

# SUPPORTING EVIDENCE FOR A LARGE ROCK FALL $9.6 \pm 1$ KA FROM GLACIER POINT IN YOSEMITE VALLEY, CALIFORNIA



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## ABSTRACT

Large boulders exceeding  $10\text{ m}^3$  in exposed volume are widely scattered throughout Upper Pines Campground in eastern Yosemite Valley, Yosemite National Park, California. These enigmatic boulders rest up to 330 m from the base of adjacent talus slopes but lack geomorphic expression typical of other large rock fall, debris flow, or glacial deposits in Yosemite. We evaluated four hypotheses for boulder deposition: (1) glacial transport during ice retreat 15–17 ka, (2) fluvial deposition during a high discharge flood event, (3) debris flow deposition, and (4) rock fall deposition. We utilized field mapping, spatial analysis, cosmogenic  $^{10}\text{Be}$  exposure dating, and X-ray fluorescence analysis to investigate possible modes of deposition. A mean boulder exposure age of  $9.6 \pm 1$  ka considerably post-dates glacial retreat from Yosemite Valley, effectively ruling out glacial deposition. Discharge and bed stress calculations indicate that although flooding was capable of entraining boulders at confined upstream locations, it is unlikely to have transported boulders as far as the Upper Pines area. Slope comparisons and evaluation of surface morphology of debris flow fans in Yosemite Valley suggest that the boulders did not result from debris flows. Geochemical results identify a majority of boulders in Upper Pines as granodiorite of Glacier Point, corresponding to bedrock samples located at the summit of Glacier Point. We interpret boulders in Upper Pines Campground to result from a single large rock fall event originating from the east face of Glacier Point circa  $9.6 \pm 1$  ka, and subsequently partially buried by alluvial fan aggradation, modifying the original geomorphic expression.

## INTRODUCTION

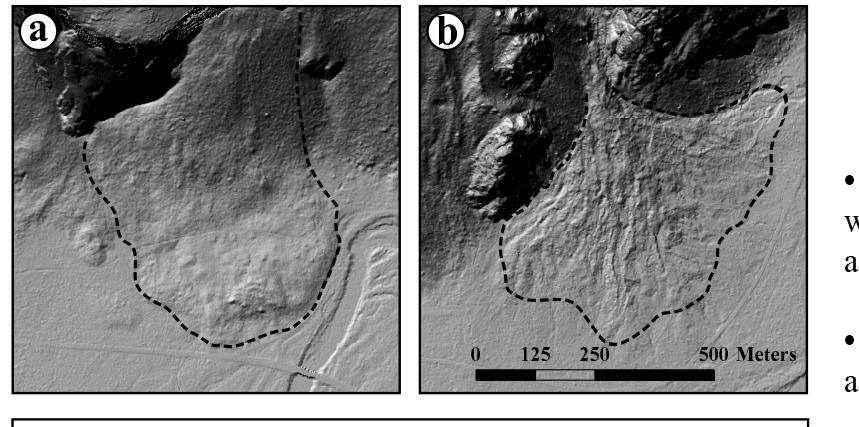
Yosemite Valley is a glacially carved valley of Late Cretaceous granitic plutons (Batemann, 1992) that have undergone multiple episodes of Pleistocene glacial erosion (Fig. 1; Matthes, 1930; Huber, 1987). Glaciation presumably left the valley floor free of detritus; slope and fluvial processes have since created extensive talus fields and fans (Fig. 2; Wieczorek and Jäger, 1996).

More than 925 rock fall and slope movements have been documented in Yosemite National Park since 1857 (Stock et al., 2013). Of particular interest are large boulder deposits (up to several million cubic meters in volume) with low surface slope angles that extend far beyond the base of talus slopes (Fig. 2a). These deposits are interpreted to represent extremely large and energetic rock falls, referred to as rock avalanches (Wieczorek et al., 1999; Stock and Uhrhammer, 2010).

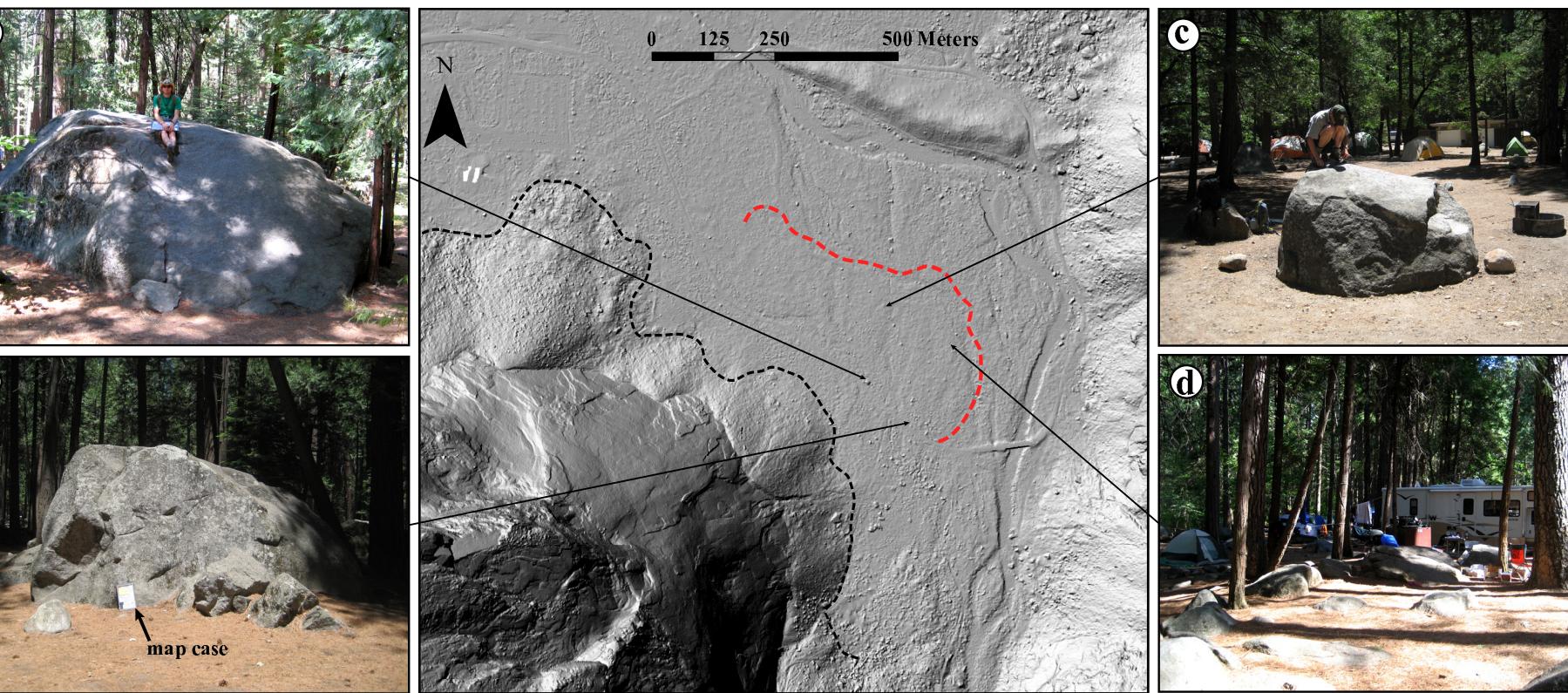
A deposit of widely scattered boulders lacking the morphology of a glacial, rock fall, or fluvial deposit, rests on the alluvial fan surface of Upper Pines Campground (Fig. 3).

**GEOLOGIC SETTING**  
Hypothesis 1: Glacial Deposit (reject)  
• Two primary bedrock units - Half Dome Granodiorite, and granodiorite of Glacier Point - Inferred subunit of leucocratic Half Dome Granodiorite (Fig. 4)  
• Half Dome Granodiorite bedrock exposure continues ~15 km up drainage - Could be found in glacial, rock fall, fluvial, and debris flow deposits  
• Granodiorite of Glacier Point exposed on Glacier Point and up Illilouette Creek - Could be found in rock fall, fluvial, or debris deposits but not glacial deposits - Illilouette drainage free of ice during LGM (Alpha et al., 1987)  
• Leucocratic facies of Half Dome Granodiorite is part of a mafic-felsic lithologic cycle mapped west of Tenaya Lake by Coleman et al. (2012)  
- Sharp western leucocratic contact that grades into an eastern mafic margin - Generally thin and discontinuous bodies; subparallel to the outer contact

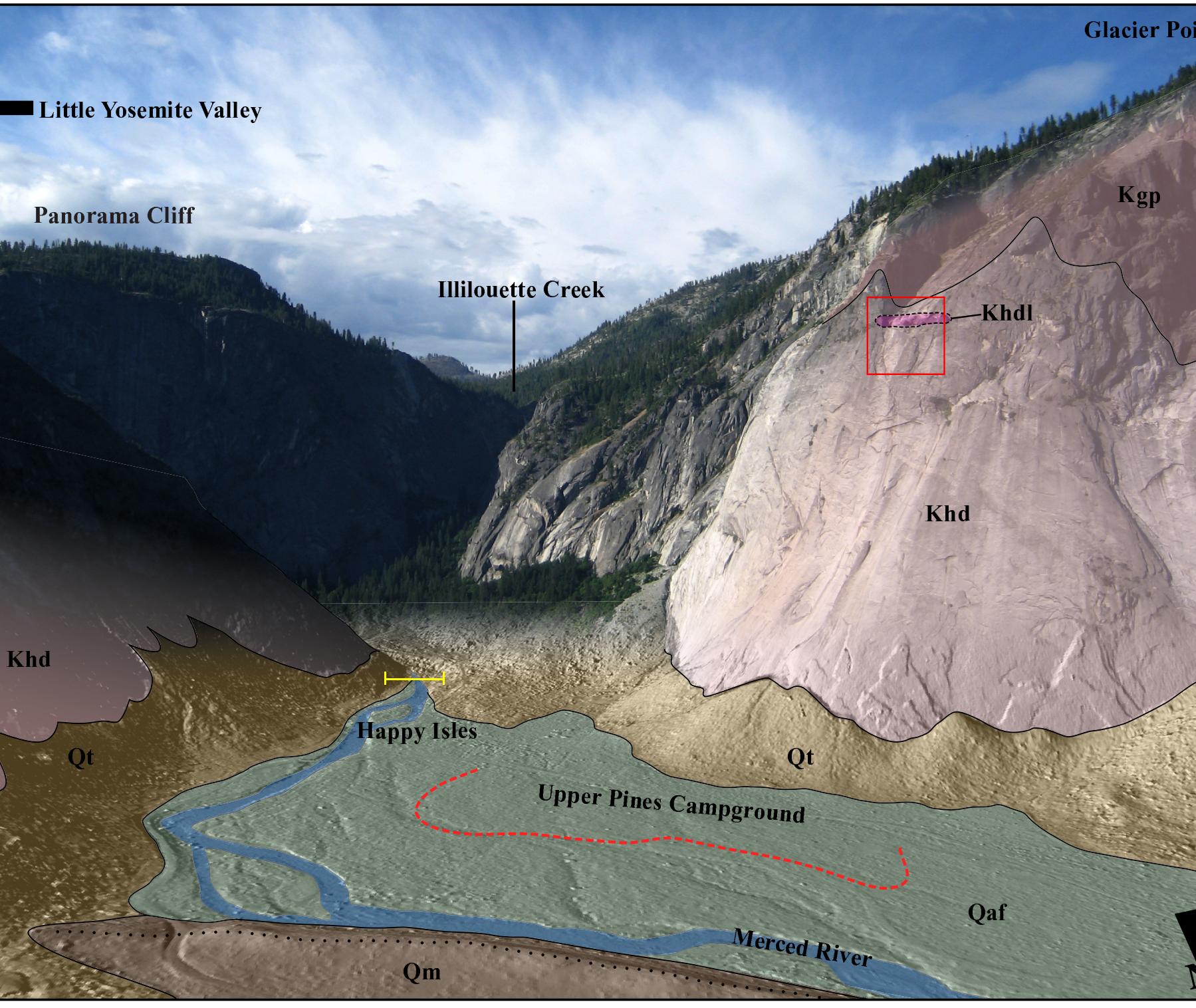
**Late Quaternary History**  
• LGM glacier was present between 28 and 14.5 ka and is thought to have terminated west of Bridalveil Fall (Fig. 1; Huber, 1987; Bursik and Gillespie, 1993; Phillips et al., 2009; Rood et al., 2011).  
• Prominent recessional moraine near El Capitan dammed melting ice water and created a shallow lake (Fig. 1; Matthes, 1930; Huber and Snyder, 2007).  
• Alluvial sedimentation advanced a delta westward infilling the lake and creating a topography. (b) Eagle Creek debris flow fan; note the well-defined fan extruding out into Yosemite Valley and rough channelized surface.



**Figure 2.** Hillshade of: (a) El Capitan Meadow rock avalanche; note the distinct distal edge and hummocky topography; (b) Eagle Creek debris flow fan; note the well-defined fan extruding out into Yosemite Valley and rough channelized surface.



**Figure 3.** Hillshade of Upper Pines Campground boulder deposit/alluvial fan surface and photo locations. The dashed red line indicates the extent of mapped boulders and the black dashed line indicates the location of the active talus slope. Compare this hillshade with Figure 2a and 2b and note the lack of pronounced geomorphic expression in Upper Pines Campground. (a) Boulder UPC-4, yielding a cosmogenic nuclide exposure age of  $5.7 \pm 0.1$  ka; (b) UPC-1, yielding an exposure age of  $10.23 \pm 0.23$  with an exposed height of 3.5 m; (c) Boulder UPC-5, yielding an exposure age of  $8.9 \pm 0.8$  ka and 1.4 m in exposed height. (d) Note the inset appearance of these boulders within the fan surface.



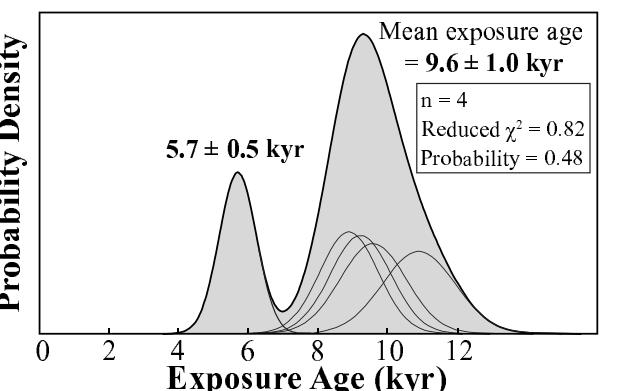
**Figure 4.** Photo of Glacier Point viewed from the northeast and overlain upon a hillshade produced from a 1 m LiDAR DEM, exposing the bare earth topography of the Upper Pines Campground alluvial fan. Granodiorite of Glacier Point/Half Dome Granodiorite boundary is from Peck (2002). Dashed red line marks the approximate boundary of mapped boulders within Upper Pines Campground; black dotted line represents the moraine crest; yellow line represents the cross section used for paleodischarge and shear stress calculations. Qaf - alluvial fan, Qt - active talus, Qm - LGM moraine, Khd - Half Dome Granodiorite, Khd - leucocratic Half Dome Granodiorite, Kgp - granodiorite of Glacier Point. Red box indicates location of Fig. 5 xRez imagery.

## METHODS

- Hand and GPS mapped 270 boulders visually estimated  $>1\text{ m}^3$ . Measured boulder dimensions as a cube and imported dataset into ArcMap GIS
- Sampled 5 boulders in campground for cosmogenic beryllium-10 exposure ages
- Collected 36 hand samples for XRF analysis - 8 bedrock samples of granodiorite of Glacier Point, 6 bedrock samples of Half Dome Granodiorite, 22 from boulders in Upper Pines Campground
- Mapped inferred leucocratic zone using high-resolution xRez imagery (Fig. 5)

## RESULTS

- Boulder metrics increase from NW to SE (Fig. 6)
- Excluding UPC-4, 4 out of 5 boulders sampled for  $^{10}\text{Be}$  are between  $8.9 \pm 0.8$  and  $10.9 \pm 1.0$  ka. - Mean age  $9.6 \pm 1$  ka (Fig. 7; Table 1)
- XRF analysis indicate multiple boulder lithologies within bedrock ranges (Fig. 8)



**Figure 7.** Probability density distributions of  $^{10}\text{Be}$  exposure ages for campground boulders with summary statistics. Results indicate two events;  $5.7 \pm 0.5$  ka and  $9.6 \pm 1$  ka. Retreat of the LGM glacier from Yosemite Valley is inferred to have occurred 15–17 ka.

## DISCUSSION

### Hypothesis 1: Glacial Deposit (reject)

- All ages considerably post date the inferred timing of deglaciation
- Absence of large Cathedral Peak Granodiorite boulders as seen within Yosemite Valley glacial deposits
- Excluding UPC-4, we interpret a single depositional event at  $9.6 \pm 1$  ka

### Hypothesis 2: Flood Deposit (reject)

- Calculated discharge and flow velocity using the Manning's Equation with cross section depths of 5m, 10m, and 15m (Table 2)
- Used UPC-1 and 4 to represent boulder diameter for critical shear stress needed for entrainment (Fig. 3b and 3c)
- Critical shear stress achieved at the cross section; however, flow is unlikely to maintain water depths required for entrainment on open fan; UPC-4 located ~1 km from cross section
- Intact moraines in Little Yosemite Valley suggest the required discharge has not occurred

- Merced River cutbank adjacent to the campground exposes the interior of the alluvial fan (Fig. 9). We interpret boulders  $<1\text{ m}^3$  as fluvially deposited but not boulders  $>1\text{ m}^3$

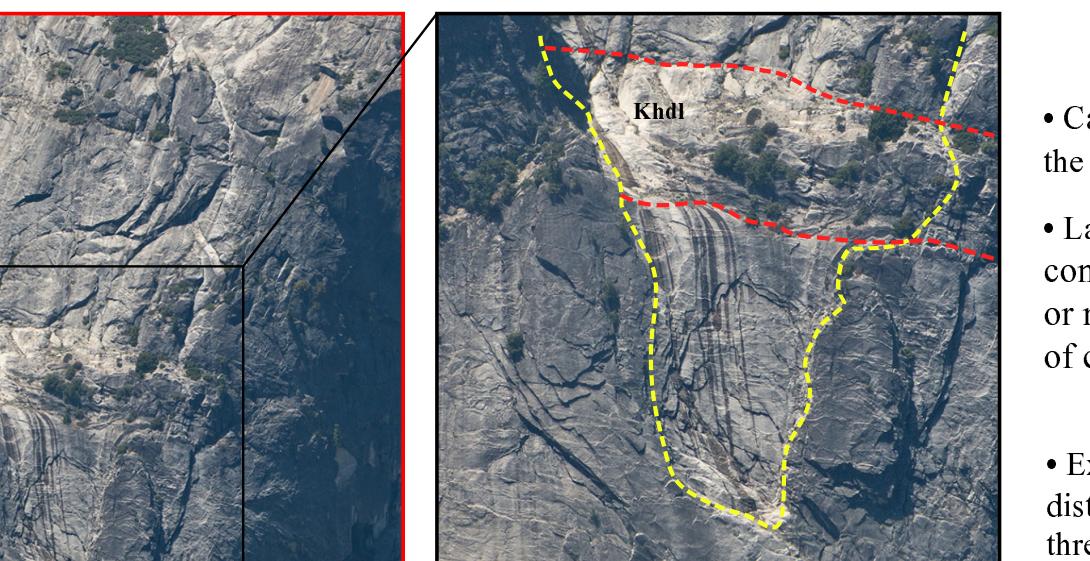
### Hypothesis 3: Debris Flow Deposit (reject)

- Campground fan surface slope is  $0.8^\circ$ , contrasting with the  $7^\circ$  to  $24^\circ$  of other recognition debris fans (Fig. 2b)
- Lack of debris flow morphology, e.g. distinguishable cone-shaped, rough channelized surface with V-shaped or rectangular channel cross sections, and lateral ridges of coarse rock debris (Bertolo and Wieczorek, 2005)

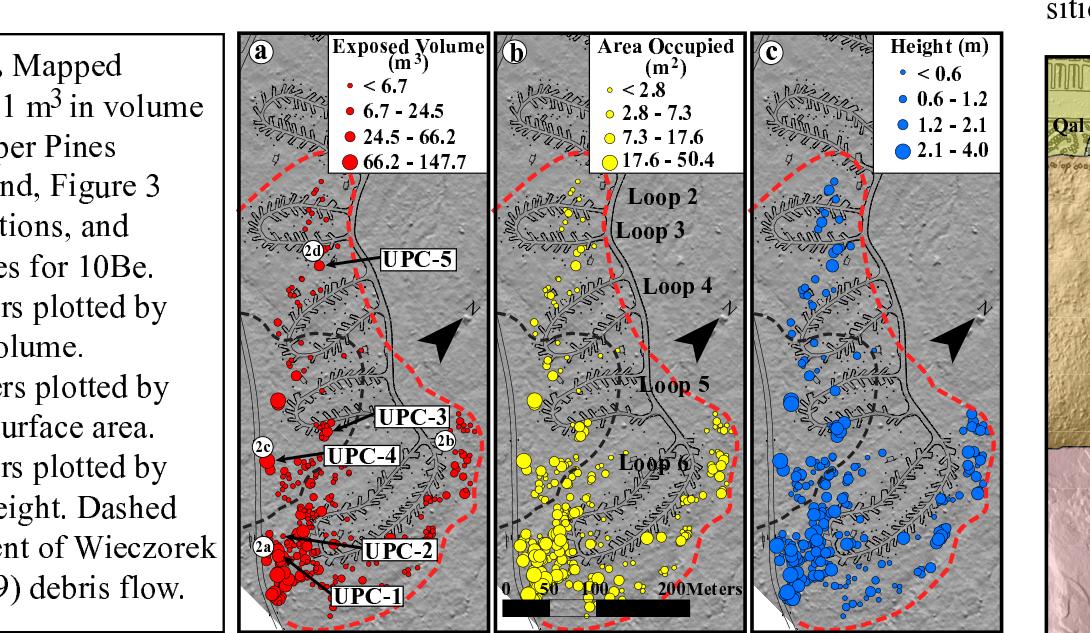
### Hypothesis 4: Rock Fall Deposit (accept)

- Exposure ages for boulders of known lithology (UPC-1, 2, 4, and 5), boulder maximum distance of ~500 m from cliff face, inferred leucocratic zone support, and scar crossing three lithologic units support a single rock fall event at  $9.6 \pm 1$  ka (Fig. 10)
- Lack of characteristic rock fall surface morphology best explained by aggradation of the valley floor. Radiocarbon samples collected ~1.7 km NW of the campground overlap exposure ages within analytical uncertainty and indicate  $>2.5$  m of alluvial fill after deposition of radiocarbon samples (Fig. 11)

**Figure 8.** Harker variation diagrams of XRF analysis. Boulders sampled for  $^{10}\text{Be}$  (red diamonds) fall within Khd and Kgp bedrock ranges as do others samples collected in the Upper Pines Campground (blue squares).



**Figure 5.** xRez imagery of Glacier Point. See Fig 4 for photo location. Dashed yellow = massive scar (possible source area); dashed red = inferred Khd.



**Figure 6.** Mapped boulders  $>1\text{ m}^3$  in volume within Upper Pines Campground, Figure 3 photo locations, and sample sites for  $^{10}\text{Be}$ . (a) Boulders plotted by exposed volume. (b) Boulders plotted by occupied surface area. (c) Boulders plotted by exposed height. Dashed line is extent of Wieczorek et al. (1999) debris flow.

Sample	Lat/Long (N/W)	Elevation (m)	Thickness (cm)	$^{10}\text{Be}$ Production rate (atoms/yr)	Shielding factor	Erosion rate (m/yr)	Mass (kg)	$^{10}\text{Be}$ carrier (mg)	$^{10}\text{Be}$ concentration ( $\times 10^{-12}$ atoms/m²)	Exposure age (ka)
UPC-1	37.7327/119.5608	1226	4	9.69	0.269	0.00065	99.780	0.3897	3.95	$10.9 \pm 1.0$
UPC-2	37.7330/119.5606	1225	3.5	9.85	0.269	0.00065	99.590	0.3913	3.54	$9.59 \pm 0.95$
UPC-3	37.7324/119.5617	1222	3	9.76	0.269	0.00065	100.068	0.4090	3.25	$9.23 \pm 0.87$
UPC-4	37.7336/119.5610	1223	4.5	9.44	0.268	0.00065	100.495	0.4069	2.02	$5.71 \pm 0.53$
UPC-5	37.7336/119.5616	1218	2	9.82	0.269	0.00065	94.103	0.4080	2.98	$8.99 \pm 0.84$

**Table 1.** Cosmogenic  $^{10}\text{Be}$  data and exposure ages for campground boulders

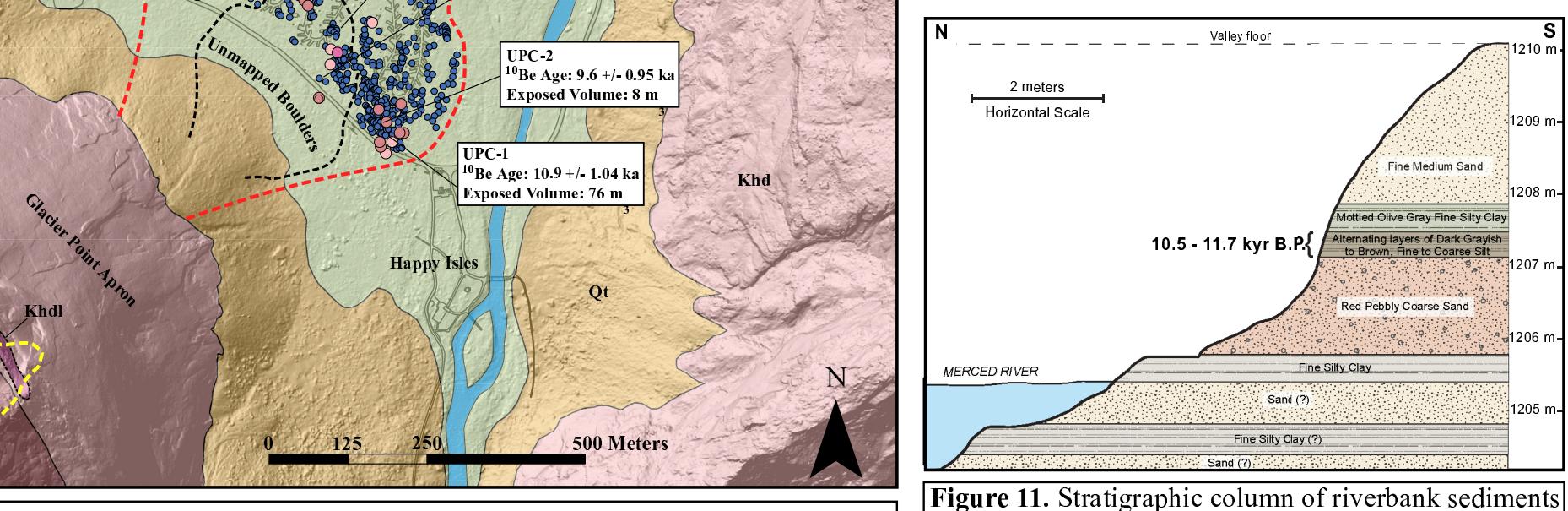
## DISCUSSION CONTINUED

### Hypothesis 4: Rock Fall Deposit (accept)

- Exposure ages for boulders of known lithology (UPC-1, 2, 4, and 5), boulder maximum distance of ~500 m from cliff face, inferred leucocratic zone support, and scar crossing three lithologic units support a single rock fall event at  $9.6 \pm 1$  ka (Fig. 10)
- Lack of characteristic rock fall surface morphology best explained by aggradation of the valley floor. Radiocarbon samples collected ~1.7 km NW of the campground overlap exposure ages within analytical uncertainty and indicate  $>2.5$  m of alluvial fill after deposition of radiocarbon samples (Fig. 11)



**Figure 9.** Merced River cut bank exposing the interior of the alluvial fan near Upper Pines Campground.



**Figure 10.** Mapped boulder locations, lithologies, and exposure ages. Dashed yellow delineates a possible rock fall source area within a topographic gap that crosses the three lithologic units represented in mapped boulders; dashed black line is the extent of Wieczorek et al. (1999) mapped debris flow; dashed red line is the inferred extent of the 9.6 ± 1 ka rock fall event. Qaf - alluvial fan, Qt - active talus, Qm - LGM moraine, Khd - Half Dome Granodiorite, Khd - leucocratic Half Dome Granodiorite, Kgp - granodiorite of Glacier Point.

## ACKNOWLEDGMENTS

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