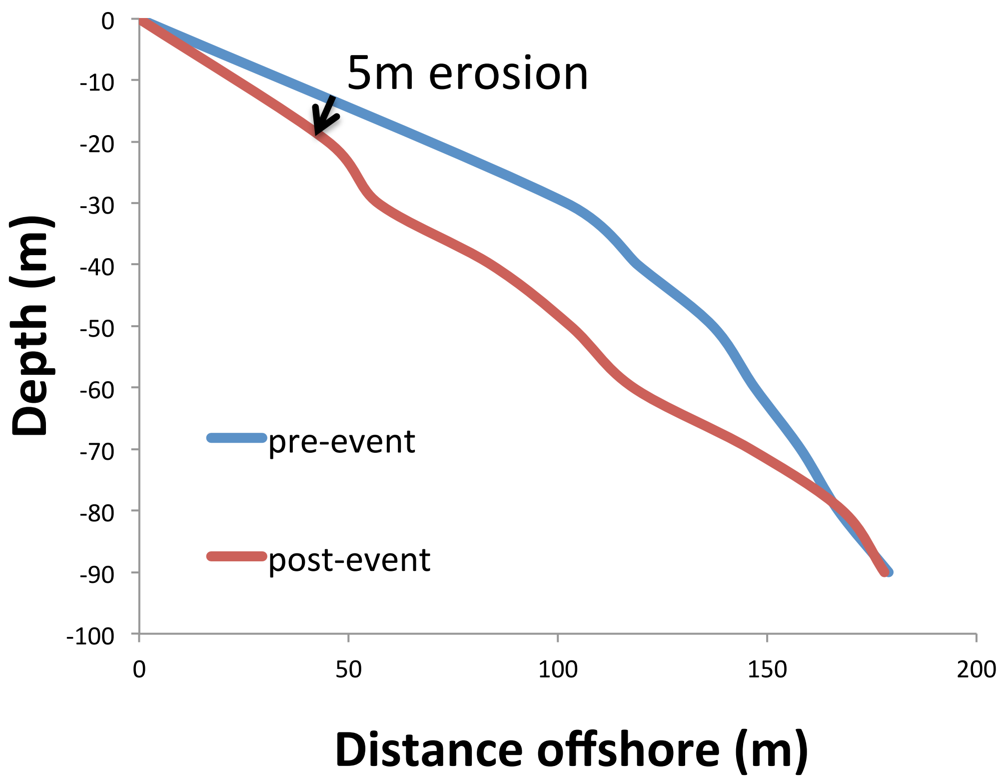


displaced coarse material
depositional boundary
pre-event bathymetry
90
80
70
60
50
40
30
0
0
thalweg profile
pre-event shoreline
0
Scale: 1:10,000
200
100
0
200
Metres



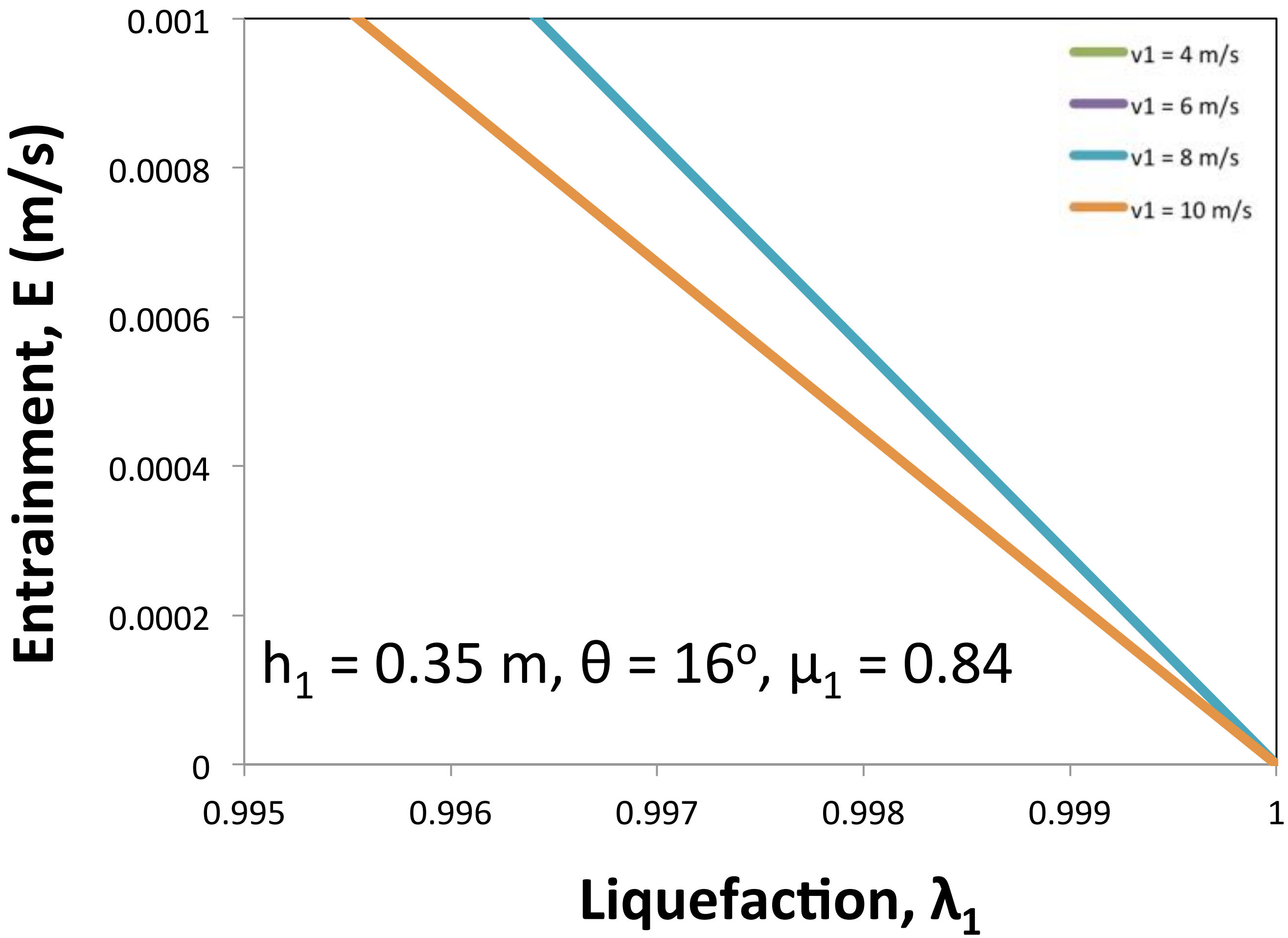
Slope angle = 16°
Slope angle = 24°
pre-event
post-event
Depth (m)
Distance offshore (m)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
0
20
40
60
80
100
120
140
160
180
200

- Test case: measured erosion rate, E_m, for 5 m of scour in the large scour channel:

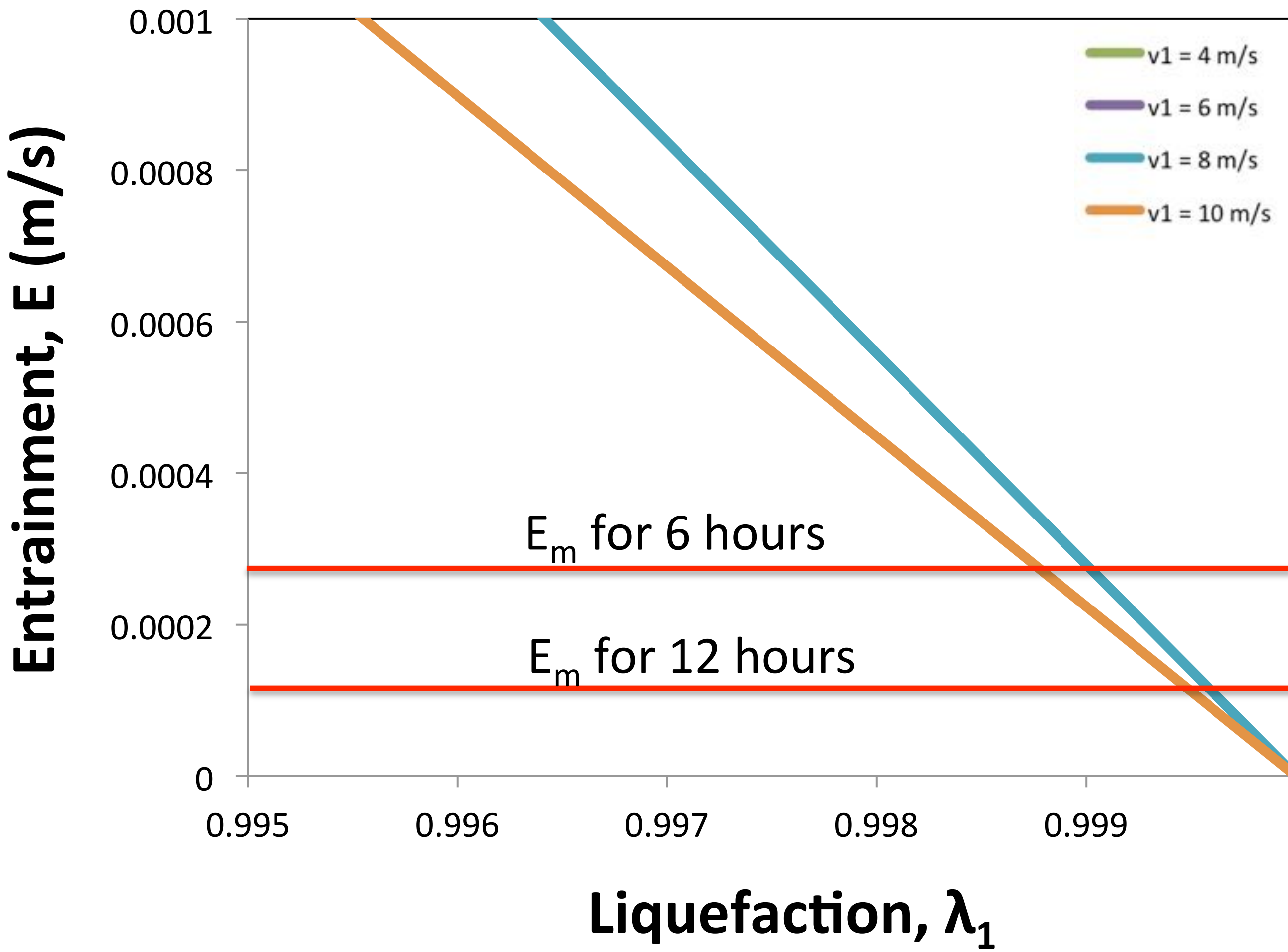


Duration (hours)	12	8	6
Em (m/s)	0.0001157	0.0001736	0.0002314

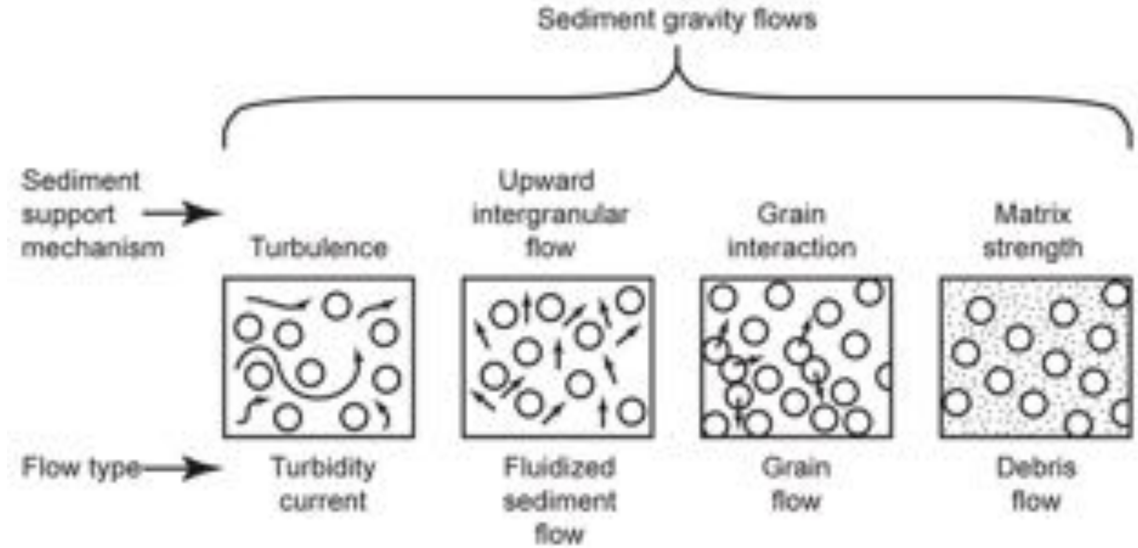
- Suberial debris flow thickness at Hazeltine Creek mouth is estimated at h_1 = 0.35 m
- Gradient of Hazeltine Creek fan-delta near creek mouth is $\theta = 16^o$
- In experimental and natural subaerial debris flows:
  - μ_1 = 0.84 - 0.97
  - λ_1 = 0.5 - 0.8
  - v_1 = 3.9 - 12 m/s



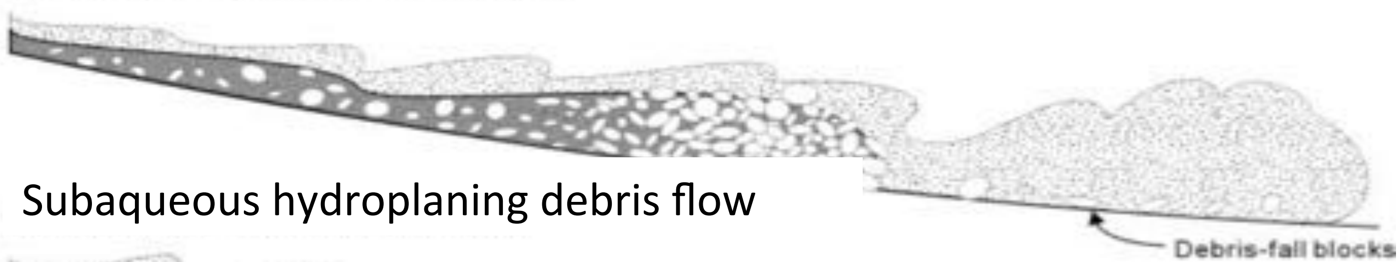
Entrainment, E (m/s)
0.001
0.0008
0.0006
0.0004
0.0002
0
0.995
0.996
0.997
0.998
0.999
1
Liquefaction, λ1
v1 = 4 m/s
v1 = 6 m/s
v1 = 8 m/s
v1 = 10 m/s
h1 = 0.35 m, θ = 16o, μ1 = 0.84



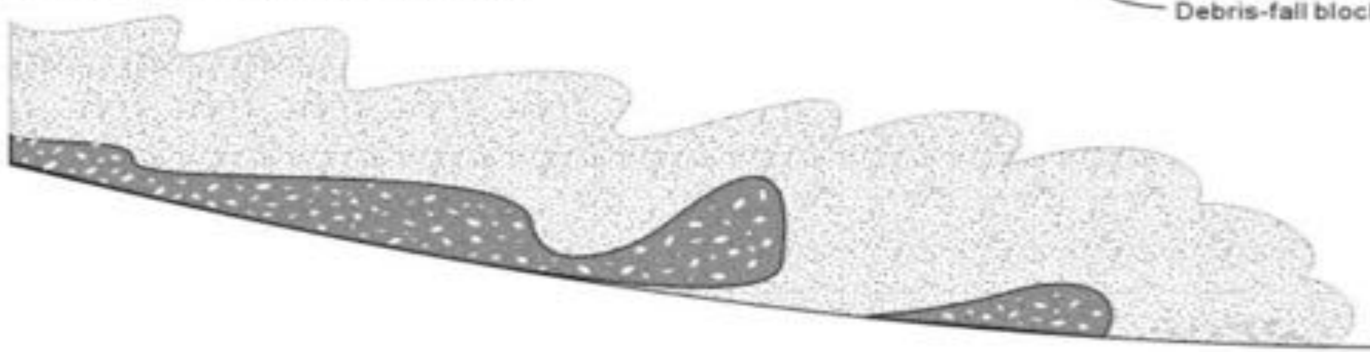
0.001
0.0008
0.0006
0.0004
0.0002
0
0.995
0.996
0.997
0.998
0.999
1
Entrainment, E (m/s)
Liquefaction, λ_1
v1 = 4 m/s
v1 = 6 m/s
v1 = 8 m/s
v1 = 10 m/s
E_m for 6 hours
E_m for 12 hours



Subaqueous non-hydroplaning debris flow



Subaqueous hydroplaning debris flow



Sohn et al. 2002, Terra Nova.

Summary so far…

- Failure of the Mt. Polley mine tailings dam caused $14x10^6$ m^3 of sediment and interstitial water to flow into Quesnel Lake
- The resulting subaqueous debris flow in Quesnel Lake eroded $1.5x10^6$ m^3 of fan-delta fine cobbles and gravel
- A test case of the Iverson (2012) debris flow entrainment model suggests that the erosional debris flows in Quesnel Lake were nearly liquefied

What now?

- Carry on with Iverson model

Go for it!

- A different approach/model?
  - Sedflux (Hutton and Syvitski 2008)
  - Suggestions?


But wait, there’s more!

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journal homepage: www.elsevier.com/locate/agee

Dark matter debris flows in the Milky Way

Mariangela Lisanti [a,*], David N. Spergel [b]

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[b] Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08540, USA