Multi-millennial increased **humidity** in the **Atacama Desert** during **MIS 5e**: evidence from a **lacustrine** record in southern Peru

Marco Nieslony [a], Swann Zerathe [b], Pierre Valla [b], Diana Ochoa [c], Luis Albinez [d], Dulio Gomez [d], Fabrizio Delgado [d], Xavier Robert [b], Laurence Audin [b], Regis Braucher [e], Audrey Taillefer [f]

- [a] Faculty of Science, Charles University, Prague, Czech Republic
- [b] Institute of Earth Sciences (ISTerre), University Grenoble Alpes, University Savoie Mont Blanc, CNRS, IRD, IFSTAR, 38000, Grenoble, France
- [c] University of Salamanca, Salamanca, Spain
- [d] INGEMMET, Instituto Geológico, Minero y Metalúrgico, Lima, Perú
- [e] Aix-Marseille Univ., CNRS, IRD, Coll. France, UM 34 CEREGE, Technopôle de l'Environnement Arbois-Méditerranée, BP80, 13545 Aix-en-Provence, France
- [f] Géosciences Environnement Toulouse, CNRS, IRD, UT, Observatoire Midi-Pyrénées, 14 av. E. Belin,
- 31400 Toulouse, France

PICO talk

Study site overview

Methods and Results

Conclusion

(Additions)

Charles University

Overview

Approach

Conclusion

Atacama hyper-arid since 10Ma, but:

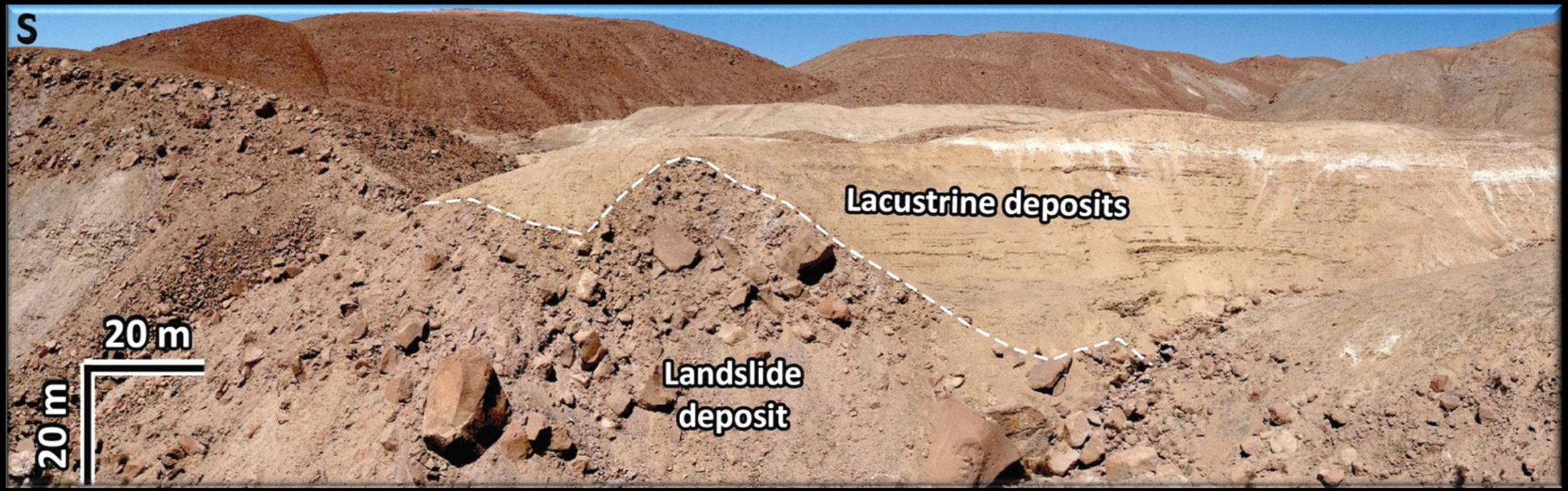
- Roperch et al. 2017: **Wetland, MIS 3**
- Bartz et al. 2020: **Alluvial Fan, MIS 3**
- Ritter et al. 2018: **Paleolake, MIS 11**
- Ritter et al. 2019: **Paleolake, MIS 5b/e & MIS 7**
- Wennrich et al. 2024: **Claypan, MIS 3**

→ Pleistocene Interglacials

Overview | **Approach** | Conclusion

Answer **question** of:

- Environmental conditions during lake lifetime
- Respective timing / duration



…trough analysis of **incised lacustrine deposits** with:

- Sediment analysis
- OSL dating
- ^{10}Be Cosmo dating
- Diatom/Pollen
- XRF

Overview

Methods

Conclusion

Paleo-Climate

→ Semi-humid, stable, prolonged

Timeframe

→ 115 till 133ka, MIS5e, Interglacial

Prolonged discontinuity hyper-aridity in **northern** Atacama

Ritter et al. 2019: Paleolake, **MIS 5e**, 5b & 7

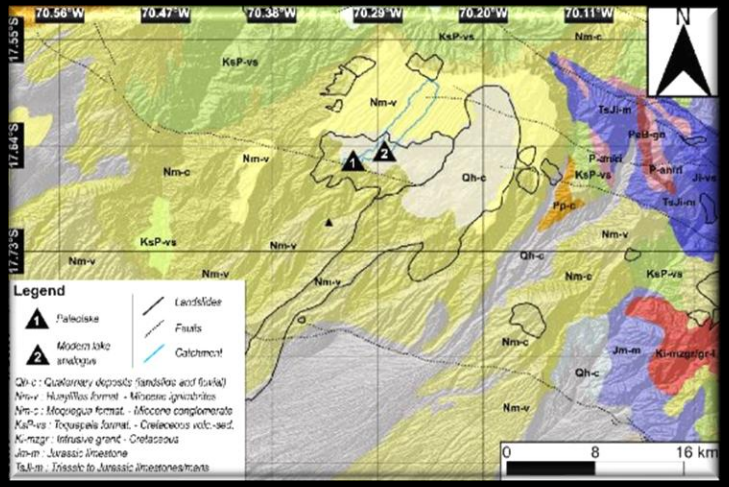
Thank you

→ Screen PICO3.10

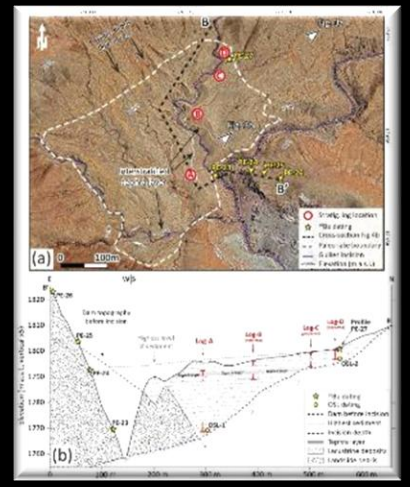
Free cake (maybe)

Study site overview

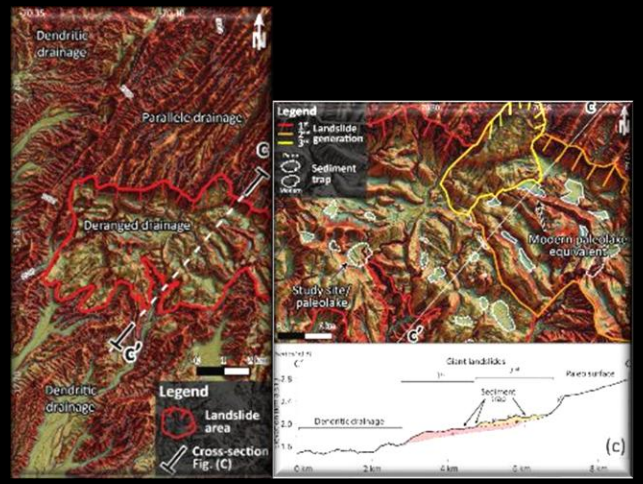
Geologic map



Local overview

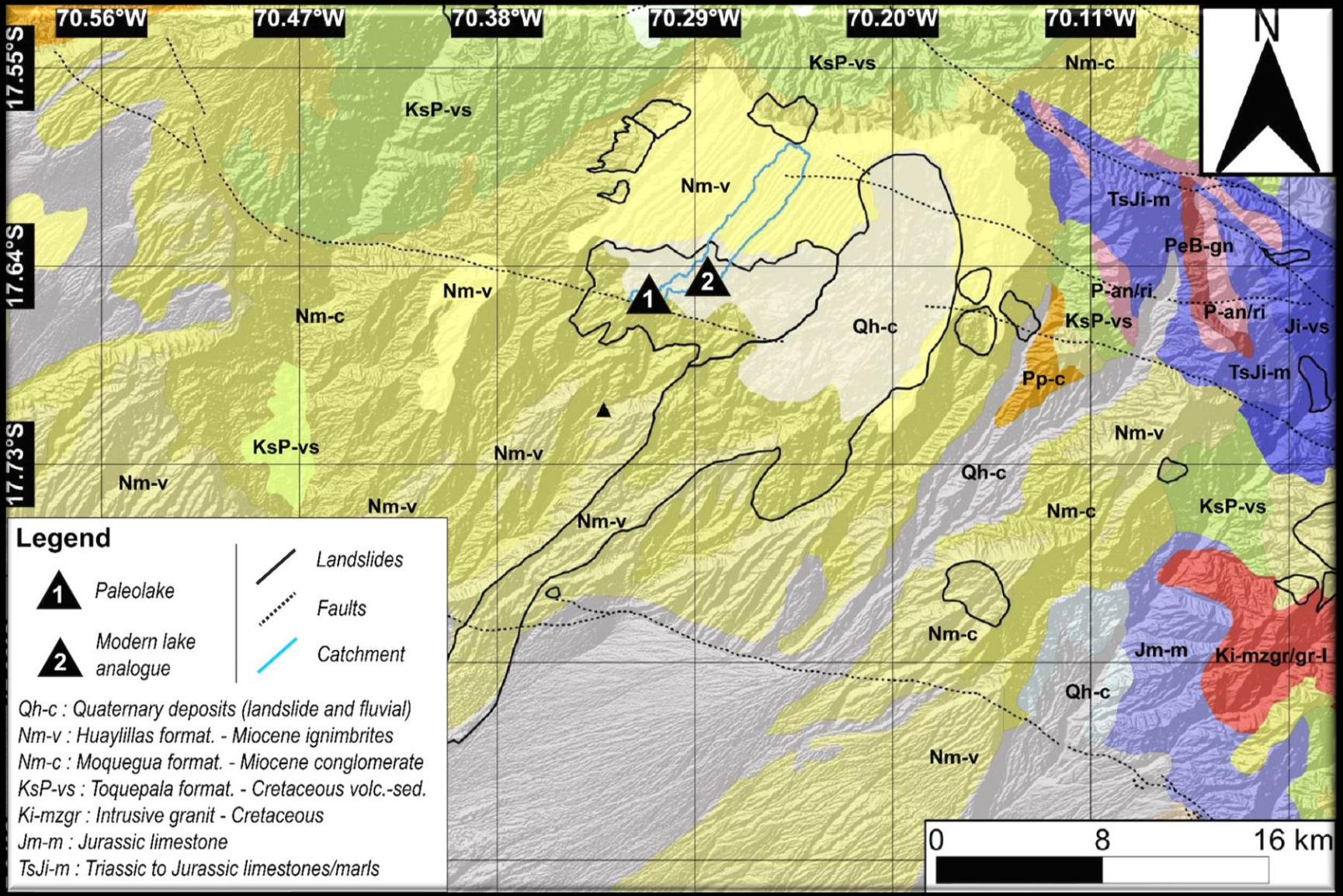


Regional overview



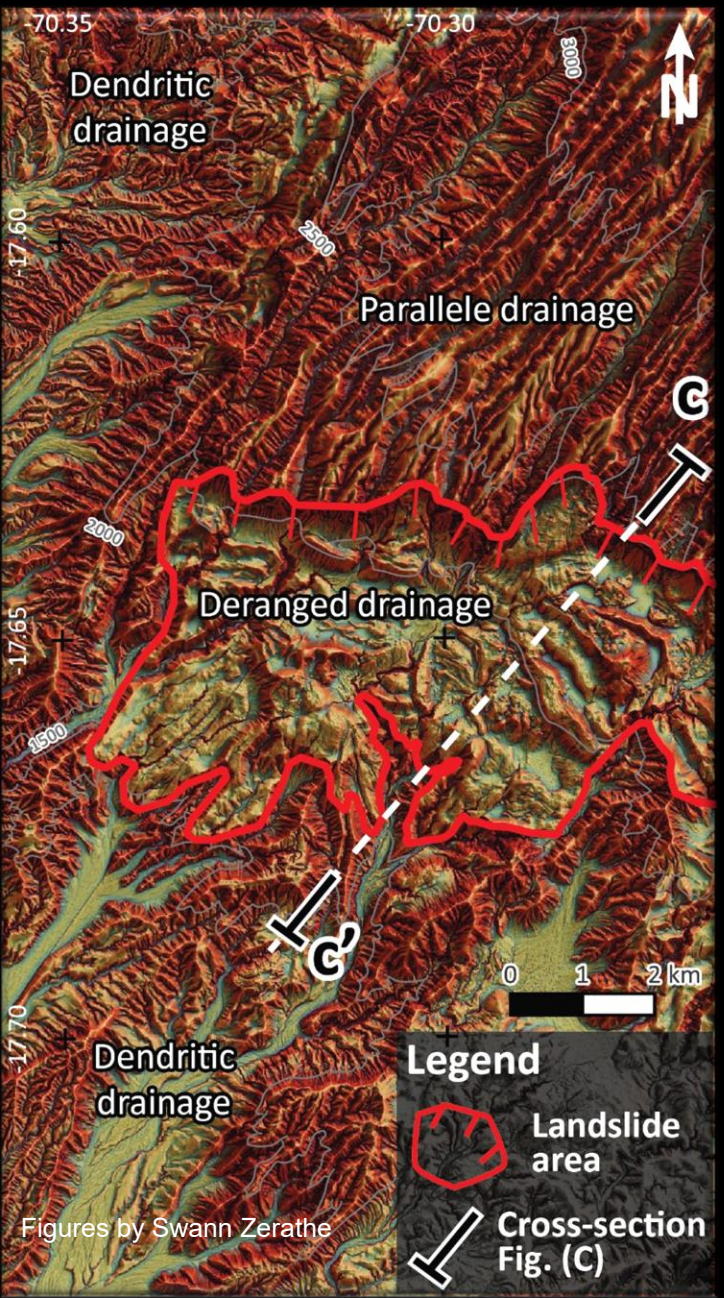
In-field overview

Geologic map

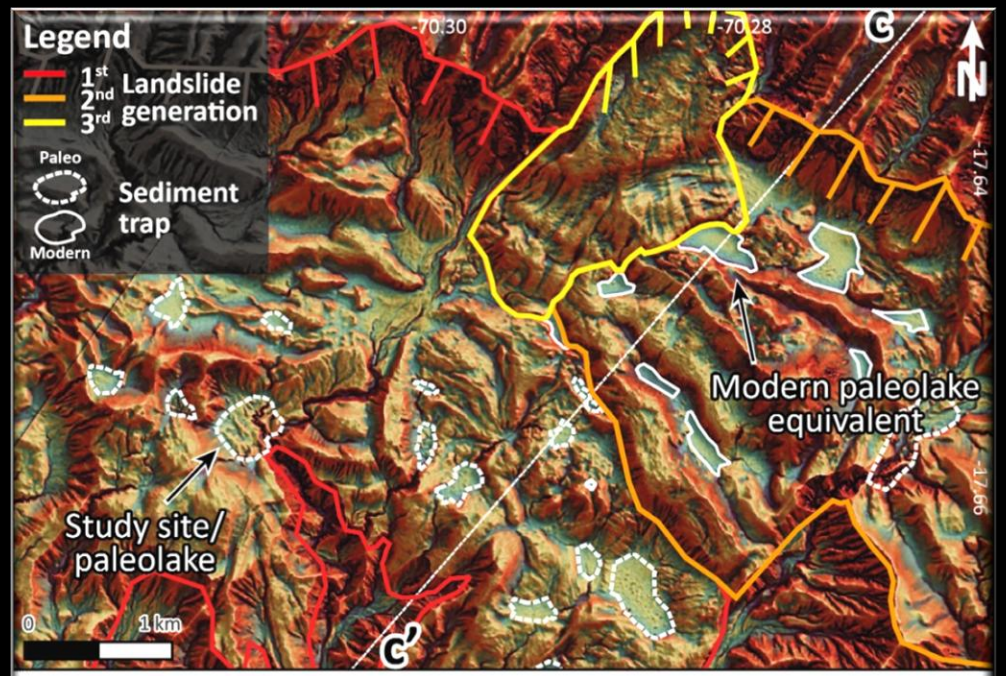


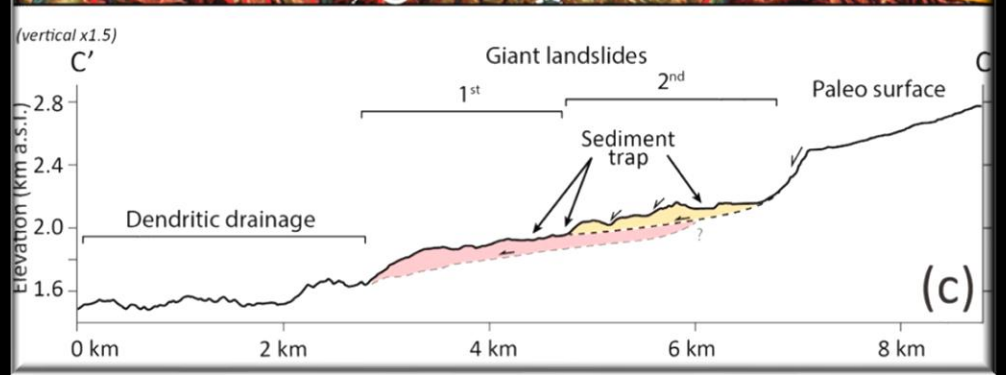
- Quartz-poor, feldspar-rich:
  → only Feldspar dating
- Calcium carbonate(calcite) missing:
  → Advantage(?) for XRF

Regional overview



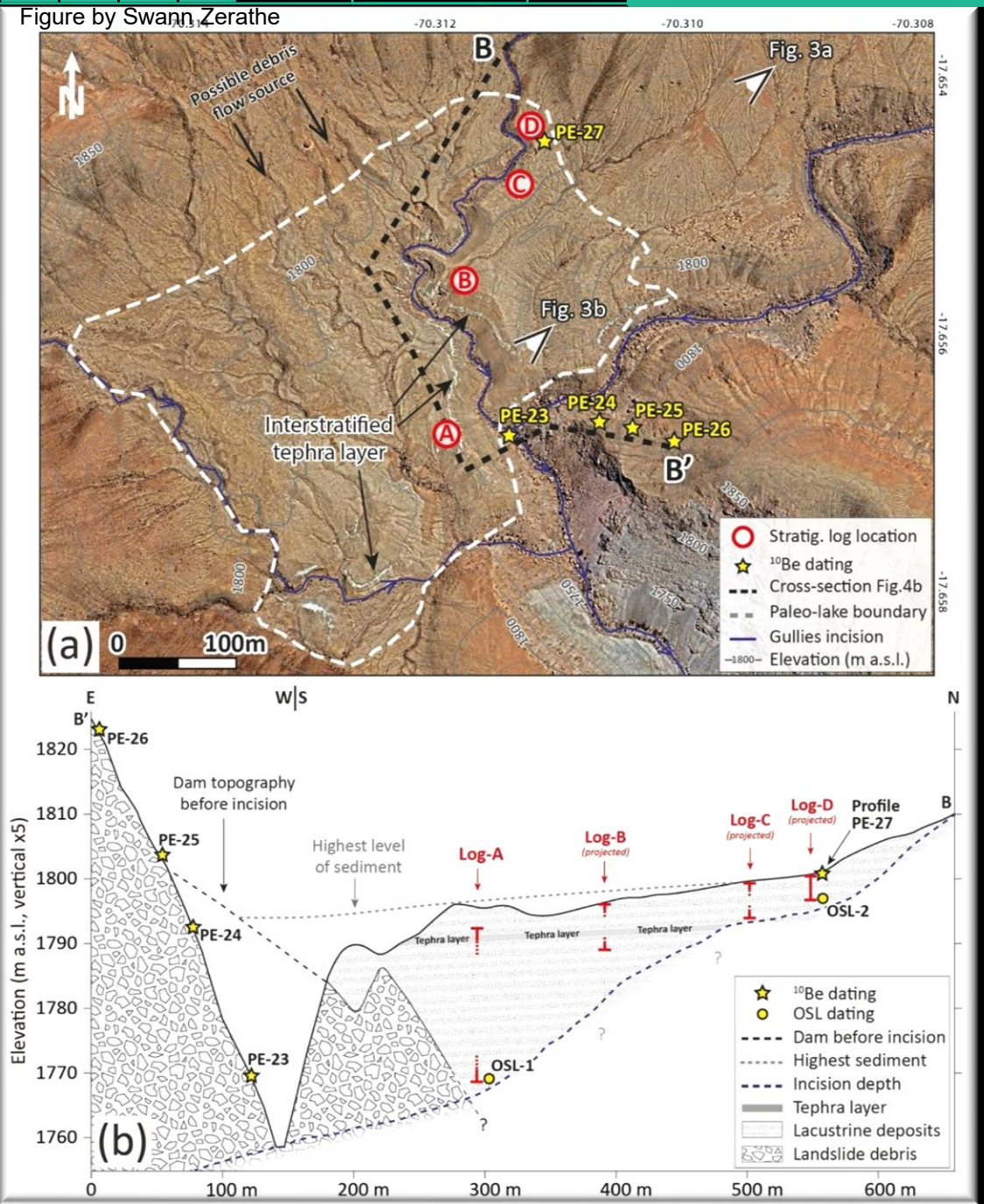
Figures by Swann Zerathe





- ~2000masl
- Heavily overprinted, earthquake prone landscape
- Several traps, e.g., modern lake *equivalent* north of study site
- Paleo-landslides:
  - → Imbricated
  - → Deep-seated
  - → Min. 4 major ruptures since 600ka
  - → 20 to 300 ka recurrence interval

Figure by Swann Zerathe



Local overview

- River-incised sediment fill, 250m long transect
- Four outcrops investigated:
  - LOG-A, -B, -C, -D
  - LOG-A → largest, deepest incised, main focus
- Two OSL samples taken:
  - OSL-1 → Sediment exposure base (LOG-A)
  - OSL-2 → Sedimentation top (LOG-D)
- Two cosmo sampling spots:
  - Surface transect on incised landslide dam
  - Depth profile on sedimentation top (LOG-D)

3D view here

In-field overview

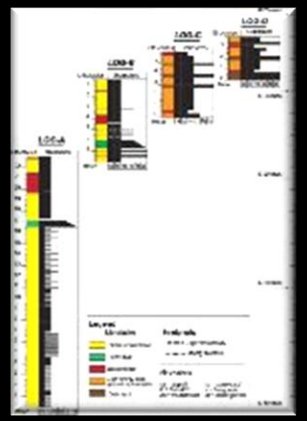
- River-incised sediment fill, 250m long transect
- Sediment deposit dammed by landslide deposition
- Deposit dimensions
  - 20-30 m thick
  - 2.25 to 4.25 km extension
  - ~9.5 km²

3D view here

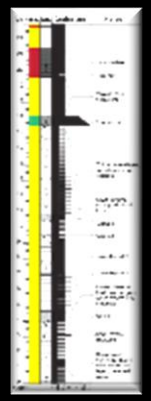
Methods and Results

Sedimentology

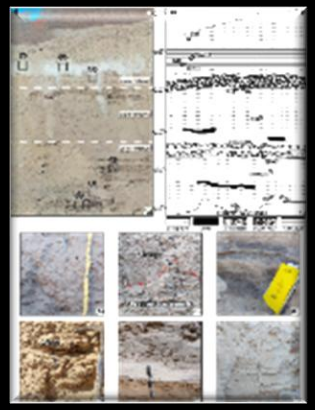
All outcrops



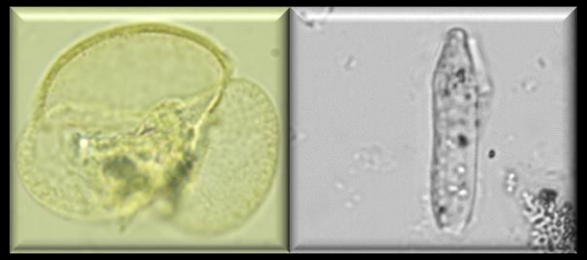
Main outcrop



Sediment structures



Pollen & Diatoms

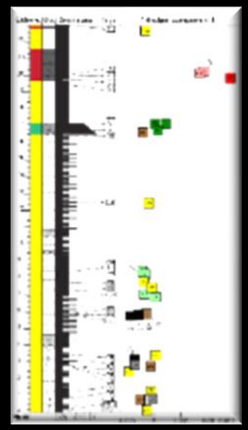


OSL

Approach and results

XRF

X-ray fluorescence



^{10}Be Cosmo

Surface trench

Depth profile

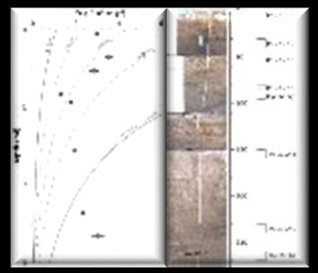
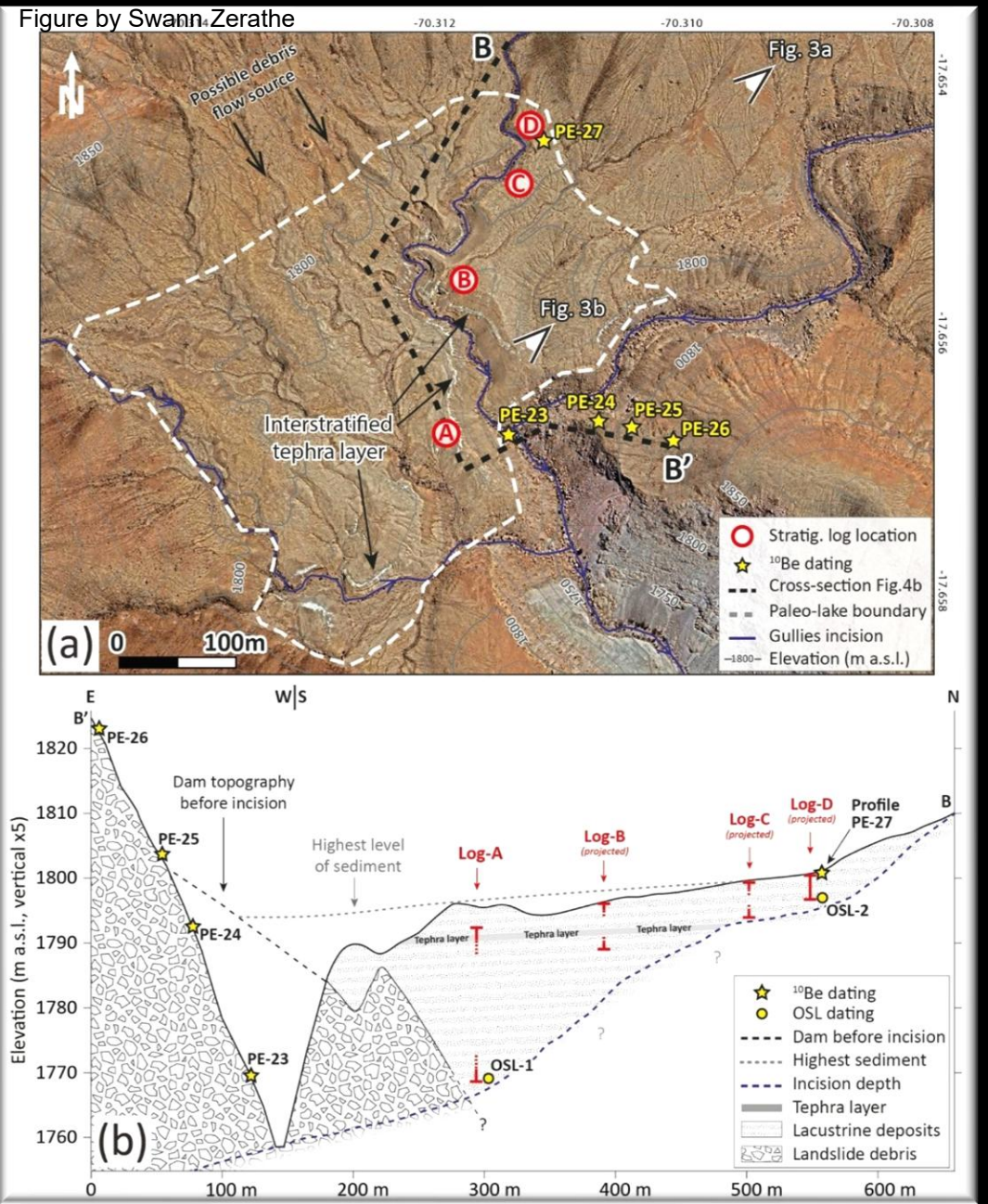
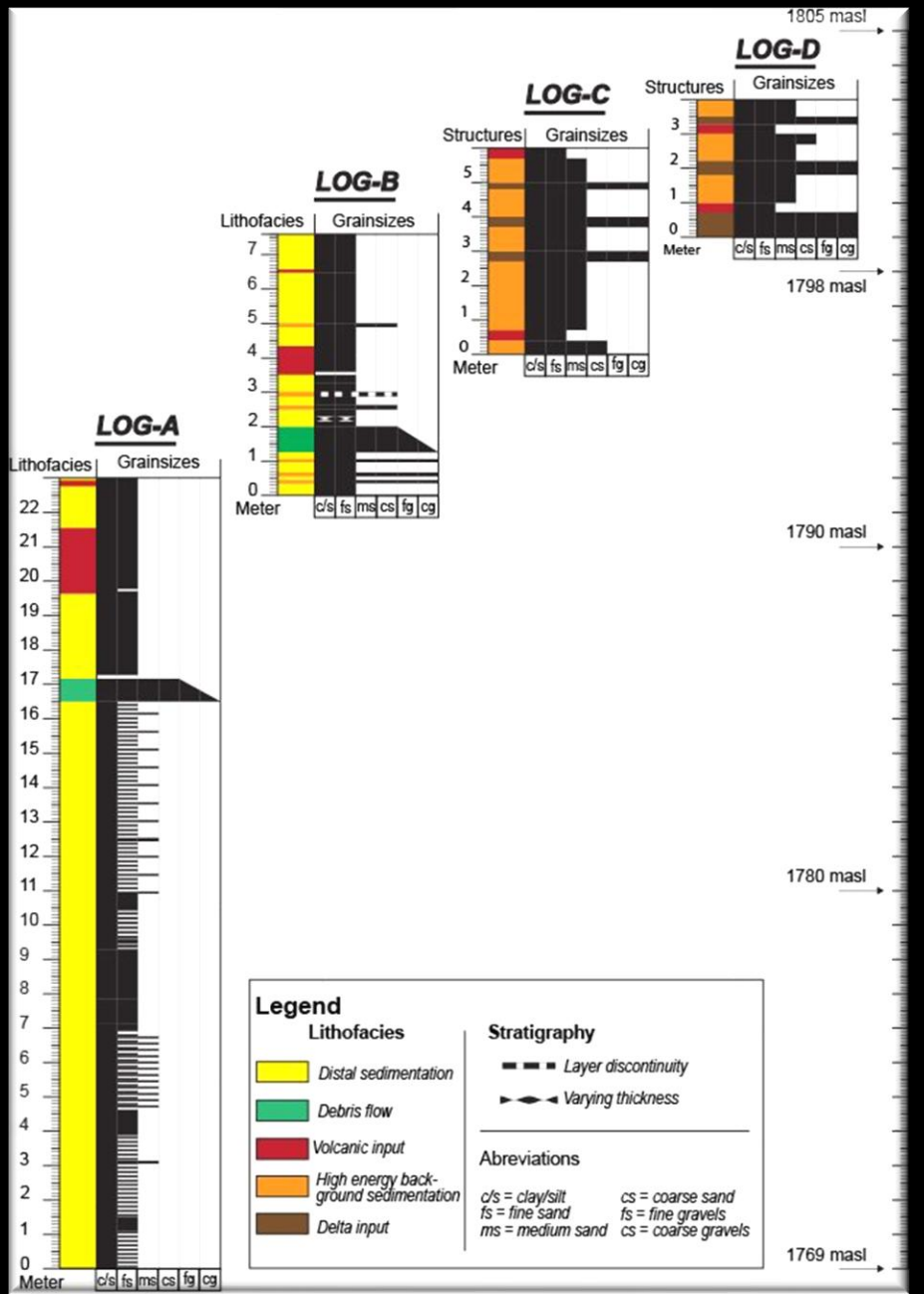


Figure by Swann Zerathe





Sedimentology
All outcrops

- 34m exposed vertical relief in total
- Fine grains in distal part (LOG-A, LOG-B)
- Coarse grains in river delta (LOG-C, LOG-D)
- Allignment trough tephra- and debris flow layer

3D view here

Sedimentology
Main outcrop

Upper interval (16.5-23m)

- Background sedimentation became structureless
- 0,5m thick *debris flow layer*
- 2m *volcanic tephra layer*

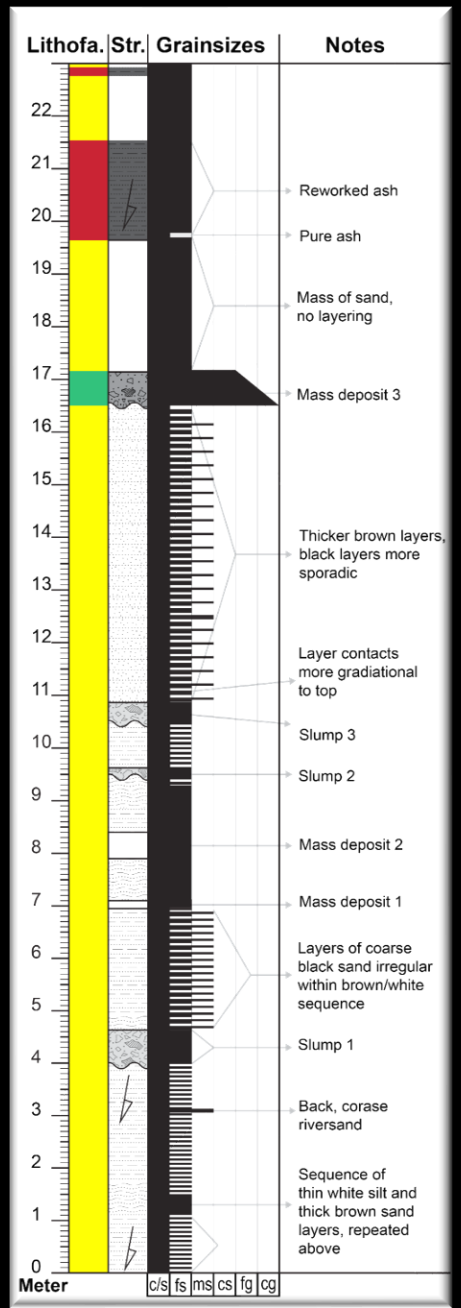
Middle interval (7-16.5m)

- Transition from *sharp to gradational contacts* of white silt/brown sand layers towards higher altitudes

Lower interval (0-7m):

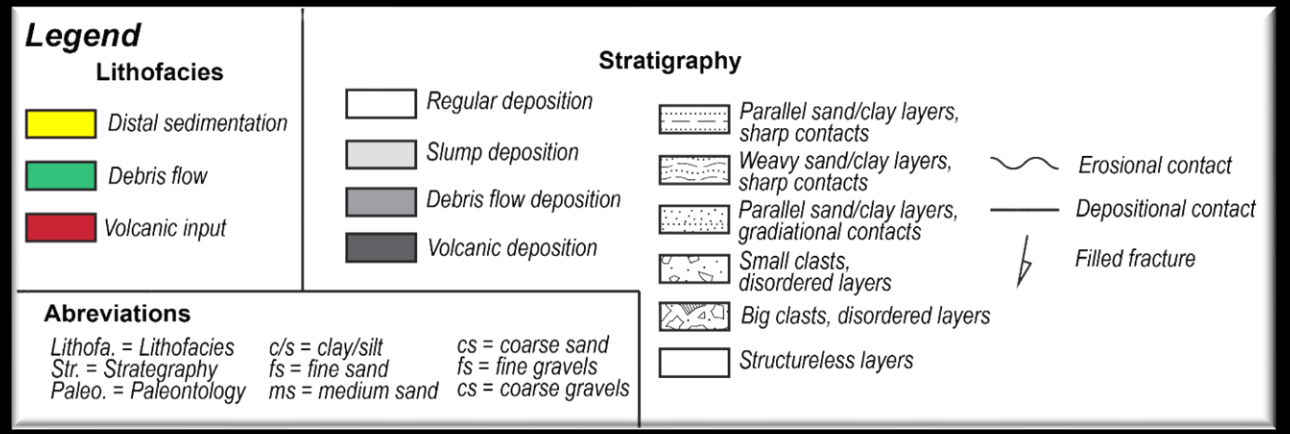
- Irregularly imbedded black *medium sand layers*
- One distinctively thicker sand horizon (at 1,25m)
- *Erosional slump* & *desiccation cracks*

LOG-A / Main Outcrop

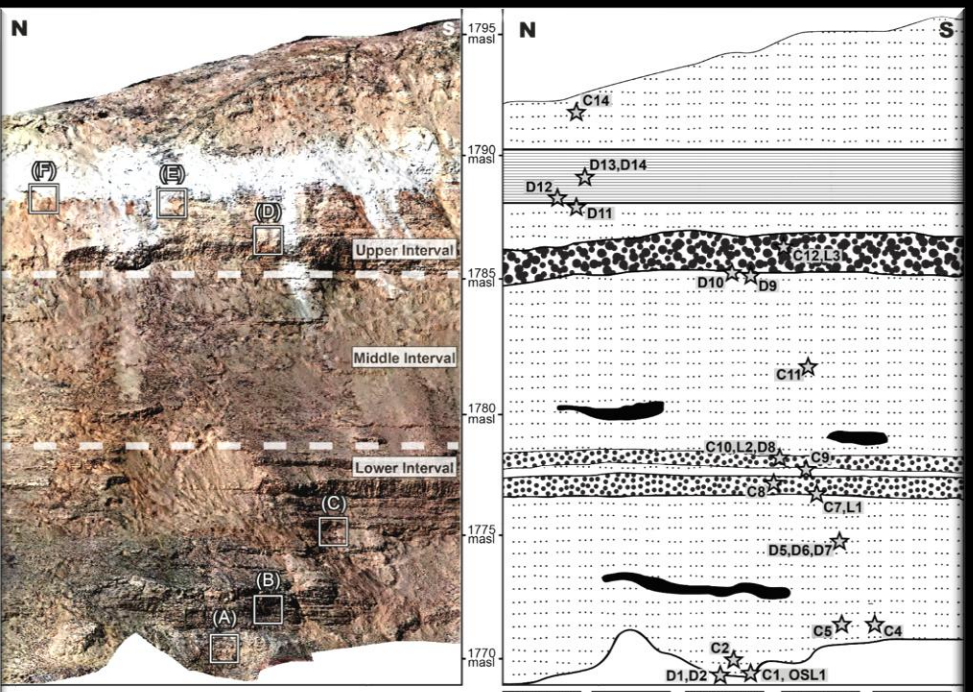


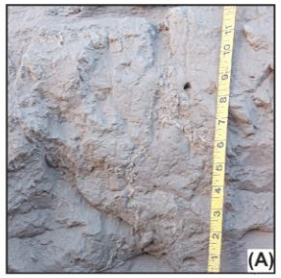
- Main interest through:
  - Longest stratigraphic succession (23m)
  - Deepest incision
  - Distal lake area / adjacent to landslide
- Distal (background) sedimentation:
  - Mainly *alternating white silt & brown fine sand layers*
  - Individual thickness 1-10 cm

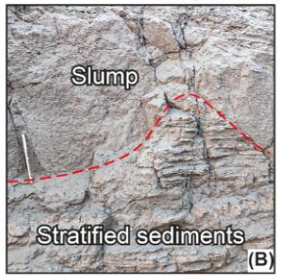
Extended view including XRF and Diatom/Pollen here

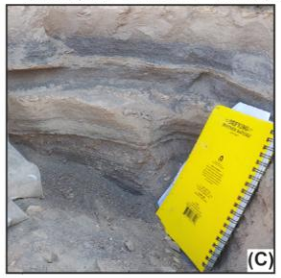


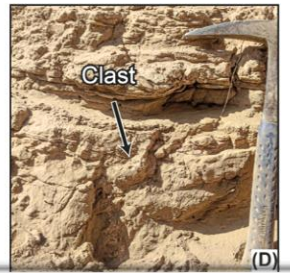
Main Outcrop

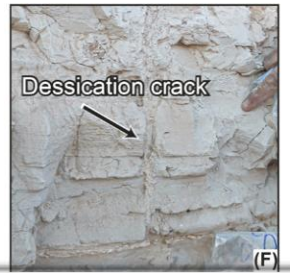










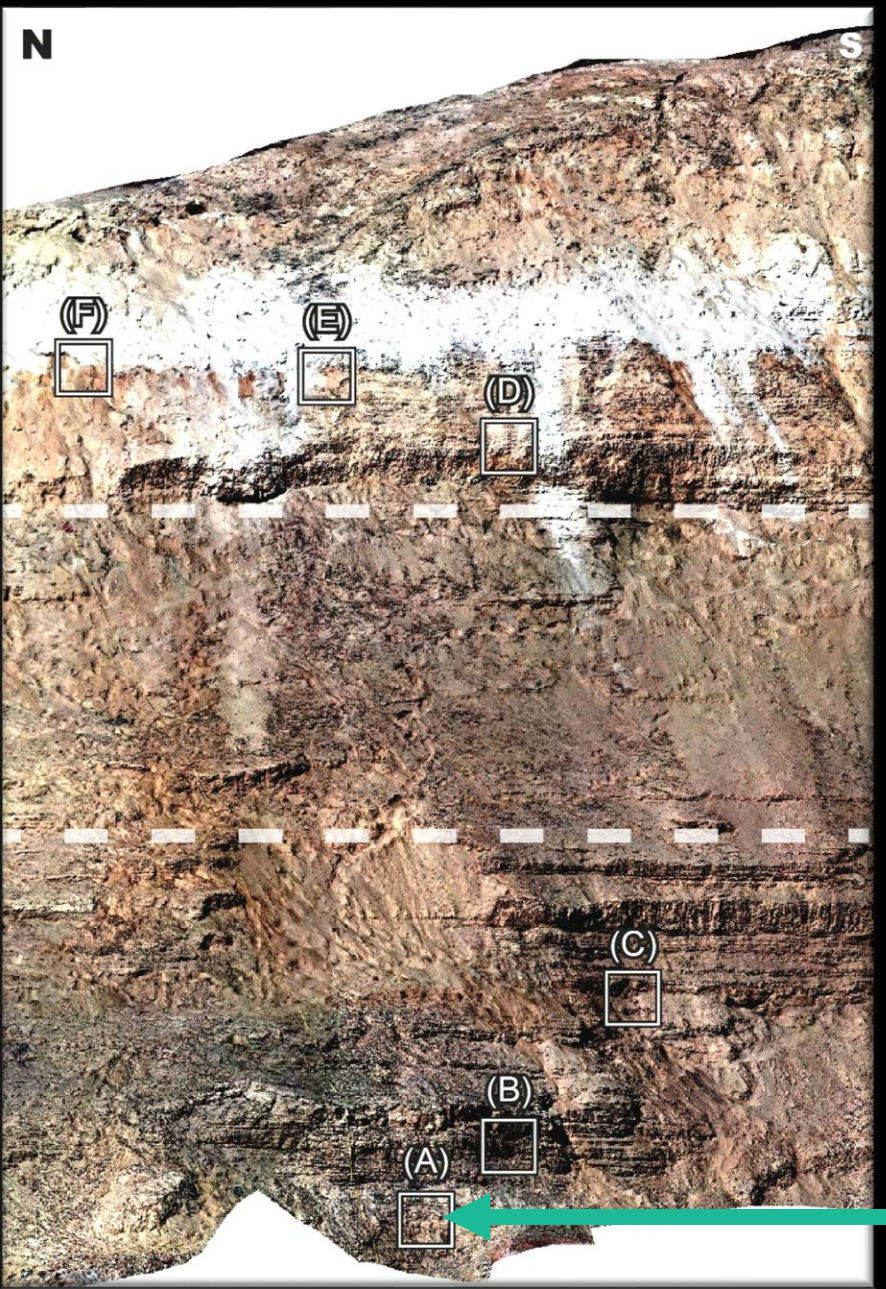


Sedimentology
Sedimentary structures

- 27 sediment samples collected from 24 distinct layers
- (A): *Desiccation cracks*
- (B): *Slump eroded stratified lacustrine layers*
- (C): *Iterative layers (background sedimentation)*
- (D): *Cm to dm large debris flow clasts*
- (E): *Sharp tephra contact*
- (F): *Desiccation crack in tephra layer*

Microscopical analysis here

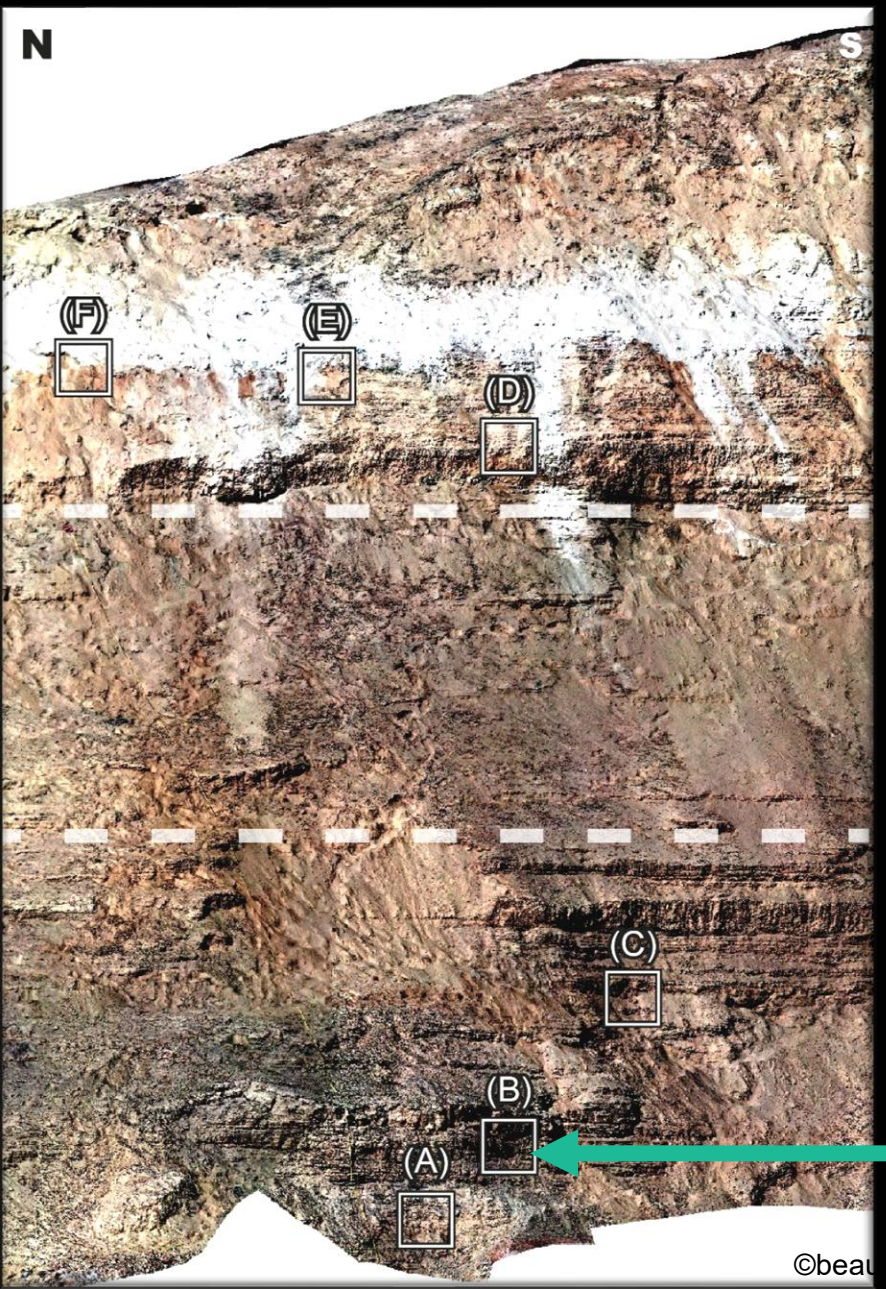
Main Outcrop



(A): Desiccation cracks

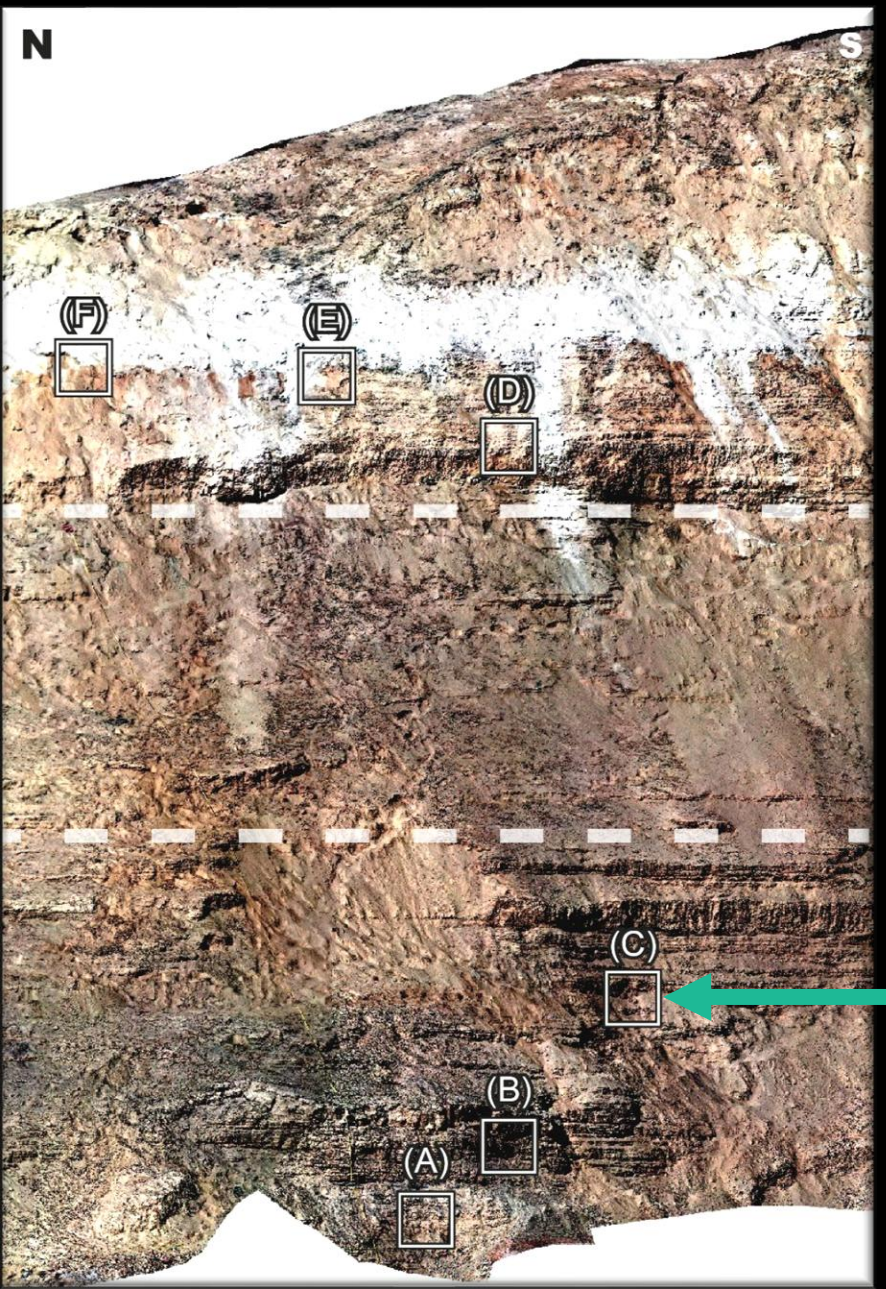
Desiccation cracks in modern lake equivalent here

Main Outcrop

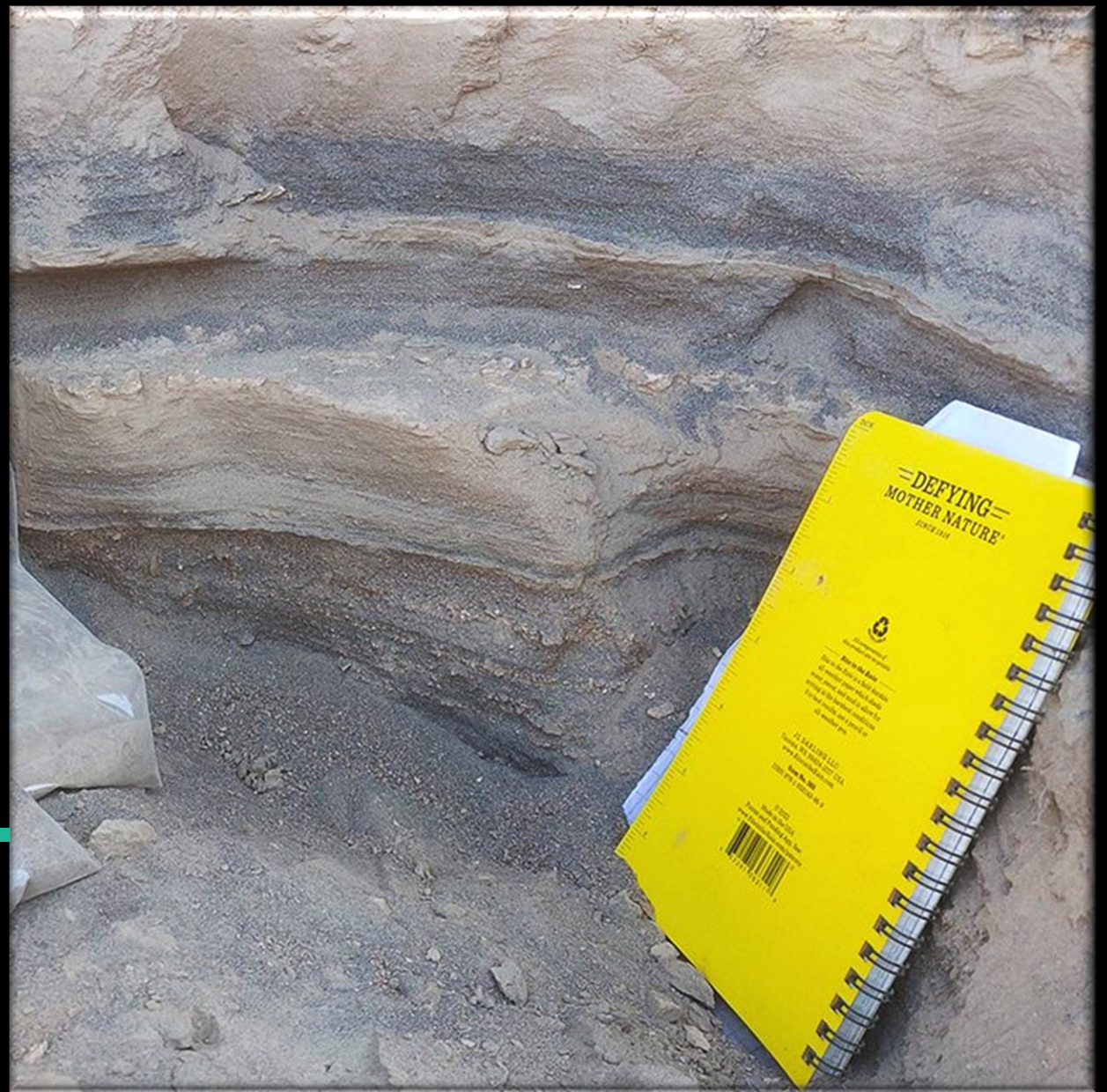


(B) Slump eroded stratified lacustrine layers

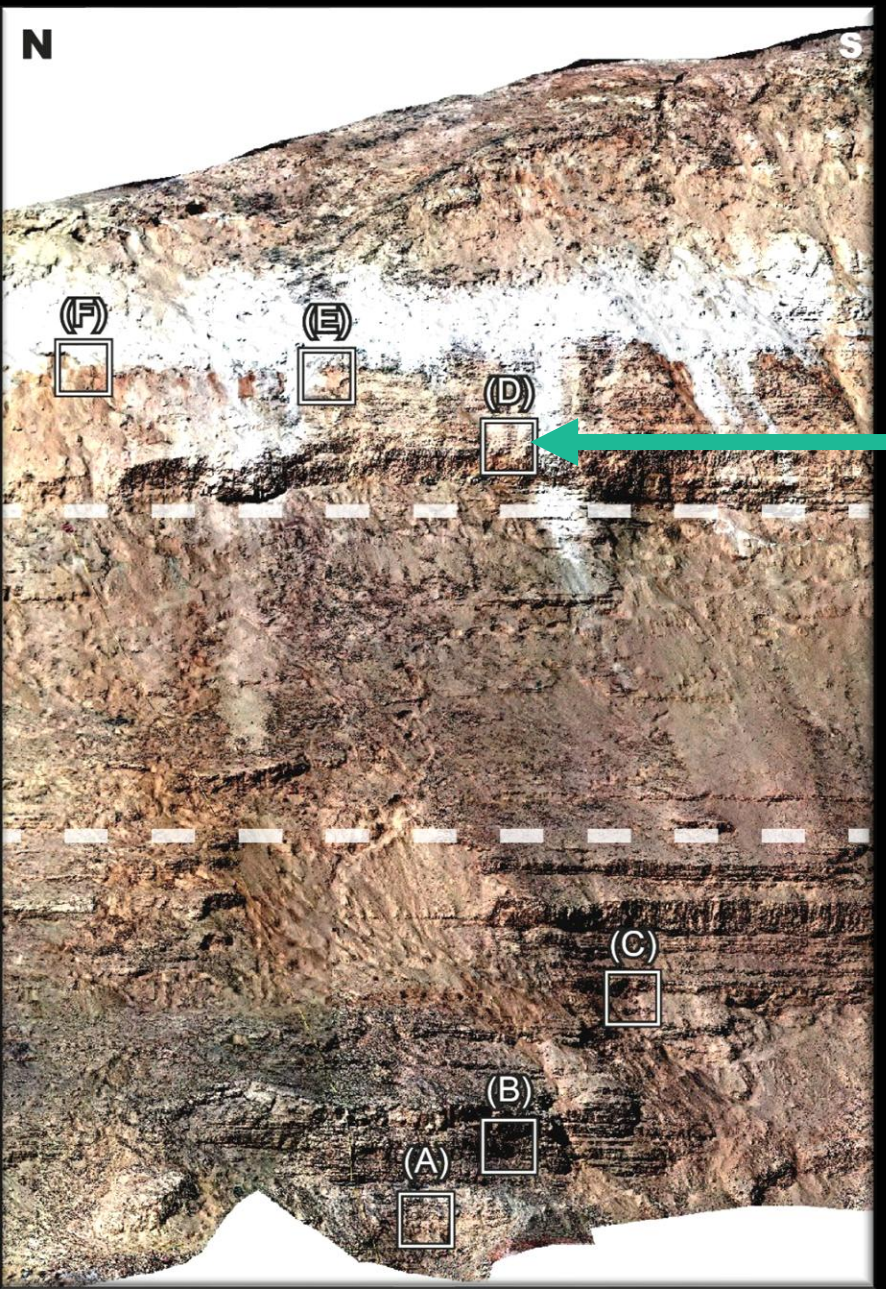
Main Outcrop



(C) Iterative layers (background sedimentation)



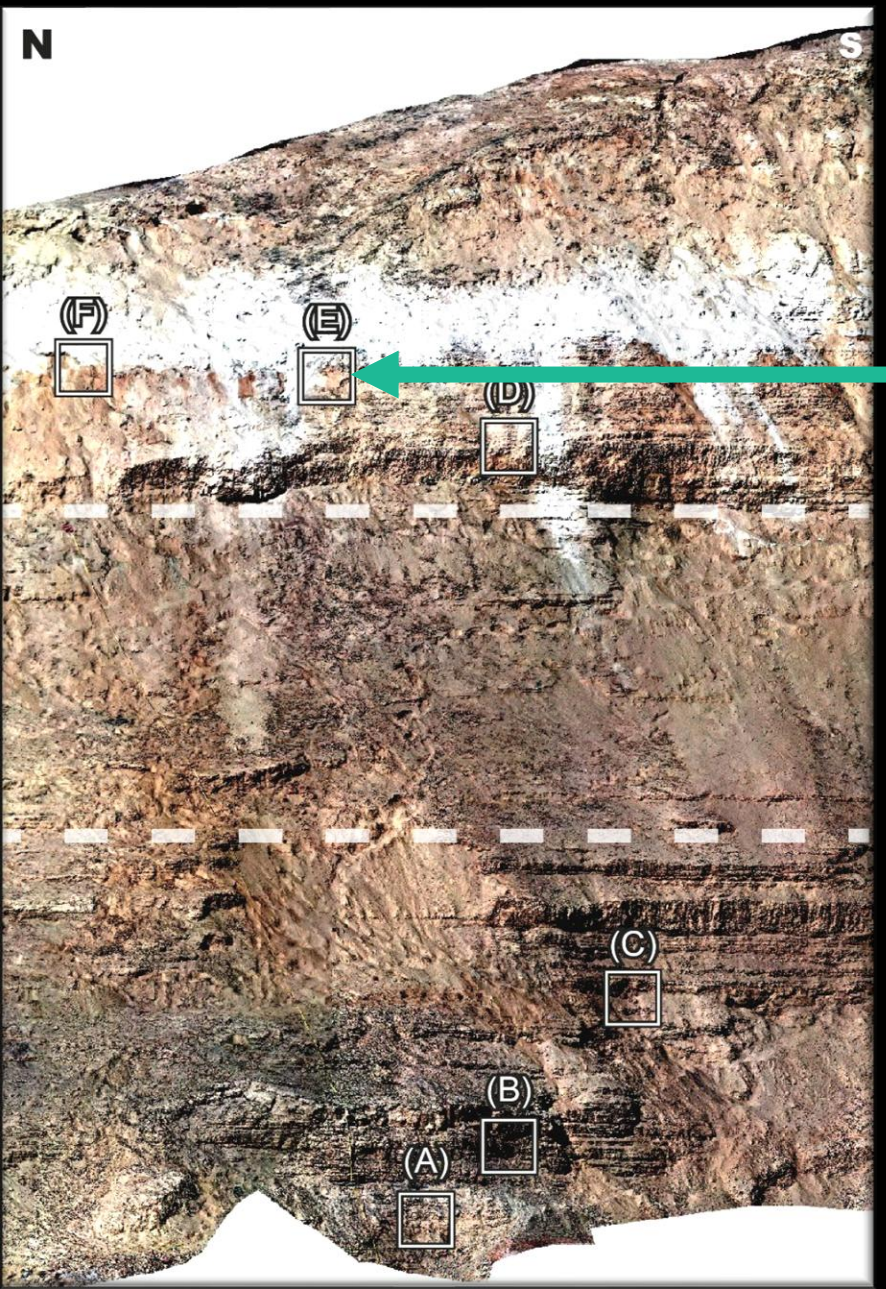
Main Outcrop



(D) Cm to dm large debris flow clasts

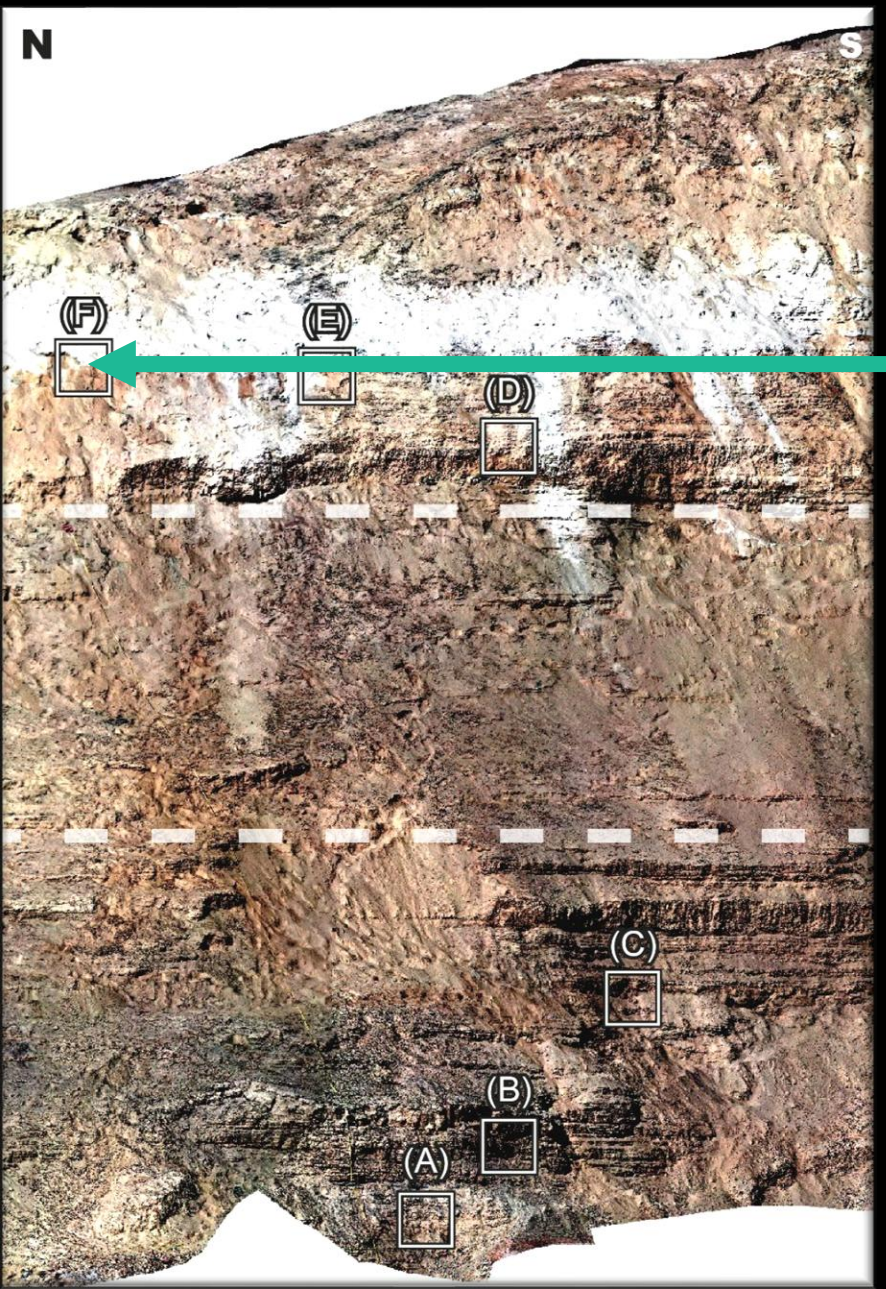
Larger clasts image here

Main Outcrop



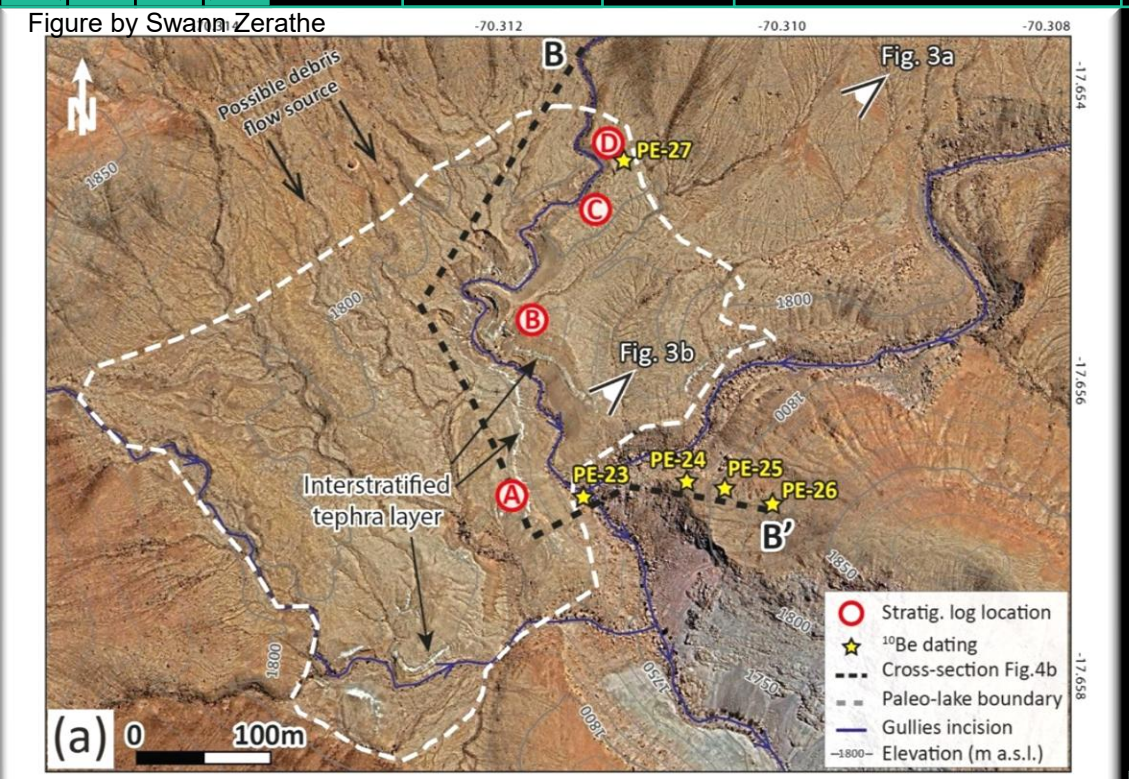
(E) Sharp ash contact

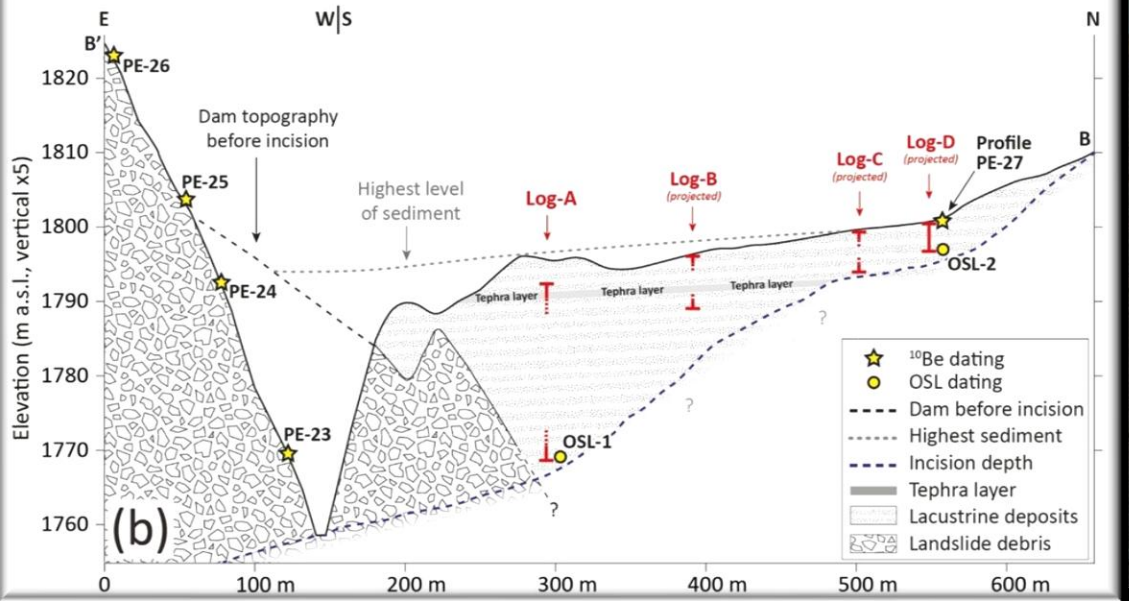
Main Outcrop



(F) Desiccation crack in tephra layer

Figure by Swann Zerathe





OSL

- OSL-1 (lower, lake inception): 133±14ka
- OSL-2 (upper, lake demise): 115±16ka

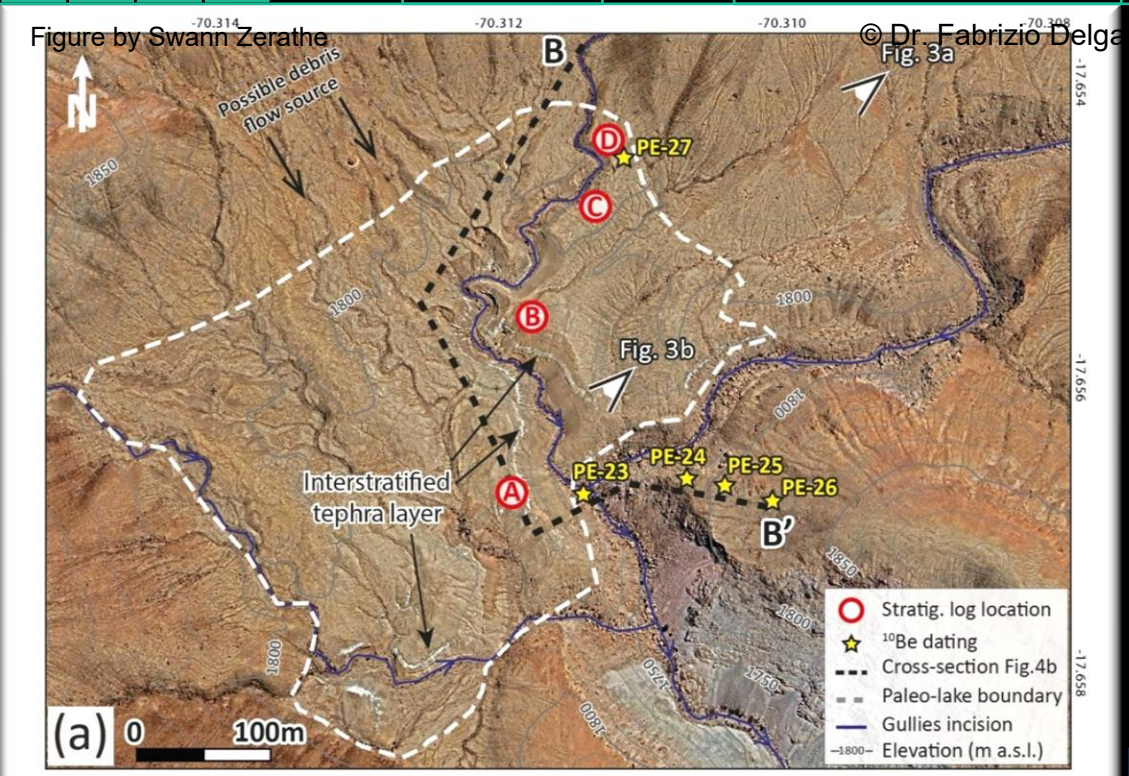
→Consistent with stratigraphy
→Almost perfectly within MIS5e (130-115ka)

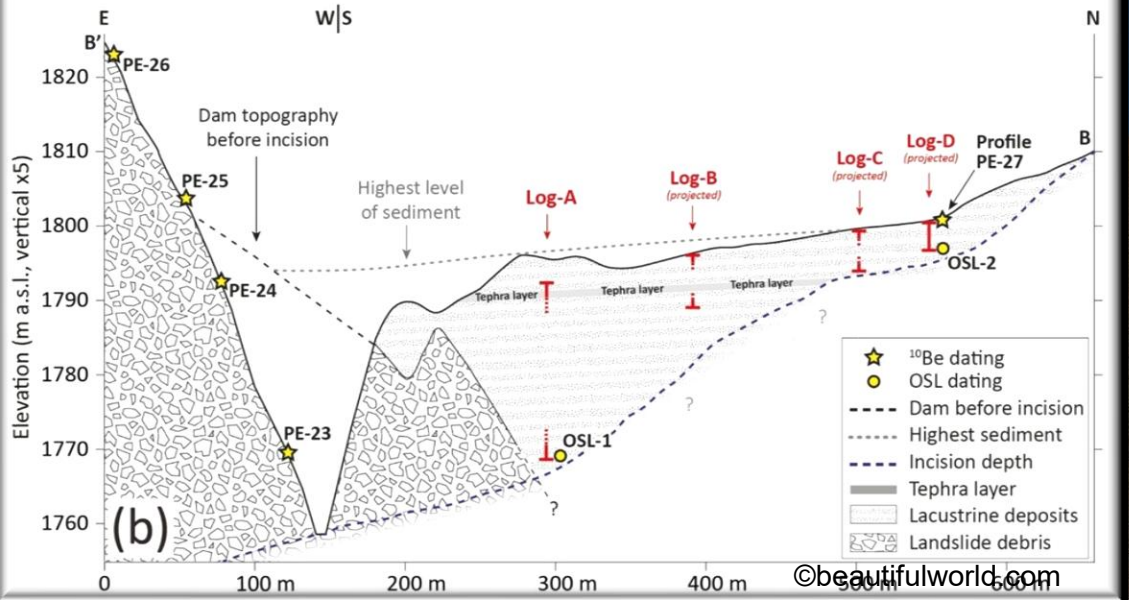
OSL input data and extended results here

Sampling spot OSL-1

Sampling spot OSL-2

Figure by Swann Zerathe





Cosmo surface dating

- **PE-26** at **503±34ka**: Dam emplacement
- **PE-25** at **222±19ka**: Intermediate incision
- **PE-24** at **115±9ka**: Lake termination (OSL-2 overlap, 115±16ka)
- **PE-23** at **29±5ka**: Subsequent incision

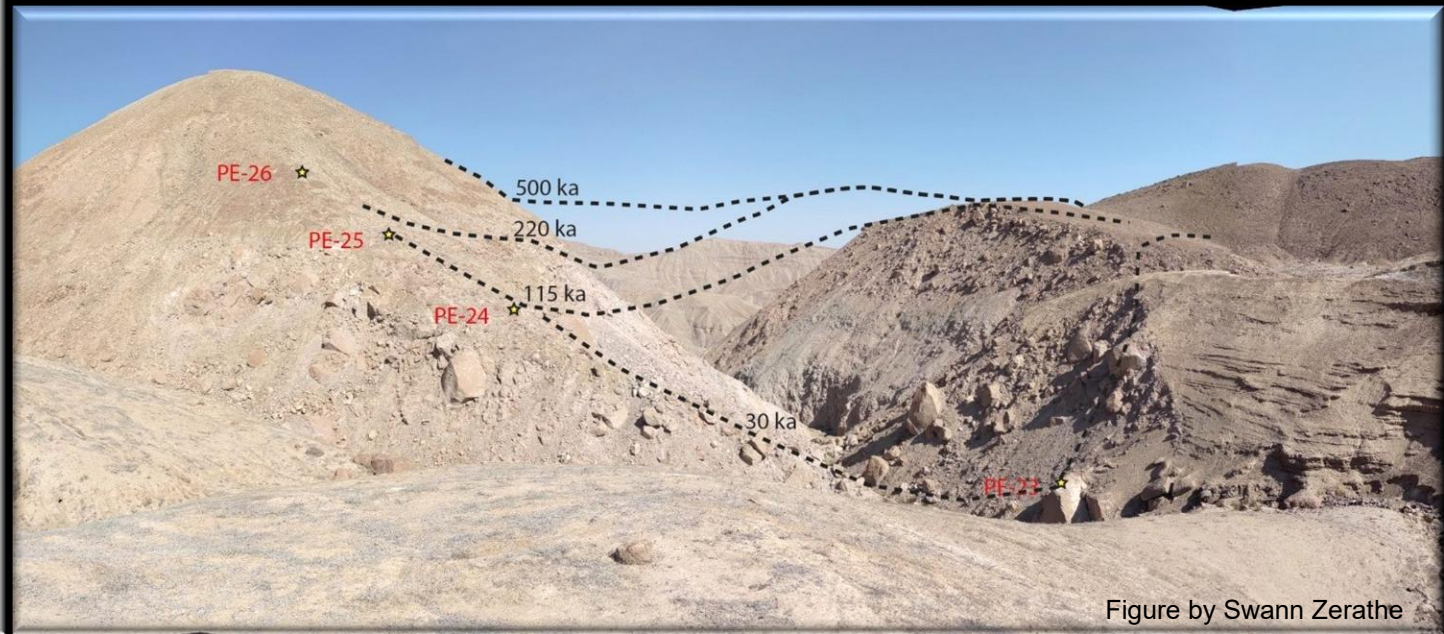
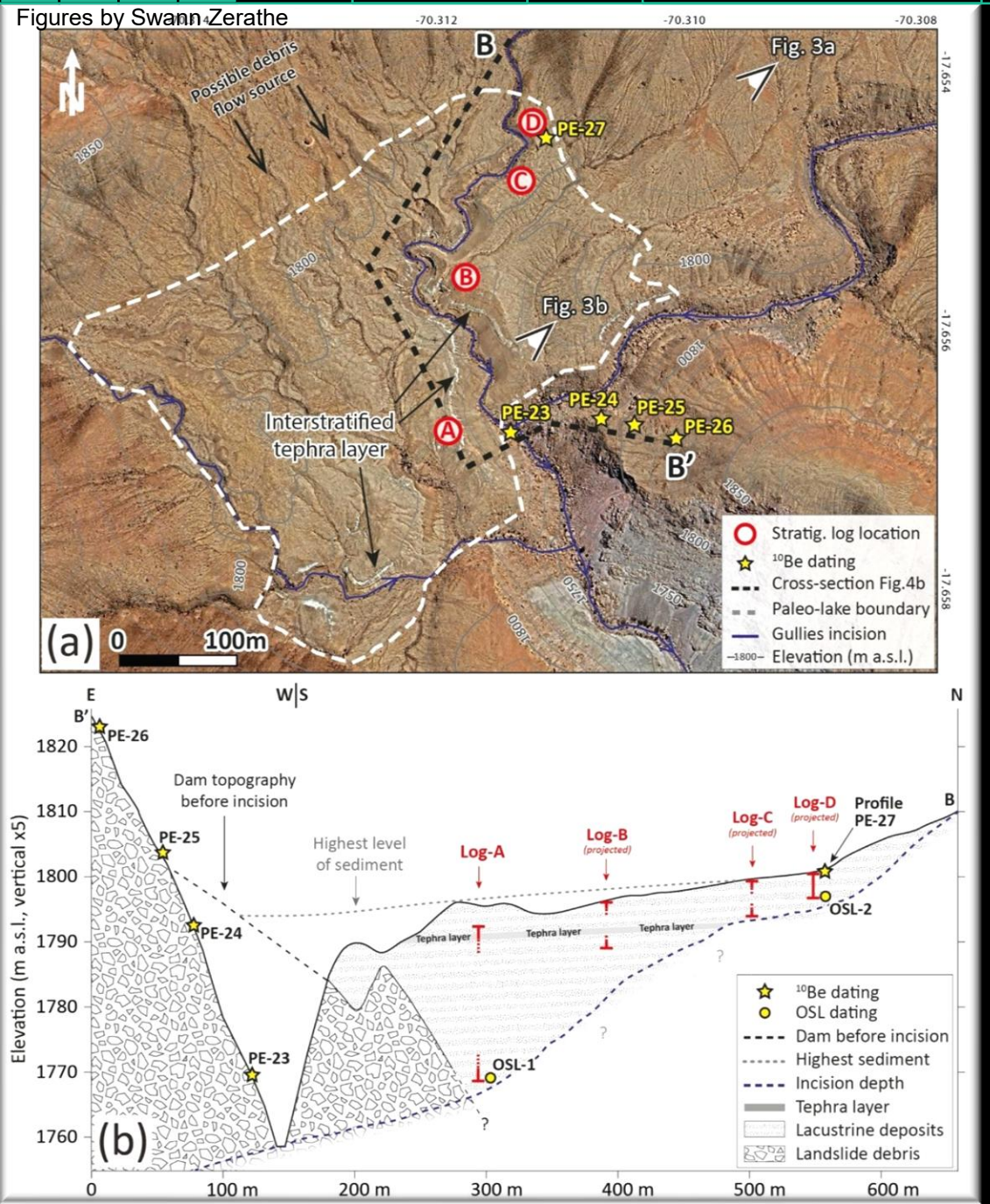


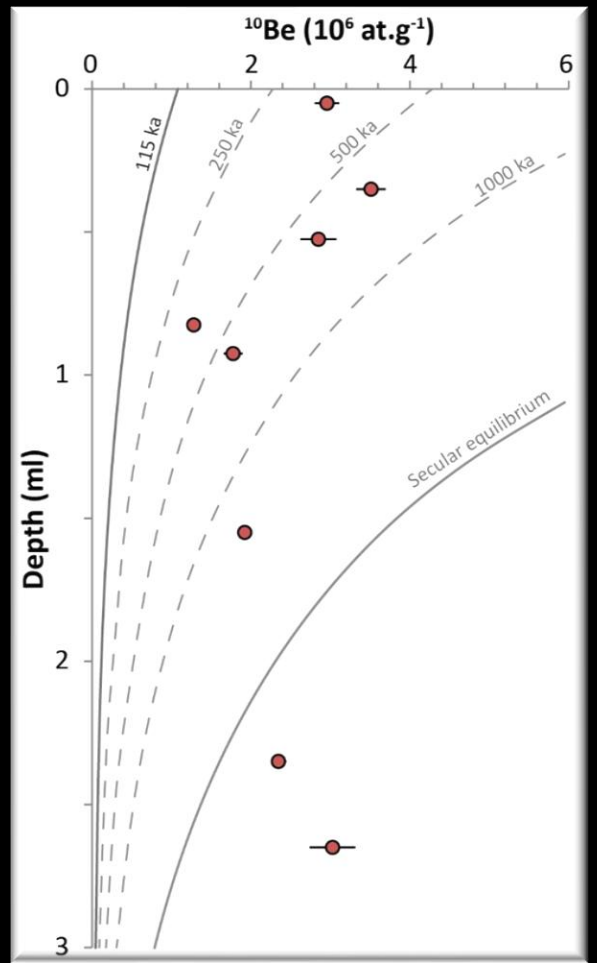
Figure by Swann Zerathe

Figures by Swann Zerathe



Cosmo depth profile

- Profile **PE-27** at LOG-D to constrain lake termination timing
- But: scattered concentration, no systematic decrease with depth
- So: Only useful for inference of catchment wide erosion rate (varying from 1 to 7 m/Ma)



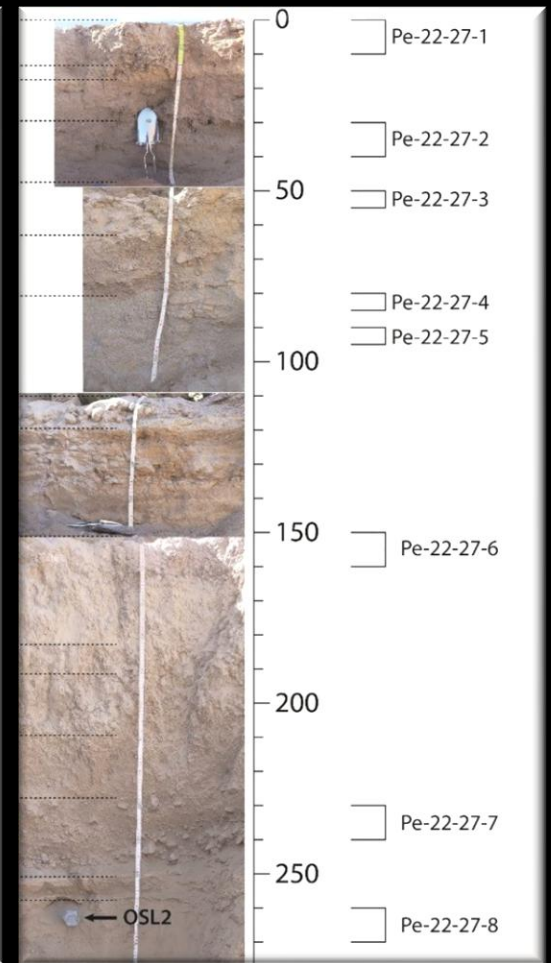
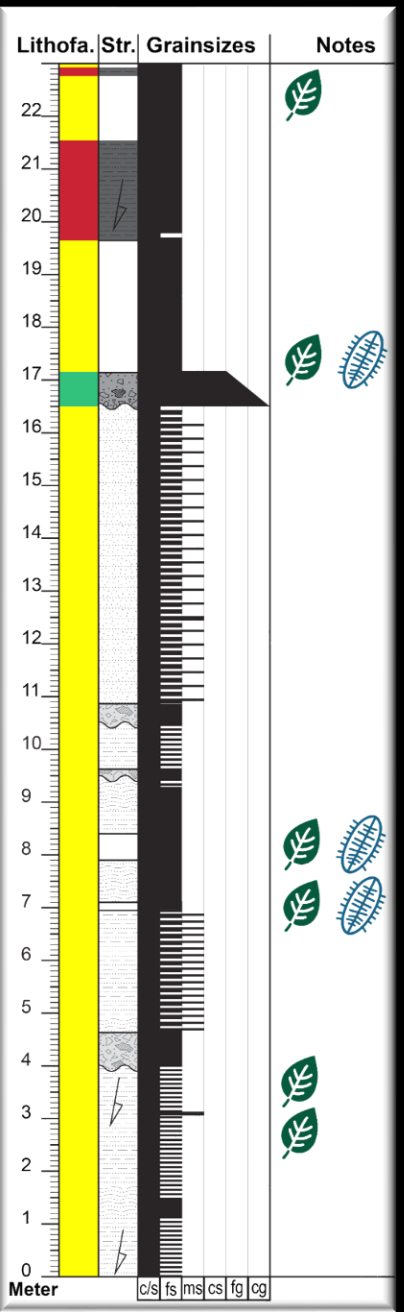


Table results here

LOG-A / Main Outcrop

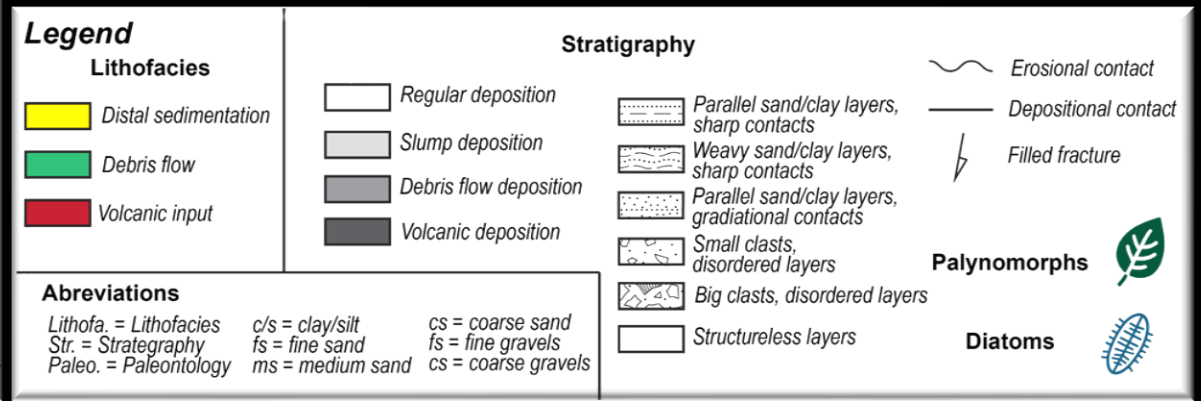


Diatoms and Pollen

Podocarpus (Pollen)
- Tree-like structure
- E.g. at <20°C, 200mm/a

Cymbella (Diatom)
- Benthic species
- E.g. at deep lake bottoms

Hantzschia (Diatom)
- “Dry-habitant from”
- E.g. in mosses



→ Overall indication towards semi-humid conditions

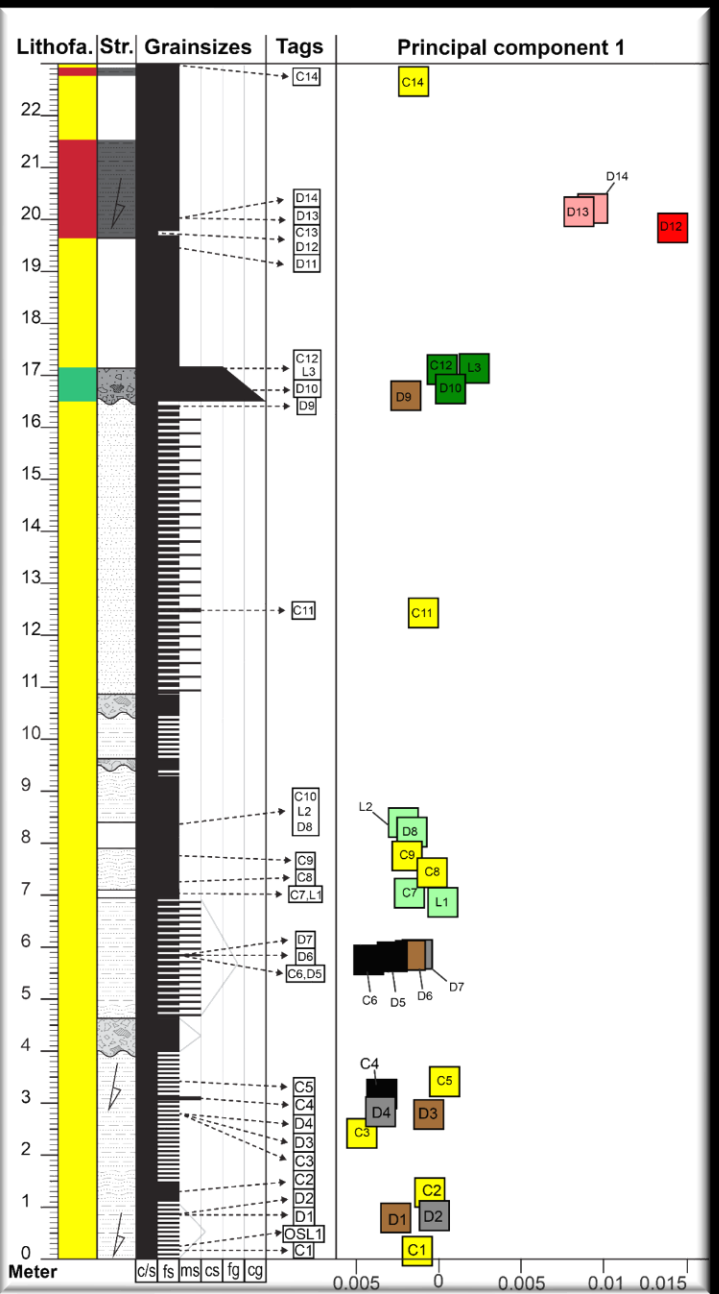
→ Consistent with sediment-ology observations

Extended pollen results here

Extended diatom results here

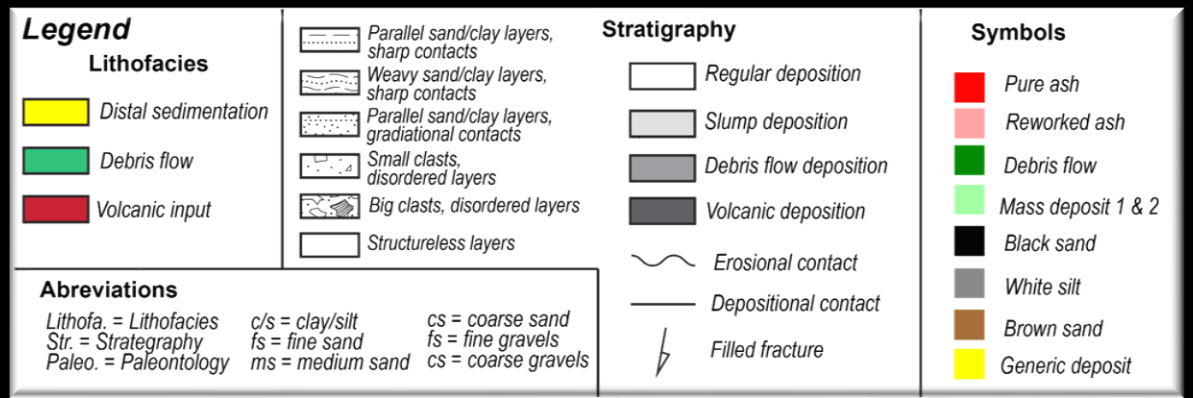
LOG-A / Main Outcrop

XRF



- Detection of general paleoenvironmental changes during deposition
- 34 samples measured (Paleolake: 31, Lake analogue: 3)
- PCA 1 (70% total variance) and Ti, K, Ca, Ba investigated

- **Results:**
  - Tephra values significantly different
    → XRF measurement valid
  - General little variety for PCA and single elements
    → Overall stable conditions
    → Consistent with sediment observations (desiccation cracks top + bottom)
    → But: Modern lake analogue samples are comparable



Extended results here

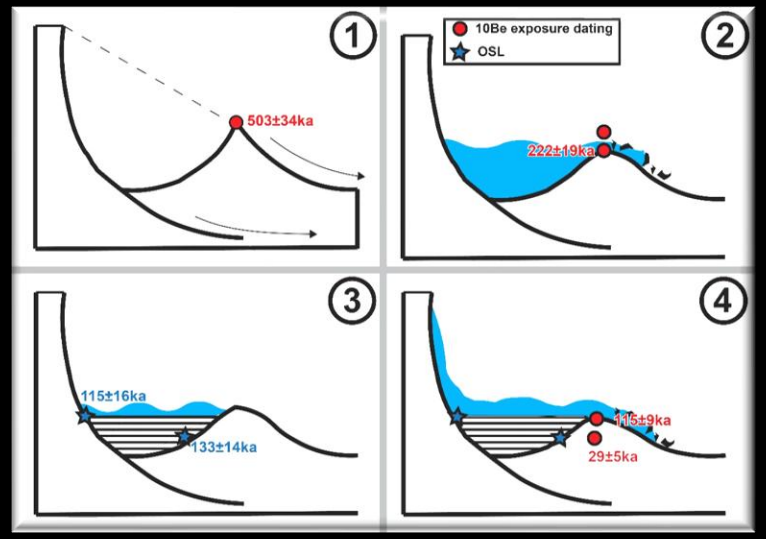
Conclusion

Sedimentology

- Iterative layering, fine distal grains / coarse delta grains:
  → **lake-, i.e. non-arid environment**
- Desiccation cracks, debris flow:
  → **non-humid environment**

Dating (OSL & Cosmo)

- OSL-1 (133±14ka), OSL-2 (115±16ka), PE-24 (115±9ka):
  → **Lake existence only in MIS 5e**
- PE-25 (222±19ka) & PE-23 (29±5ka)
  → **Fluvial activity before and after**



Diatoms

+ In-situ proxies
- Spectrum of (non-arid) habitats

Pollen

+ Direct environment foodprint
- Potentially not local

XRF

- Prevailing, overall stable conditions (but low confidence)

Follow-up tasks

Additional OSL results:

- Centre of deposit (OSL-1 & -2 error overlap issue)

Manual layer counting:

- Estimate temporal repetition (ENSO-like?)

Contextualise against current literature

Additions

3D Overview

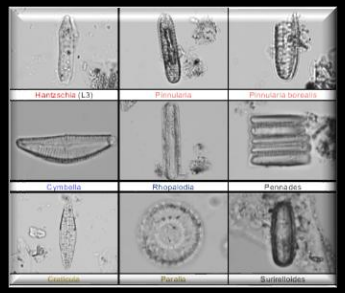
Background layering

Modern lake equivalent

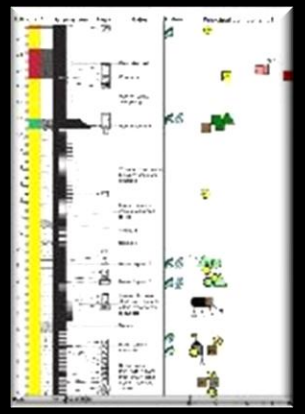
Extended pollen results

Sample	Taxa
C14	Nigrospora, **Polypodiisporites**
C12	*Cyperopollenites*, **Sporomorfo**, Nigrospora
L3	*Clavainaperturdites, Clavapollenites, Cyperopollenites,* ***Deltoidospora****, Echistephanocolporites, Echistephanoporites, Echitricolp(or)ites, Foveomonocolpites, Foveotricolpites, Heterocolpites, Ladakipollenites, Leavigatosporites, Malvacipollis, Monoporites, Perisyncolpites, Polyleptis,* **Polypodiisporites,** *Psilamonocolpites, Psilaperporites, Psilapollenites, Psilatricolporites, Psilatriporites, Psilatriporites, Rettricolporites, Rhoipites, Rugustephanoporites*
C10	*Cyperopollenites,* **Laevigatosporites**, Spore indet, Tetraploa, Nigrospora
L2	*Clavainaperturites, Clavatricolporites, Cyperopollenites, Echistephanocolporites, Echistephanocolporites, Ephedripitesmout,* **Laevigatosporites**, *M. annulatus, Monoporopollenites,* **Perinomonoletes**, *Perisyncolpites, Podocarpus , Polyleptis,* **Polypodiisporites**, *Psilatricolporites, Rhoipites, Striostephanoporites*
C7	*Cyperopollenites, Echitriporites,* Nigrospora, *Podocarpus , Sporomorfo,* Tetraploa
C5	Fungi hifa, Nigrospora, **Polypodiisporites**, Tetraploa, **Verrumonoletes**
C3	Nigrospora, **Polypodiisporites**
C3	Nigrospora, **Polypodiisporites**

Extended diatom results



LOG-A extended

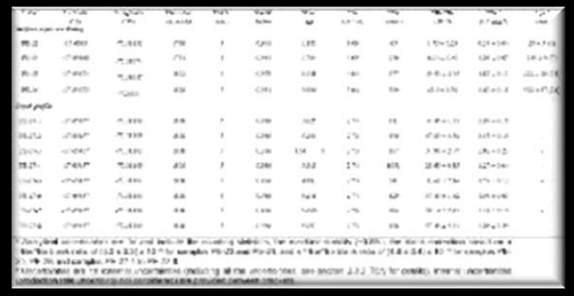


Large debris flow clasts

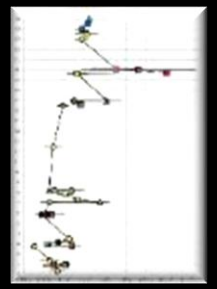
OSL values

Microscope results

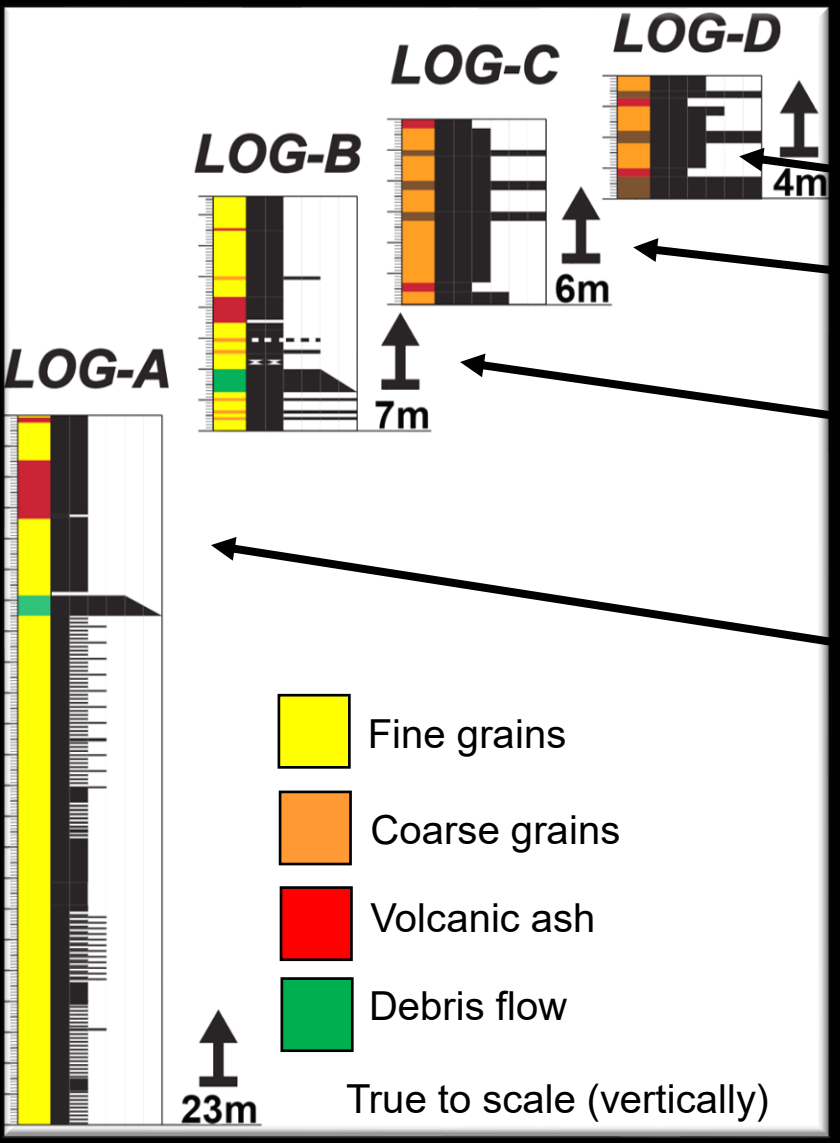
Cosmo values

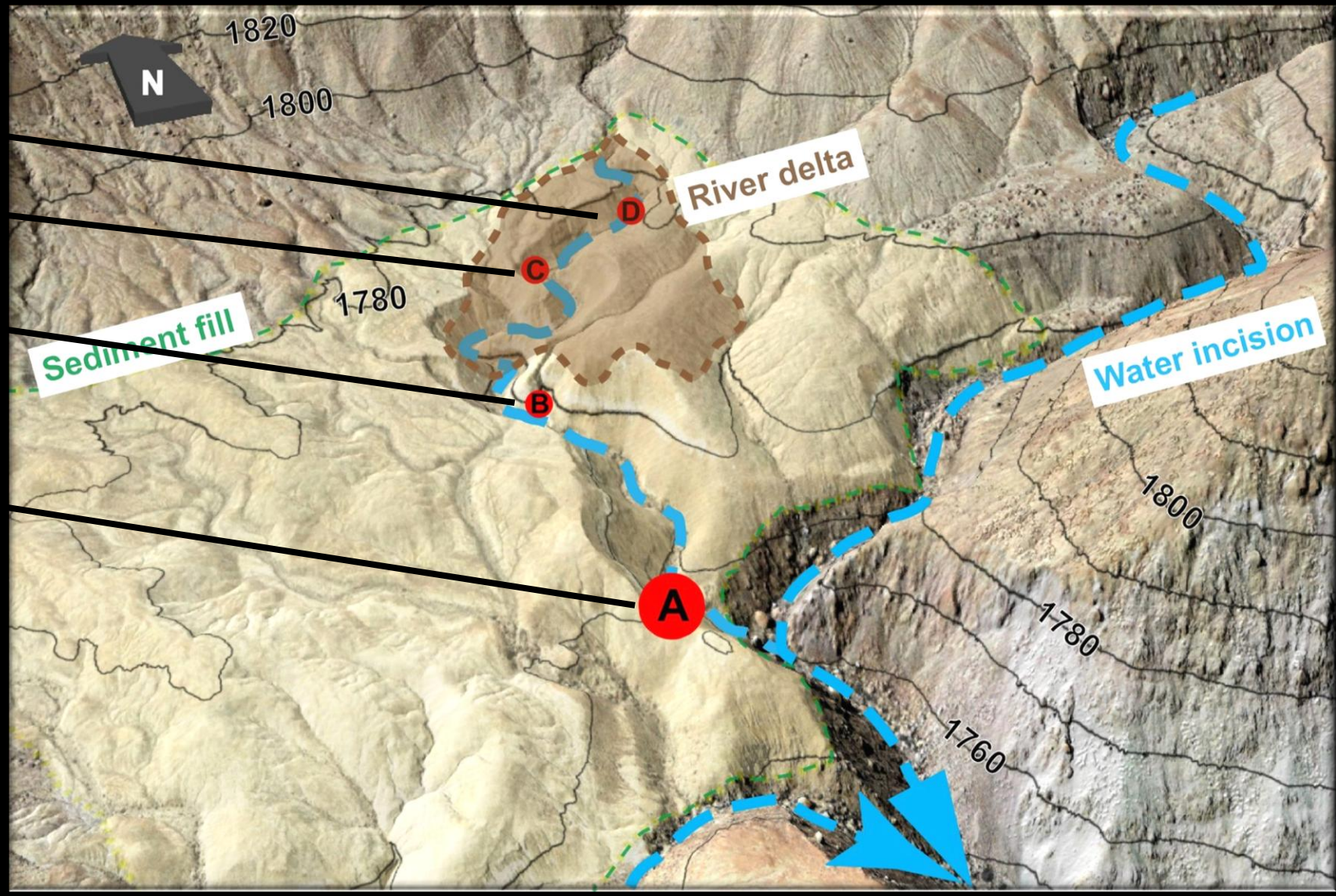


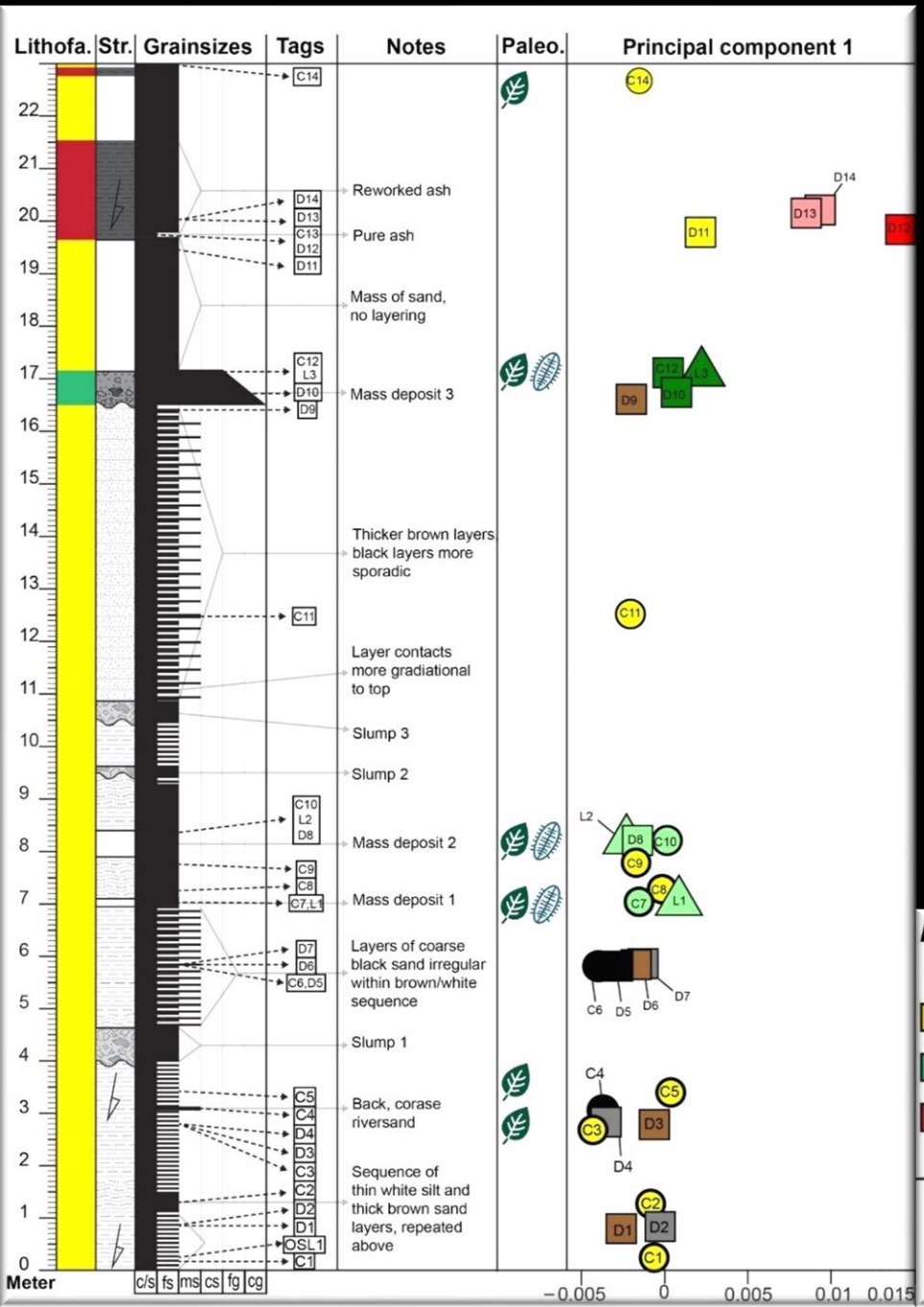
Extended XRF results



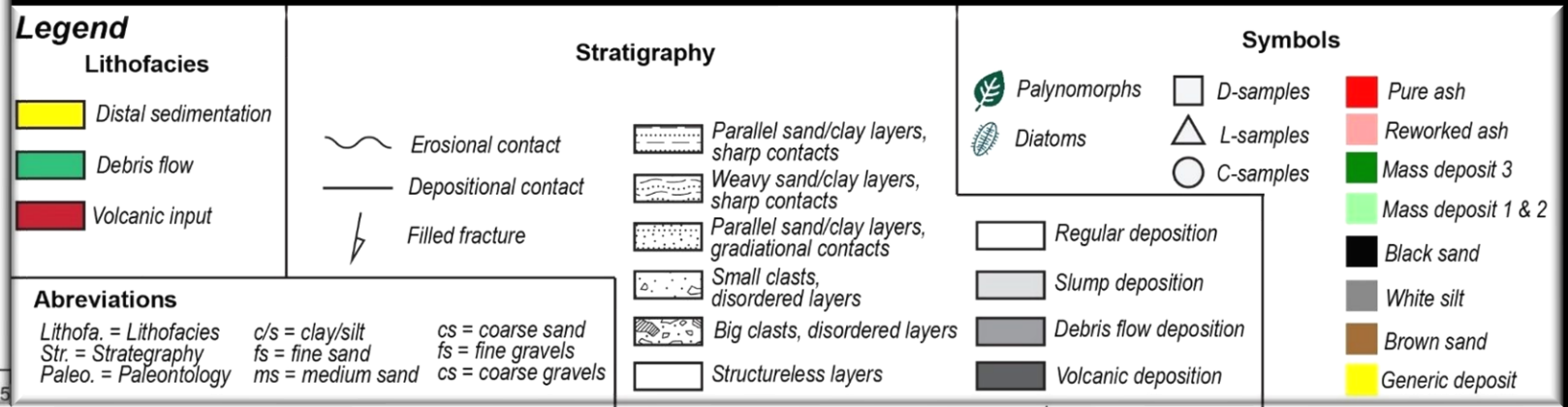
3D lake overview





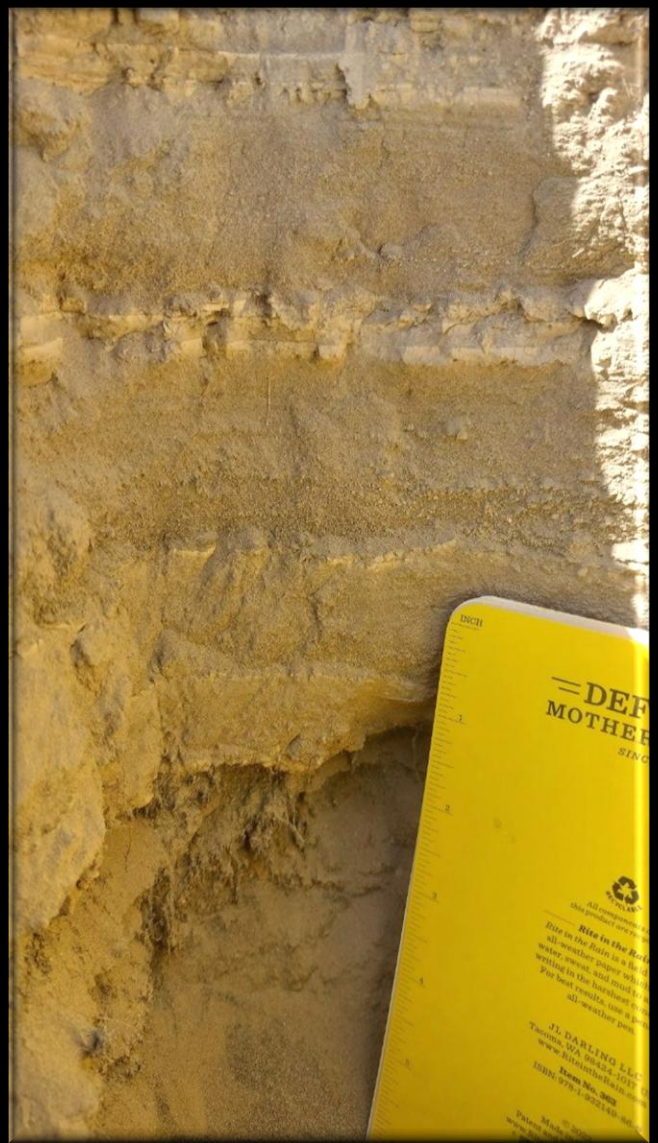


LOG-A extended

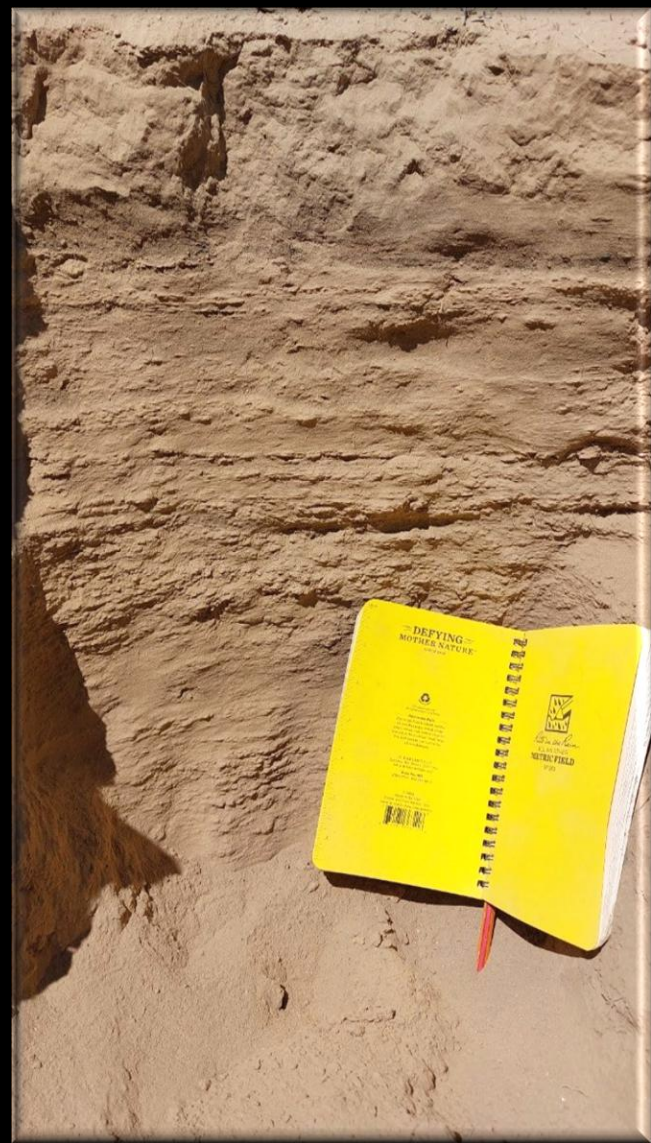


Background sedimentation layering

Sharp contacts at lower elevations of main outcrop



Gradational contacts in higher elevations of main outcrop



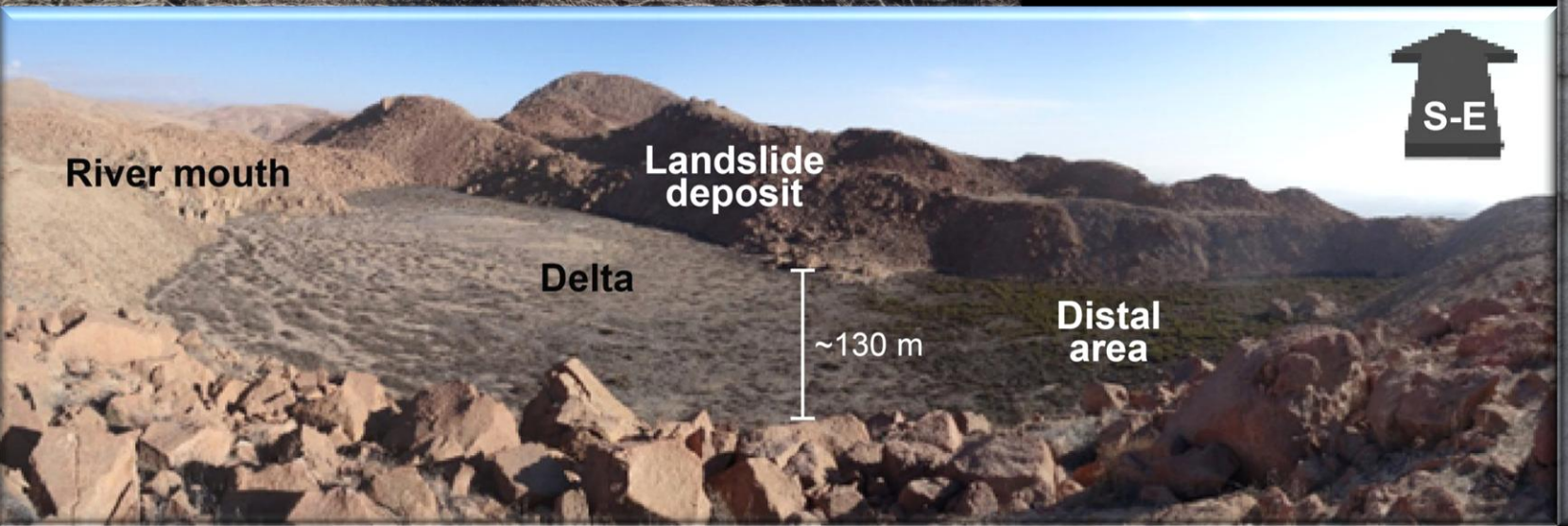
Larger debris flow clasts

Microscopical analysis

Rounding generally poor, slightly better in consolidated layers

Tag	Nature	Grainsize (mm, most/min./max)	Grain colours	Rounding	Sphericity	Shapes	Sorting
Z3	Silt Analogue	-	Most: Yellowish white, Few: black, red	-	-	-	1
Z2	Sand Analogue	0.07/0.01/0.2	Most: White, yellow Few: Black, red, brown	-	1,2,3	1,2,3	2-3
Z1	Generic Analogue	0.03/0.01/0.1	Most: Whiteish yellow, Few: black, red, yellow	edgy, 0	1,2,3	1, few 2,3	2
Dρ	Gravel sand	0.05/0.01/0.25	Most: Yellow, Few: black brown, white	-	1,2, few 3	1,2,3	4
C14	Generic deposit	0.04/0.01/0.2	Most: Yellow, Few: black, brown, white	edgy, 0	2	1, 2, few 3	2-3
D14	Reworked ash (thick)	-	Most: white, yellow, Few: red, black, brown, yellow	edgy,0	1,2,3	1, few 2,3	3
D13	Reworked Ash (thin)	-	Most: white, yellow, Few: red, black	-	-	-	1
D12	Pure ash	-	Most: white, Few: Black red, yellow	-	-	-	1
D11	Generic deposit	0.05/0.01/0.15	Most: Yellow, Few: black , white, reddish brown	edgy, 0, 1	1, few 2, 3	1, few 2,3	3
L3	Mass deposit 3	0.03/0.01/0.15	Most: Yellow, Few: Red, black, white	0	1,2,3	1, 2	2-3
C12	Mass deposit 3	0.03/0.01/0.2	Most: Yellow, Few black, red, brown, white	0	1,2	1, 2	3
D10	Mass deposit 3	0.05/0.01/0.2	Most: Yellowish white, Few: black, brown, red	edgy, 0	1,2,3	1, 2	3-4
D9	Brown sand	0.07/0.01/0.4	Most: Yellowish white, Few: Black, brown, red	edgy, 0	1,2,3	1, 2, few 3	2-3
C11	Generic deposit	0.1/0.01/0.6	Most: Yellow, Few: black, brown, red, white	edgy, 0	1,2,3	1,2	2-3
L2	Mass deposit 2	0.03/0.01/0.15	Most: yellow, Few: black, white, red	edgy	1,2,3	1, few 2	3-4
C10	Mass deposit 2	0.05/0.01/0.15	Most: yellow, Few: Red, brown, white, black	0	1,2	1, 2	2
D8	Mass deposit 2	0.05/0.01/0.2	Most: white, Few: Red, brown, black, yellow	edgy, 0	1,2, few 3	1,2, few 3	1
C9	Generic deposit	?/0.01/0.4	Most: Yellow, Few: red, brown, white, black	edgy, 0	1,2,3	1,2	3
C8	Generic deposit	0.07/0.01/0.4	Most: Yellow, white, Few: Red, brown, black	edgy, 0	1,2,3	1,2	2
L1	Mass deposit 1	0.05/<0.01/0.1	Most: yellow, black, brown, Few: red	0, 1	1,2,3	1,2	2
C7	Mass deposit 1	<0.01/<0.01/0.05	Most: yellow, Few: black, red, brown	-	-	-	-
D7	White silt	0.01/0.01/0.3	Most: Yellow, Few: Black, brown, red, white	-	-	-	1
D6	Brown sand	0.07/0.01/0.3	Most: Yellow, white, Few: Black, brown, red	edgy, 0	1, 2, 3	1,2,3	2
D5	Back Sand	0.5/0.01/1	Most: Black, white, grey, Few: brown, red	edgy, 0	1, 2	1	3
C6	Back Sand	0.4/0.1/0.8	Most: Black,, Few: Red, yellow, white, grey	0, 1	2	1, few 2	3
C5	Generic deposit	<0.01/<0.01/0.05	Most: Whitish yellow, Few: Black, Red	-	-	-	1
C4	Back sand	0.4/0.2/1	Most: Black, Grey, Few: Red, yellow	edgy	2	1, few 2	4
D4	White silt	0.01/0.01/0.1	Most: White, Few black, yellow, brown	-	-	-	1
D3	Brown sand	0.05/0.01/0.2	Most: White, yellow, Few: Red, brown, black green	edgy, 0	1,2,3	1, few 2	2-3
C3	Generic deposit	0.05/0.01/0.1	Most: Whitish yellow, Few: Pure yellow, red, brown	edgy, 0	1,2,3	1, few 2,3	2
C2	Generic deposit	0.05/0.01/0.4	Most: whiteish yellow, Few: reddish yellow, black	edgy, 0	1,2,3	1,2,3	3
D2	White silt	0.01/0.01/0.1	Most: bright yellow, Few black, brown, red	-	-	-	1
D1	Brown sand	0.1/0.01/0.3	Most: white, yellow., Few red, brown, black, green	edgy, 0	1,2,3	1,2,3	3
C1	Generic deposit	0.1/0.01/0.25	Most: Bright yellow, Few: Reddish yellow, black	edgy, 0	1,2,3	1,2,3	3-4

Modern lake equivalent



OSL input data and extended results

Sample	Method	Location			Radionuclide concentration			Total dose rate (Gy/ka)	CAM[b] uncorrected De (Gy)	OD (%)	Fading g_{2days} (%/decade)	Age (ka)
		Altitude (masl)	Lat. (°S)	Long. (°W)	K (%)	U (ppm)	Th (ppm)					
OSL1	IR50	1770	17.6543	70.3113	1.85 ± 0.09	1.80 ± 0.09	8.30 ± 0.42	3.18 ± 0.16	189.13 ± 13.8	20.3	6.23 ± 0.13	120 ± 12
OSL2	IR50	1801	17.6543	70.3113	1.58 ± 0.08	1.62 ± 0.08	7.73 ± 0.39	2.98 ± 0.16	120.04 ± 7.54	18.4	10.64 ± 0.25	212 ± 127
OSL1	pIRIR225	1770	17.6543	70.3113	1.85 ± 0.09	1.80 ± 0.09	8.30 ± 0.42	3.18 ± 0.16	372.55 ± 33.48	20.3	1.34 ± 0.25	133 ± 14
OSL2	pIRIR225	1801	17.6543	70.3113	1.58 ± 0.08	1.62 ± 0.08	7.73 ± 0.39	2.98 ± 0.16	216.31 ± 9.72	18.4	4.42 ± 0.73	115 ± 16

High fading rates for IR50 results, massive error for IR50 OSL-2

→ Excluded from interpretation

Cosmo input data and extended results

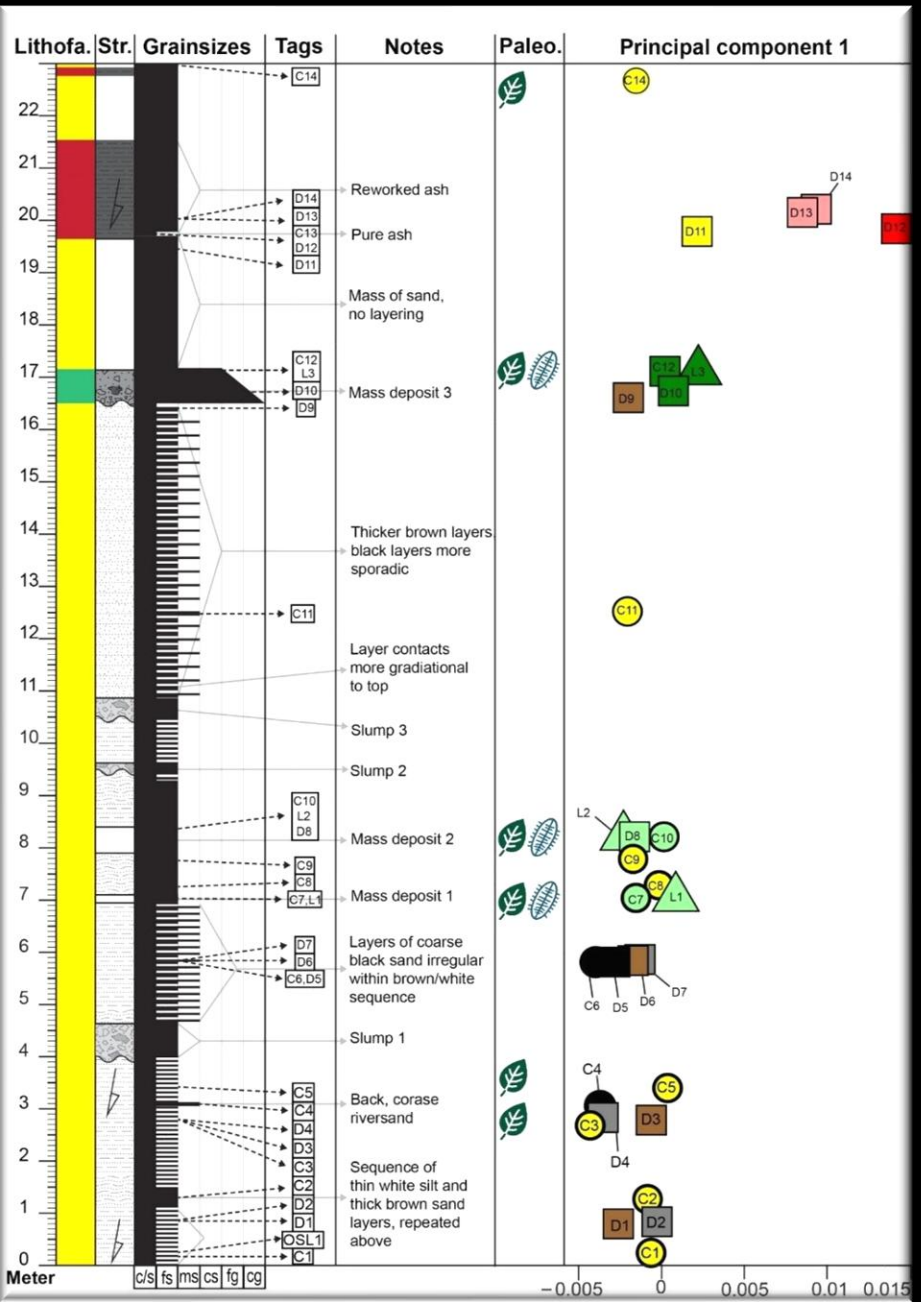
Label	Latitude (°S)	Longitude (°W)	Elevation (m a.s.l.)	Thick. (cm)	Sheild. factor	Mass (g)	^{9}Be (10^{19} at)	^{10}Be counts	$^{10}Be/^{9}Be$ (10^{-14})	^{10}Be [a] (10^{6} at.g^{-1})	Age [b] (ka)
urface exposure dating											
PE-23	-17.6568	-70.31133	1768	5	0.961	1.855	3.09	65	1.75 ± 0.23	0.24 ± 0.04	29 ± 5 (4)
PE-24	-17.65668	-70.31074	1791	1	0.984	1.704	3.09	236	6.04 ± 0.40	1.04 ± 0.07	115 ± 9 (7)
PE-25	-17.65674	-70.31047	1802	4	0.979	6.348	3.04	477	39.59 ± 2.35	1.87 ± 0.11	222 ± 20 (14)
PE-26	-17.65675	-70.3101	1820	5	0.981	3.996	3.04	509	48.5 ± 2.39	3.66 ± 0.18	502 ± 37 (24)
epth profile											
PE-27-1	-17.65457	-70.31109	1808	5	0.986	3.025	2.74	411	33.46 ± 1.73	2.99 ± 0.16	-
PE-27-2	-17.65457	-70.31109	1808	5	0.986	5.205	2.74	396	67.89 ± 3.54	3.55 ± 0.19	-
PE-27-3	-17.65457	-70.31109	1808	5	0.986	3.54 0	2.73	167	37.90 ± 2.97	2.88 ± 0.23	-
PE-27-4	-17.65457	-70.31109	1808	5	0.986	5.313	2.74	1051	25.65 ± 0.85	1.29 ± 0.04	-
PE-27-5	-17.65457	-70.31109	1808	5	0.986	4.892	2.73	241	32.61 ± 2.14	1.79 ± 0.12	-
PE-27-6	-17.65457	-70.31109	1808	5	0.986	5.216	2.74	629	37.49 ± 1.62	1.94 ± 0.09	-
PE-27-7	-17.65457	-70.31109	1808	5	0.986	6.660	2.74	684	58.19 ± 2.41	2.37 ± 0.10	-
PE-27-8	-17.65457	-70.31109	1808	5	0.986	5.093	2.73	186	57.48 ± 5.41	3.06 ± 0.29	-

Label	Measured ^{10}Be (10^{6} at.g^{-1})	Inheritance [a] (10^{6} at.g^{-1})	Denudation rates (m.Ma^{-1}) [b]	
			~1800 m a.s.l.	~2500 m a.s.l.
PE-27-1	2.99 ± 0.16	1.9 (65%)	3	2
PE-27-2	3.55 ± 0.19	2.8 (79%)	2	1
PE-27-3	2.88 ± 0.23	2.2 (79%)	2	2
PE-27-4	1.29 ± 0.04	0.9 (66%)	7	5
PE-27-5	1.79 ± 0.12	1.4 (78%)	4	3
PE-27-6	1.94 ± 0.09	1.7 (90%)	3	2
PE-27-7	2.37 ± 0.10	2.3 (96%)	2	2
PE-27-8	3.06 ± 0.29	3.0 (98%)	2	1

[a] Calculated subtracting the theoretical ^{10}Be concentration expected for a 115 kyrs old profile (see **Error! Reference source not found.** and text for details). Percentage relative to the measured value is provided between brackets.

[b] Denudation rates calculated considering the inherited ^{10}Be and scaled for two scenarios of elevation of sediment source.

LOG-A / Main Outcrop

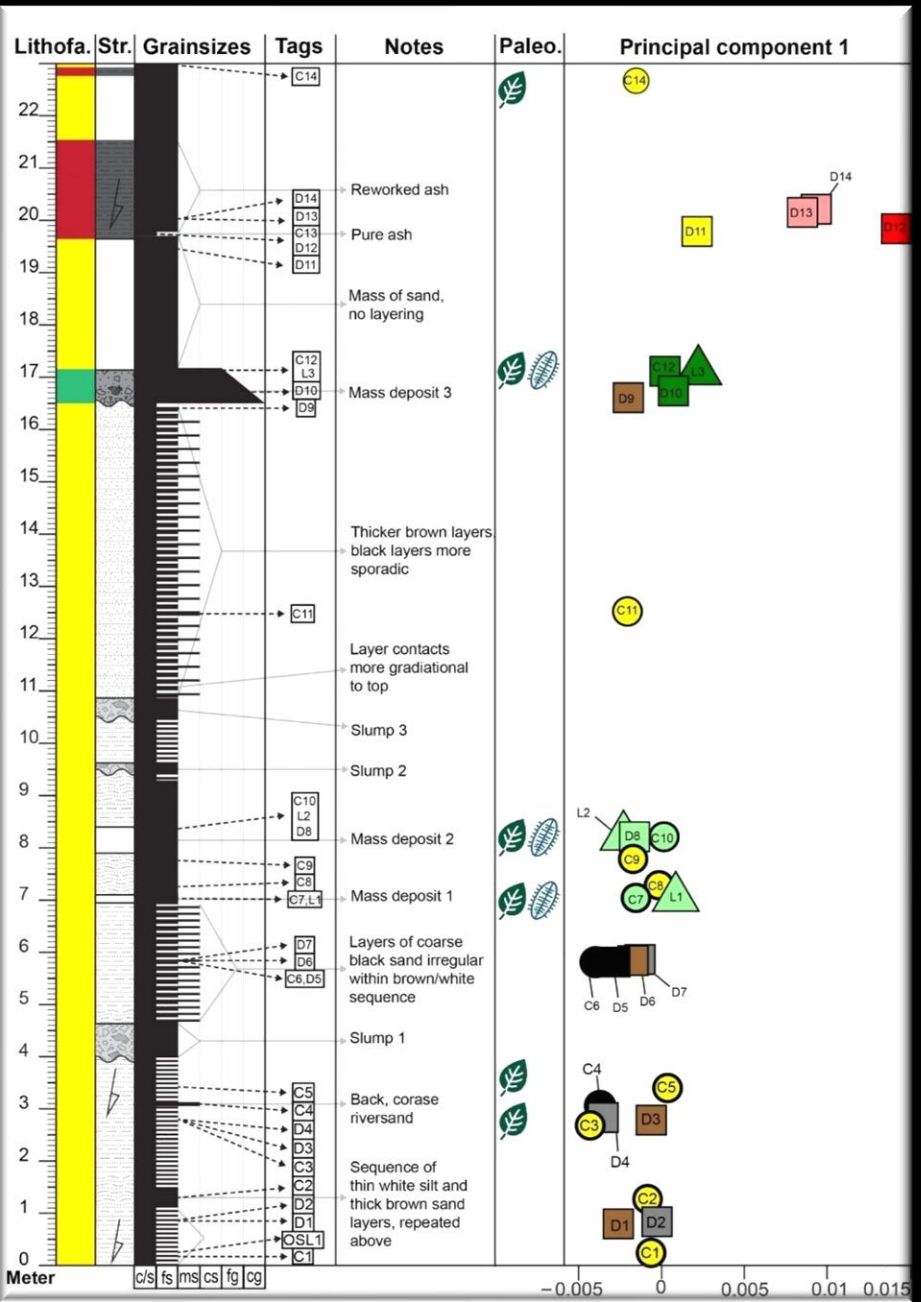


Extended pollen results

Samp.	Elevat. (m)	Sum total	Sum total, no Charcoal	Sum Charcoal	Sum Fungi	Sum Spore	Sum Pollen	IZ
C14	23	210	16	194	9	2	-	5
C12	17	126	5	121	2	2	1	-
L3	17	74	74	-	-	3	71	-
L2	8.18	35	35	-	-	6	29	-
C10	8.18	112	6	106	4	1	1	-
C7	7.02	196	10	186	6	1	3	-
C5	3.41	37	30	7	12	17	-	1
C3	2.7	38	11	27	5	6	-	-

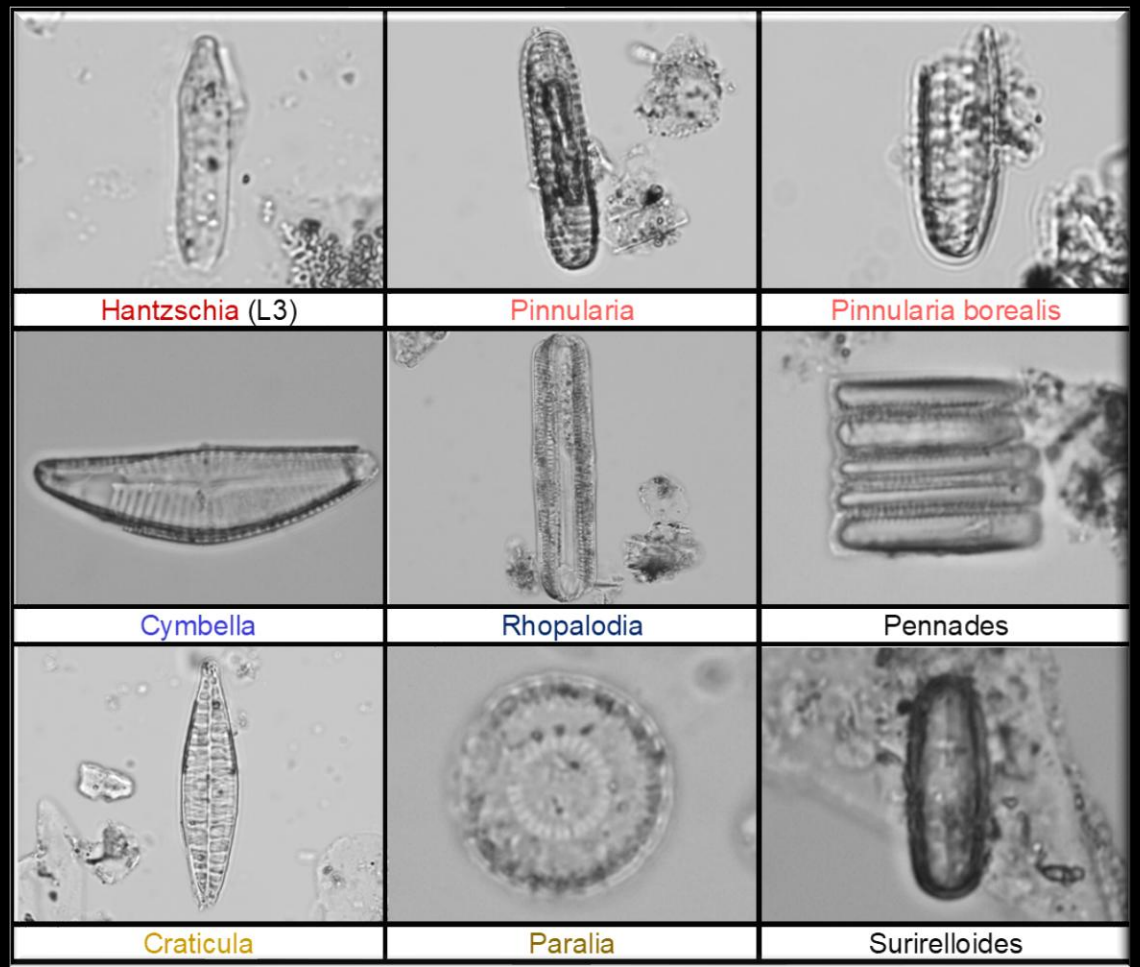
Sample	Taxa
C14	Nigrospora, **Polypodiisporites**
C12	*Cyperopollenites*, **Sporomorfo**, Nigrospora
L3	*Clavainaperturidites, Clavapollenites, Cyperopollenites,* ***Deltoidospora****, Echistephanocolporites, Echistephanoporites, Echitricolp(or)ites, Foveomonocolpites, Foveotricolpites, Heterocolpites, Ladakipollenites, Leavigatosporites, Malvacipollis, Monoporites, Perisyncolpites, Polylepis,* **Polypodiisporites**, *Psilamonocolpites, Psilaperiporites, Psilapollenites, Psilatricolporites, Psilatriporites, Psilatriporites, Retitricolporites, Rhoipites, Rugustephanoporites*
C10	*Cyperopollenites,* **Laevigatosporites**, Spore indet, Tetraploa, Nigrospora
L2	*Clavainaperturites, Clavatricolporites, Cyperopollenites, Echistephanocolporites, Echistephanocolporites, Ephedripitesmout,* **Laevigatosporites**, *M. annulatus, Monoporopollenites,* **Perinomonoletes**, *Perisyncolpites, Podocarpus , Polylepis,* **Polypodiisporites**, *Psilatricolporites, Rhoipites, Striostephanoporites*
C7	*Cyperopollenites, Echitriporites,* Nigroespora, *Podocarpus , Sporomorfo,* Tetraplo
C5	Fungi hifa, Nigrospora, **Polypodiisporites**, Tetraploa, **Verrumonoletes**
C3	Nigrospora, **Polypodiisporites**
C3	Nigrospora, **Polypodiisporites**

LOG-A / Main Outcrop



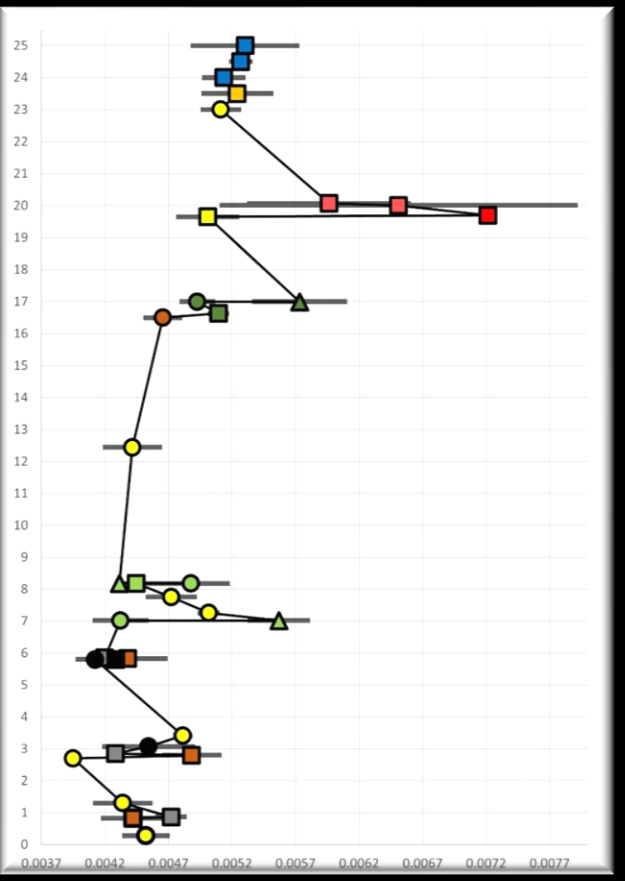
Extended diatom results

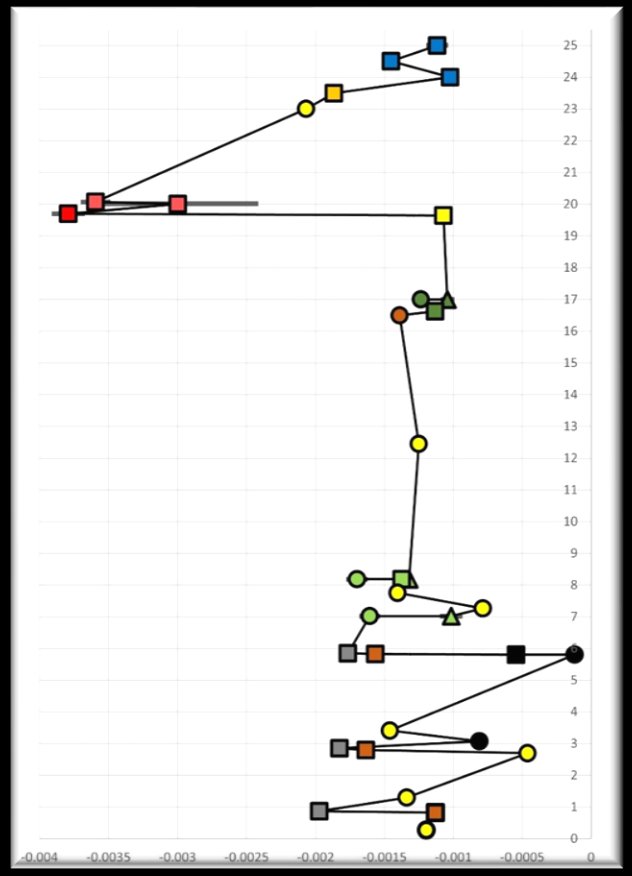
Sample	Elevation (m)	Amount	Species
L3	16.8	4	Craticula, Hantzschia, Pennades, Surirelloides
L2	8.2	3	Hantzschia, Pinnularia (borealis) (2x)
L1	7	16	Agulacodiscus, Cymbella(2x), Cymbopleura, Epithemia, Hantzschia, Ident, Paralia, Pennades, Pinnularia (borealis) (4x), Rhopalodia, Surirelloides (2x)

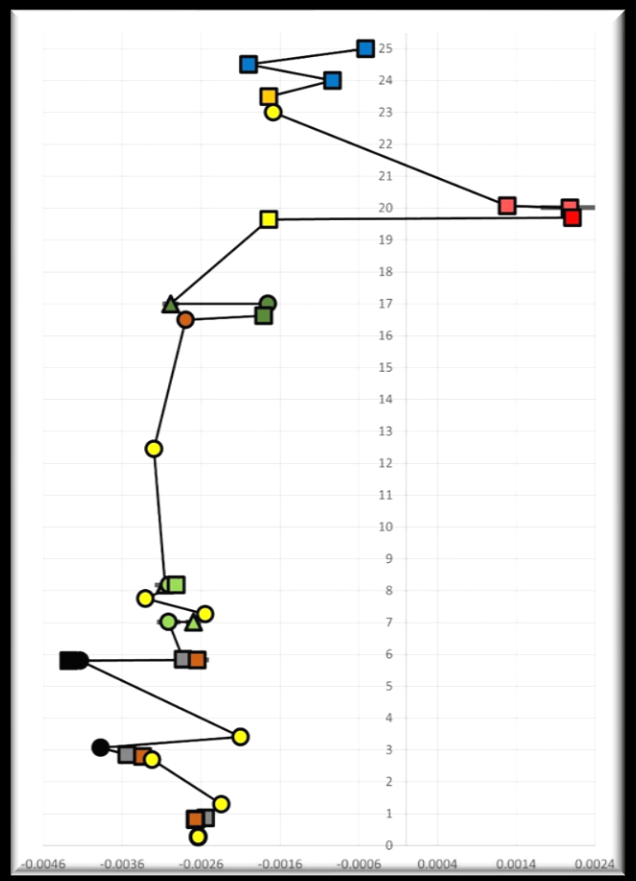


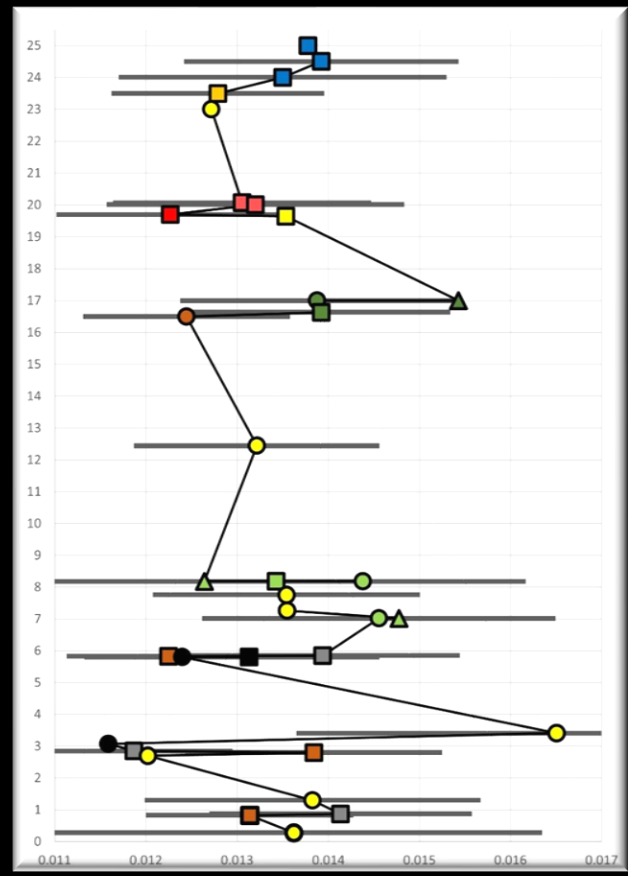
Extended XRF results

Meter









Normalized CPS

Titanium

Potassium

Calcium

Barium