A Preliminary Investigation of Cave Ice at Lava Beds National Monument, northern California

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Abstract

Although perennial ice commonly occurs in caves in Lava Beds National Monument, northern California, USA, very little is known about its age, origin, or potential to preserve information about past environmental conditions. Measurements of radiocarbon in wood samples in Caldwell Cave indicate that ice at about ~2m depth was deposited in late 1200 to late 1300 AD. Coring did not reach bedrock, and ice thicknesses in the area are often unknown, leaving the possibility that much older ice is present. Radiocarbon and tritium measurements at shallower depths in Caldwell Cave and Cox Cave indicate near surface ice was deposited in the late 1960s. Stable isotope measurements in four caves (Cox, Caldwell, Skull, and Crystal) are consistent with nearby measurements of rainwater, consistent with the hypothesis that cave ice forms by freezing of rainwater runoff and seepage of groundwater in to lava tubes.

1 Introduction

Ice deposits in caves are increasingly recognized as a potential archive of paleoclimate information (e.g., [*May et al.*, 2011] [*Persoiu and Pazdur*, 2011] [*Stoffel et al.*, 2009] [*Luscher et al.*, 2004])although the cave ice depositional environment can be complex, making interpretation of cave ice records difficult. Here we report preliminary data from extensive, but little studied, ice deposits at Lava Beds National Monument in Northern California, USA (Figure 1), providing both stable isotope data and age constraints based on tritium and radiocarbon measurements.

Lava Beds National Monument is on the northern flank of Medicine Lake Volcano in Northern California, in the southern Cascade Mountain Range, near the California-Oregon border ([*Donnelly-Nolan et al.*, 2008]. Within the monument numerous basaltic and andesitic lava flows formed lava tube caves, many containing ice deposits ([*Swartzlow*, 1935] [*Knox*, 1959]). In many cases the ice is present in pools although ice stalagmites and other formations exist. Rainwater and ground water seeping in to caves or running in to cave openings is the most likely origin of the ice deposits, which form in the sub freezing environment, presumably maintained by the stratification of cold winter air ([*Swartzlow*, 1935]) with summer temperatures maintained near freezing in part due to the presence of the ice.

Mechanisms of ice formation and preservation at this site have not been studied in detail, however.

Very little is known about the extent or age of the ice deposits, or their potential to preserve information about past environmental conditions. In addition, monument staff have observed recent ice surface elevation decreases and stains on cave walls suggest higher ice levels in the past. This possibility of long-term negative mass balance raises concern that a potentially valuable scientific resource may be at risk. Here we report preliminary data from four ice caves, including radiocarbon and tritium measurements that constrain the age of several ice deposits, and $\delta^{18}O$ and δD of ice, which may provide some constraints on the origin of the deposits.

2 Sample Locations and Sampling

Ice deposits in four caves: Caldwell, Cox, Crystal, and Skull Caves (Figure 1 and Appendix), were cored to depths between 85 and 247 cm, and sections of the cores were used for measurements of stable isotopes, conductivity, and tritium levels. Table 1 lists the depth below ground surface and distance from nearest opening for each ice deposit sampled, and elevation for each cave. Radiocarbon dating was attempted on plant material found in two locations, a small twig found in the Cox Cave core and a sample of tree bark melting out a vertical wall on the edge of the ice deposit in Caldwell Cave.

Coring was conducted using a 3-inch diameter hand auger ice coring drill typically used on glaciers. We did not reach the bottom of any of the ice deposits drilled, coring was halted at each site when we reached the limit we could drill by hand, which depended on site conditions, overhead space, and available person-power and time. Ice thickness at the sites is unknown. Cores were typically recovered in approximately 10-40 cm sections (occasionally longer) packed in plastic bags, and once coring was finished quickly transported to insulated boxes containing frozen eutectic packs. Cores were kept frozen in the insulated boxes during transit to Oregon State University and stored in a walk-in freezer at -25C.

Figure 2 shows representative photographs of the collected samples, which typically exhibit layering of cleaner and more particle-rich ice, and bubble-rich and bubble-poor ice. Bubbles range in size from sub millimeter to up to a cm. Macroscopic particles are apparent in the ice and in many cases when the ice is melted these are revealed to be disseminated fine-grained sediment.

3 Results

3.1 Chronological Information

Tritium was measured in four samples, two from the Cox Cave core and two from the Caldwell Cave Core (Table 2), at the University of Miami RSMAS Tritium Laboratory. Samples were melted and filtered at Oregon State University (0.45 micron Nucleopore filters) before analysis. Tritium was detected in the two near surface samples (37-59 cm at Cox Cave, 33-47 cm at Caldwell Cave) but not in deeper samples (Table 2). To interpret the tritium results we used tritium data from Portland, Oregon rainwater (IAEA, 2012, [*Eastoe et al.*, 2012]), calculating what the tritium concentration of samples of Portland rain would be on the date of our analyses (May 1, 2011) assuming a half-life of 12.33 years (Figure 3). Data were collected in Portland starting in 1963. Due to variability in the data from Portland it is not possible to assign an extremely precise age, but it is clear that both near surface samples date to the mid to late 1960s (Figure 3). Neither sample can predate the input of anthropogenic tritium in the atmosphere, which began in 1954 ([*Eastoe et al.*, 2012]). The deeper samples (172.5-180 cm at Cox Cave, 223-230 cm at Caldwell Cave) contain no detectable tritium therefore must predate 1954.

Carbon-14 was measured in two samples at the UC Irvine Keck Carbon Cycle Facility. One sample was a twig from 59-69 cm in Cox Cave and the second a piece of bark collected at about 200 cm depth in Caldwell Cave (Figure 4 and Table 3). The bark (believed to be *Pinus Ponderosa*) was collected from a vertical ice wall that was exposed due to melting in 2011, approximately 2 meters in horizontal distance from the core location. The Cox Cave twig contained excess ^{14}C, probably from mid 20th century atmospheric thermonuclear weapons tests. If the photosynthesized atmospheric CO_2 in the twig had the same ^{14}C content as clean air in high latitude North America the twig was formed in 1963 or 1971, based on [*Hua and Barbetti*, 2007]. This result is consistent with the tritium data discussed above.

The bark sample from Caldwell Cave had a ^{14}C age of 685±20 yrs BP. Calibration of this age using INTCAL09 ([*Reimer et al.*, 2009]) yields 2-sigma age ranges of 1274-1304 AD (77.3%) and 1365-1384 AD (22.7%) (Table 3). Thus the ice at this depth was at least 629 years old in 2013, unless the bark had aged significantly on the surface before being transported to the cave (either by animals or runoff). Given its fresh appearance (Figure 2) this seems unlikely.

3.2 Stable Isotope Data

The stable isotopes of water in precipitation are often used as indicators of environmental factors including temperature and precipitation, though the controls on the isotopic ratios of precipitation are complex. We measured $\delta^{18}O$ in filtered samples (0.45 micron Nucleopore filters) in all four cores at either the OSU CEOAS Stable Isotope Laboratory (using mass spectrometry) or the OSU Institute for Water and Watersheds Collaboratory (using laser isotope spectroscopy). For Crystal Cave and Skull Cave we also measured D/H ratios. Oxygen isotope data are plotted in Figure 5 and all isotopic data are listed in Tables 4-7.

For Crystal and Skull cave there appears to be a trend toward heavier values toward the ice surface. No such trend is evident for Cox and Caldwell Caves. No rainfall isotope data are available at the Lava Beds site, but [*Ersek et al.*, 2010] report the isotopic composition of precipitation at Oregon Caves National Monument, approximately 170 km to the west, between 2005 and 2008. Their sample collection site is at 1200 m elevation, similar, but slightly lower than the elevation of the cave sites (Table 1). The mean $\delta^{18}O$ value of the Ersek et al. data set is -11 ± 4 ‰, similar to the mean value in the present data set of -10.6±1.3. The lower range of isotopic values at Lava Beds probably reflects the fact that the samples average precipitation over longer time periods than the Ersek et al. data, that precipitation is heaviest in a restricted period of the year (fall and winter) and some homogenization of the isotopic signal due to transport of water through runoff and seepage. The similarity of the mean values between the two sites is consistent with earlier work on trends in the isotopic composition of rainfall across northern California ([*Ingraham and Taylor*, 1991]). We have not studied the site in enough detail to discern if there is an interpretable impact of isotopic fractionation during freezing, as described by [*Perşoiu et al.*, 2011].

The δD and $\delta^{18}O$ data for Crystal Cave and Skull Cave plot near, but below the global meteoric water line ($\delta D=8x\delta^{18}O+10$) and linear fits to these data have similar slopes and intercepts (Figure 6). [*Ingraham and Taylor*, 1991]) made a similar observation for the isotopic composition of rainfall across northern California.

4 Discussion and Conclusions

This preliminary investigation suggests that relatively old ice, formed between 1297 and 1394 AD, is preserved as close as 2 m from the ice surface at Caldwell Cave. Because the ice thickness at this site is not known it is possible that substantially older ice may also be present in this and other caves. Drilling deeper at this and other sites and further efforts to find material for ^{14}C dating are certainly warranted. Ground penetrating radar may allow determination of ice thickness (see [*Hausmann and Behm*, 2010]). It may also be possible to date disseminated fine-grained organic matter, and this should be investigated.

Tritium data indicate that near surface ice was deposited in the late 1960s in Cox Cave and Caldwell Cave. The age of the very surface ice is not yet known, but tritium measurements could be used to establish if there has been significant melting or non-deposition since the late 1960s. Very recently deposited ice should have low tritium concentrations. Detailed profiles of tritium or possibly other radionuclides like ^{210}Pb or ^{137}Cs could provide additional age information. Deposition of ice may be episodic and could be separated by periods of melting, therefore detailed age information will be needed to interpret environmental records from the ice.

The stable isotopic composition of the Lava Beds ice caves (Figures 5-6 and Tables 3-7) is consistent with modern measurements of the isotopic composition of precipitation further to the west, at Oregon Caves National Monument (Ersek et al., 2010). Because the ages of the cores are not very well constrained it would be premature to make any climatic interpretation of the isotopic data, although we note the somewhat more negative $\delta^{18}O$ values at deeper depths in Skull, Crystal, and Cox Caves. In future it may be possible to use the stable isotopes as an indicator of temperature change in this region ([*Ersek et al.*, 2010; *Ersek et al.*, 2012]) though further study of the modern isotopic system at the Lava Beds site would be needed to fully characterize its sensitivity to temperature and other factors that control stable isotope ratios in precipitation, including rainfall amount, air mass trajectory, and variations in humidity.

The preliminary data presented here suggest that a more comprehensive program of drilling, radiometric dating and isotopic research could recover important information about the age of the Lava Beds ice deposits and information about past environmental conditions at the site over at least the last 600 years and possibly much longer.

5 Suggestions for Future Work

A comprehensive sampling of shallow coring in all accessible caves for tritium measurements could provide an indication of whether ice surfaces are currently in negative mass balance. Ice deposited now should have very low levels of tritium, and higher levels should be found in ice from the 1960s and 1970s. More detailed tritium analysis of longer cores could establish the continuity of deposition since the 1960s.

Deeper drilling is feasible with appropriate equipment to both establish ice depth and explore the deeper sections of the ice for material datable by ^{14}C. Further exploration of vertical ice walls may also yield datable material, and the possibility of dating disseminated organic material in the cores should be explored. Ground penetrating radar may also be used to map ice thicknesses.

If adequate dating is possible, the stable isotopic composition of the additional ice cores should be measured – the isotope ratios should reflect changes in the isotopic composition of rain and snow in the region, which should depend on temperature, although a comprehensive study of these ratios in modern precipitation and water seeping in to the caves would be needed.

A program of year-round monitoring of cave temperature near the ice surface, and ice levels, should be implemented. In addition, measurements of temperature profiles in boreholes drilled in the ice might provide information about the temperature history of the sites or the origin of the ice.

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Table 1. Distances from ice to nearest cave entrance, ice depth from surface, and cave elevation (m).

Cave	Distance to Entrance	Depth from Ground Surface	Elevation
Caldwell Cave	27.4	23.2	1425
Cox Cave	12.2	22.9	1390
Crystal Cave	210.3	29.6	1524
Skull Cave	152.4	24.4	1390

Table 2. Tritium measurements made in ice samples at the University of Miami. RSMAS Tritium Laboratory. Data Release 11-023. Data are normalized to May 1 2011.

Cave	Sample Depth	Tritium Content (TU)	Sample Size (g)	Estimated Age based on Portland Rainwater (AD)
Cox Cave	37-59 cm	17.8±0.7	150	Late 1960s/Early 1970s
Cox Cave	172.5-180 cm	0.12±1.3	184	Older than 1954
Caldwell Cave	33-47 cm	38.5±0.1	243	Late 1960s/Early 1970s
Caldwell Cave	223-230 cm	0.10±0.11	168	Older than 1954

Table 3. ^{14}C measurements constraining age of cave ice deposits at Lava Beds, measured at UC Irvine Keck Carbon Cycle Facility.

Cave	Sample Depth	Collection Date	Sample Type	UCIAMS#	^{14}C Age (yr BP) or Fraction Modern	Calibrated Age (yr AD)
Cox Cave	59-69 cm		Twig	85970	$F^{14}C$=1.5055 ±0.0266[a]	NA
Caldwell Cave	~200 cm	May 12, 2011	Bark	95026	^{14}C Age = 685±20 yr[b]	1274-1304 AD (77.3%) 1365-1384 AD (22.7%).

[a] This sample contains excess ^{14}C, probably from mid 20th century atmospheric thermonuclear weapons tests. If the photosynthesized atmospheric CO_2 in the twig had the same ^{14}C content as clean air from the high latitude Northern Hemisphere (Hua and Barbetti, 2004) the twig was formed in 1963 or 1971.

[b] 2-sigma range using INTCAL09 (Reimer et al., 2009) calibration.

Table 4. Oxygen isotope values for Cox Cave core. Measurements made in OSU CEOAS Stable isotope laboratory, in per mil relative to V-SMOW.

Top Depth (cm)	Bottom Depth (cm)	$\delta^{18}O$(‰)
6.0	11.0	-11.29
11.0	25.0	-10.29
25.0	37.0	-11.65
37.0	47.0	-11.30
47.0	59.0	-11.78
59.0	69.0	-11.30
69.0	83.0	-11.53
83.0	89.0	-10.76
89.0	94.0	-11.34
94.0	99.0	-12.50
99.0	112.0	-11.66
112.0	114.0	-11.03
114.0	122.5	-12.90
122.5	131.5	-12.75
131.5	134.5	-10.73
134.5	139.5	-12.49
139.5	142.5	-12.49
142.5	146.5	-12.10
146.5	155.0	-12.60
155.0	160.0	-11.80
160.0	172.5	-11.98
172.5	180.0	-12.45
180.0	183.0	-12.22
183.0	189.0	-12.29
189.0	190.0	-12.17

Table 5. Oxygen isotope values for Caldwell Cave core. Measurements made in OSU CEOAS Stable isotope laboratory, in per mil relative to V-SMOW.

Top Depth (cm)	Bottom Depth (cm)	$\delta^{18}O$(‰)
0.0	4.0	-8.84
4.0	10.5	-8.89
10.5	18.0	-8.71
18.0	33.0	-9.90
33.0	47.0	-9.34
47.0	54.0	-10.16
54.0	63.0	-10.20
63.0	72.0	-9.98
72.0	88.5	-10.02
88.5	102.0	-10.24
102.0	104.0	-10.53
104.0	111.5	-9.15
111.5	120.8	-9.47
120.8	124.0	-11.89
124.0	130.0	-10.35
130.0	143.0	-9.71
143.0	156.0	-9.79
156.0	174.0	-9.10
174.0	177.0	-9.55
177.0	185.0	-9.84
185.0	188.0	-9.17
188.0	191.5	-9.15
191.5	193.0	-8.88
193.0	199.4	-9.98
199.4	203.5	-10.13
203.5	210.0	-9.15
210.0	215.5	-10.23
215.5	223.0	-9.68
223.0	230.0	-9.70
230.0	247.0	-11.06

Table 6. Oxygen and hydrogen isotope values for Crystal Cave core. Measurements made in OSU Institute for Water and Watersheds Collaboratory, in per mil relative to V-SMOW. Duplicate measurements were made on most samples.

Top Depth (cm)	Bottom Depth (cm)	δ^{18}O(‰)	δ^{18}O(‰)	δ^{18}O(‰) Mean	δD(‰)	δD(‰)	δD(‰) Mean
0.0	4.4	-8.11	-8.36	-8.23	-60.28	-61.08	-60.68
7.3	13.0	-8.22	-8.47	-8.34	-60.62	-62.10	-61.36
13.0	15.0	-8.47	-8.54	-8.51	-62.00	-62.44	-62.22
15.0	18.5	-9.06	-9.01	-9.04	-66.57	-64.02	-65.29
18.5	25.5	-8.60	-8.68	-8.64	-63.40	-63.43	-63.41
25.5	35.0	-8.50	-8.56	-8.53	-63.53	-63.16	-63.34
35.0	46.2	-9.14	-9.12	-9.13	-66.86	-65.69	-66.28
46.2	52.0	-7.45	-8.62	-8.04	-61.30	-62.47	-61.89
52.0	62.0	-9.41	-9.45	-9.43	-69.28	-69.15	-69.21
62.0	69.0	-10.36	-10.39	-10.38	-77.41	-77.19	-77.30
69.0	84.5	-11.77	-11.62	-11.70	-87.45	-87.28	-87.37

Table 7. Oxygen isotope values for Skull Cave core. Measurements made in OSU Institute for Water and Watersheds Collaboratory, in per mil relative to V-SMOW. Duplicate measurements were made on most samples.

Top Depth (cm)	Bottom Depth (cm)	δ^{18}O(‰)	δ^{18}O(‰)	δ^{18}O(‰) Mean	δD(‰)	δD(‰)	δD(‰) Mean
0.0	4.4	-9.11	-9.42	-9.26	-60.28	-61.08	-60.68
7.3	13.0	-8.68	-8.79	-8.73	-60.62	-62.10	-61.36
13.0	15.0	-9.87	-9.85	-9.86	-62.00	-62.44	-62.22
15.0	18.5	-9.92	-10.06	-9.99	-66.57	-64.02	-65.29
18.5	25.5	-10.40	-10.35	-10.38	-63.40	-63.43	-63.41
25.5	35.0	-13.31	-11.58	-12.44	-63.53	-63.16	-63.34
35.0	46.2	-12.85	-12.93	-12.89	-66.86	-65.69	-66.28
46.2	52.0	-11.14	-11.15	-11.14	-61.30	-62.47	-61.89
52.0	62.0	-11.29	-11.35	-11.32	-69.28	-69.15	-69.21
62.0	69.0	-12.20	-12.24	-12.22	-77.41	-77.19	-77.30
69.0	84.5	-12.14	-11.13	-11.64	-87.45	-87.28	-87.37

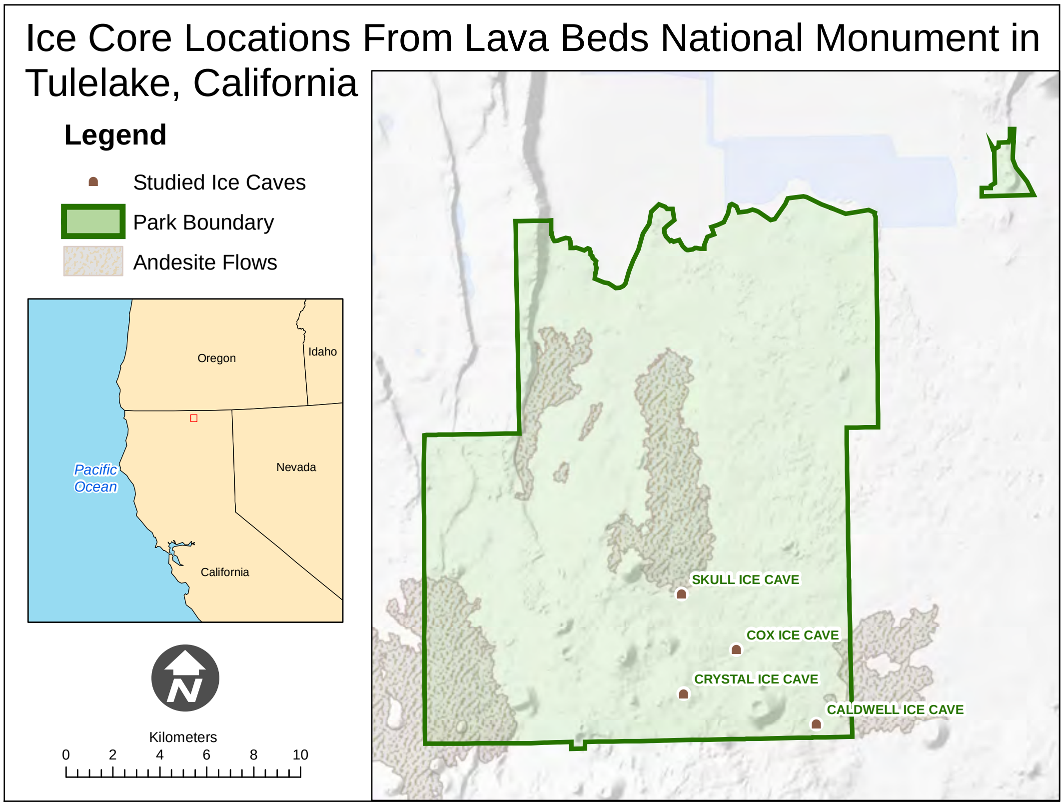


Figure 1. Location of Lava Beds National Monument and caves discussed in this paper.

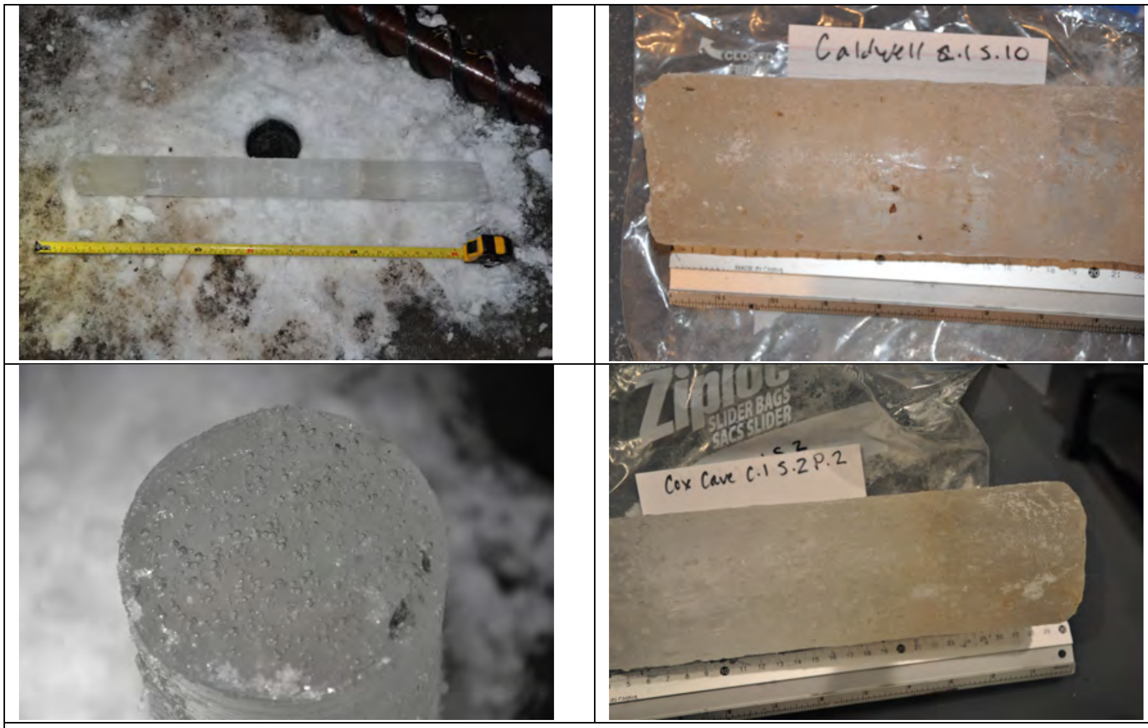


Figure 2. Photographs of representative sections of ice cores from Cox Cave and Coldwell Cave.

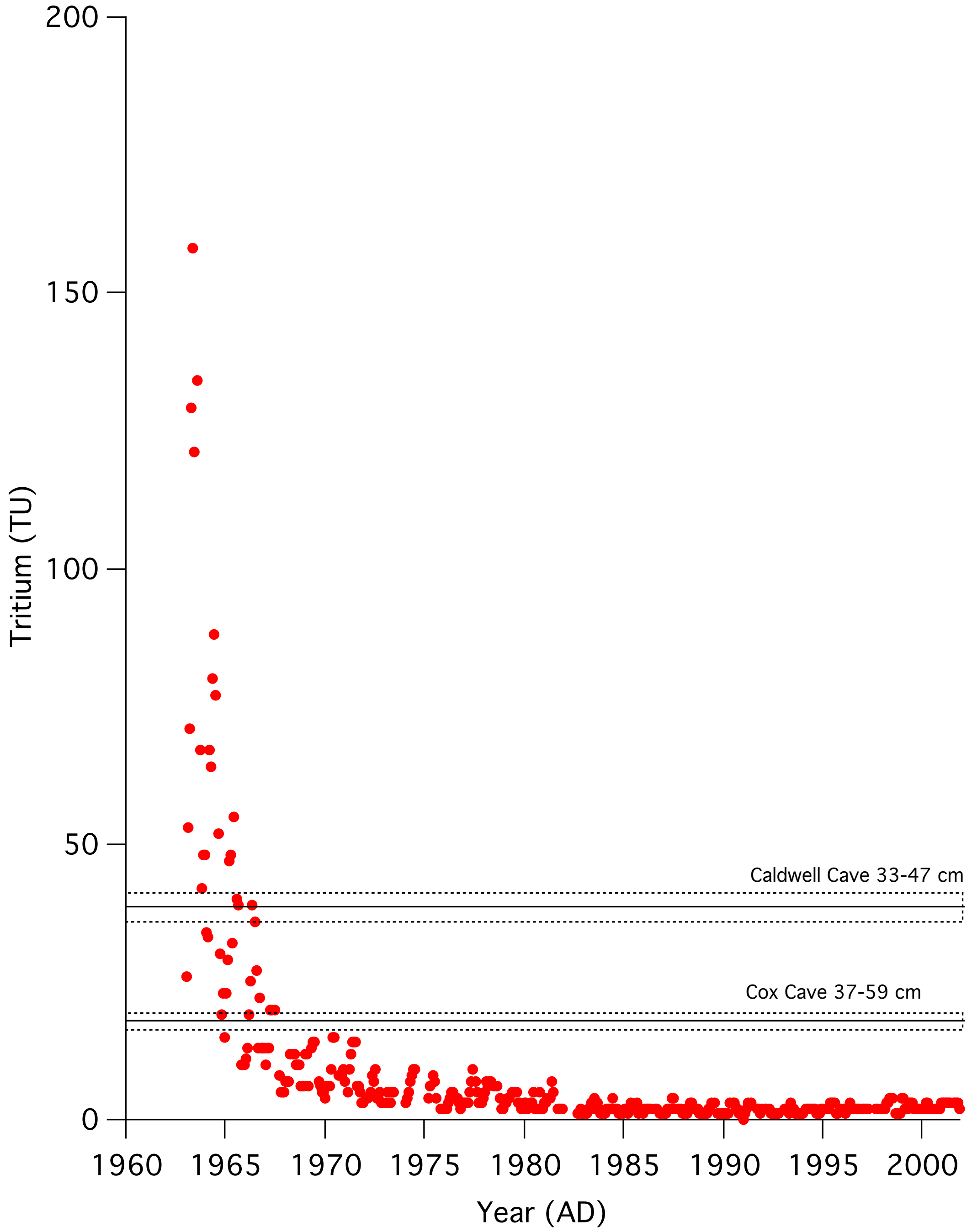


Figure 3. Tritium data collected at Portland Oregon, adjusted for radioactive decay to the date of ice cave sample analysis (May 1, 2011). Horizontal lines show the mean and 2-sigma range of measured tritium in shallow samples from Cox and Coldwell Caves. The intersections of those lines with the tritium data from Portland show that the ice samples probably date to the late 1960s to early 1970s.

Figure 4. Left: Photograph of Coldwell Cave ice wall and bark sample collected at about 2 m depth. Vertical scale of photograph is ~ 1m. Right: Close up view of ~ 2-3 cm sample of Ponderosa Pine bark embedded in ice.

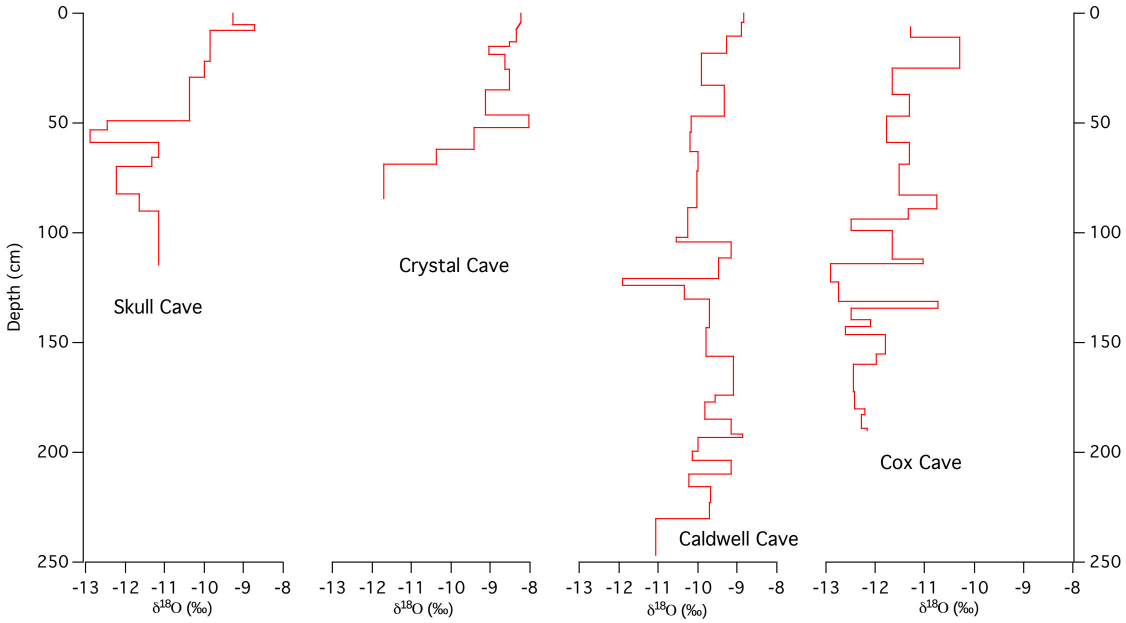


Figure 5. δ18O (‰, VSMOW) for ice samples from four ice cores at Lava Beds National Monument as a function of depth.

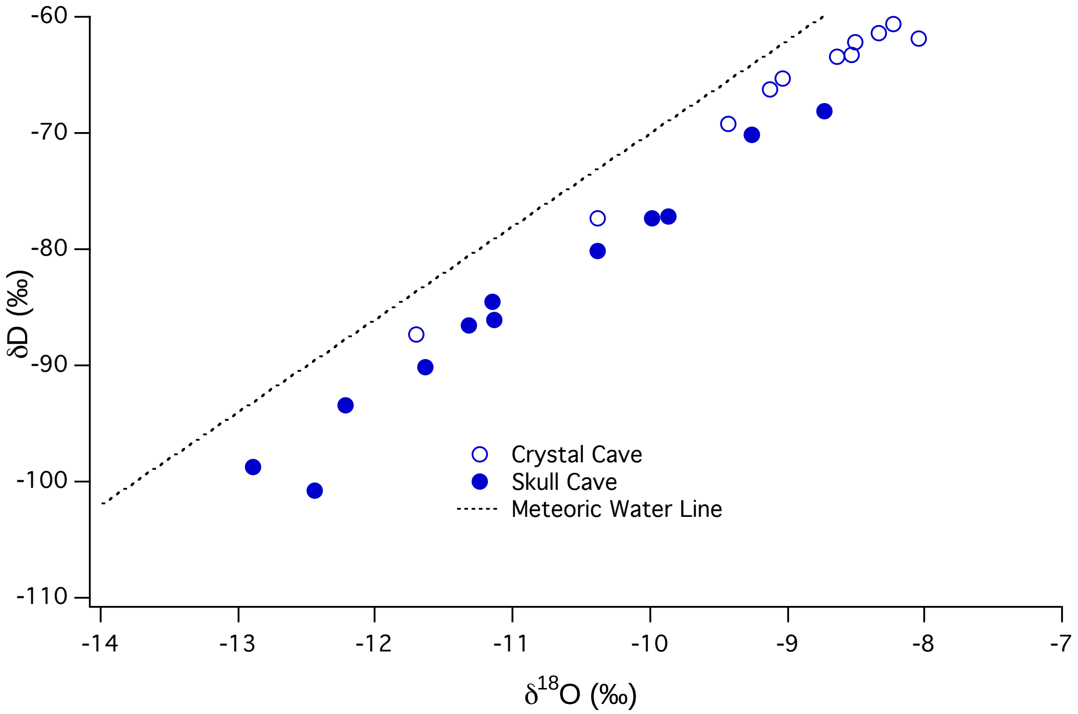
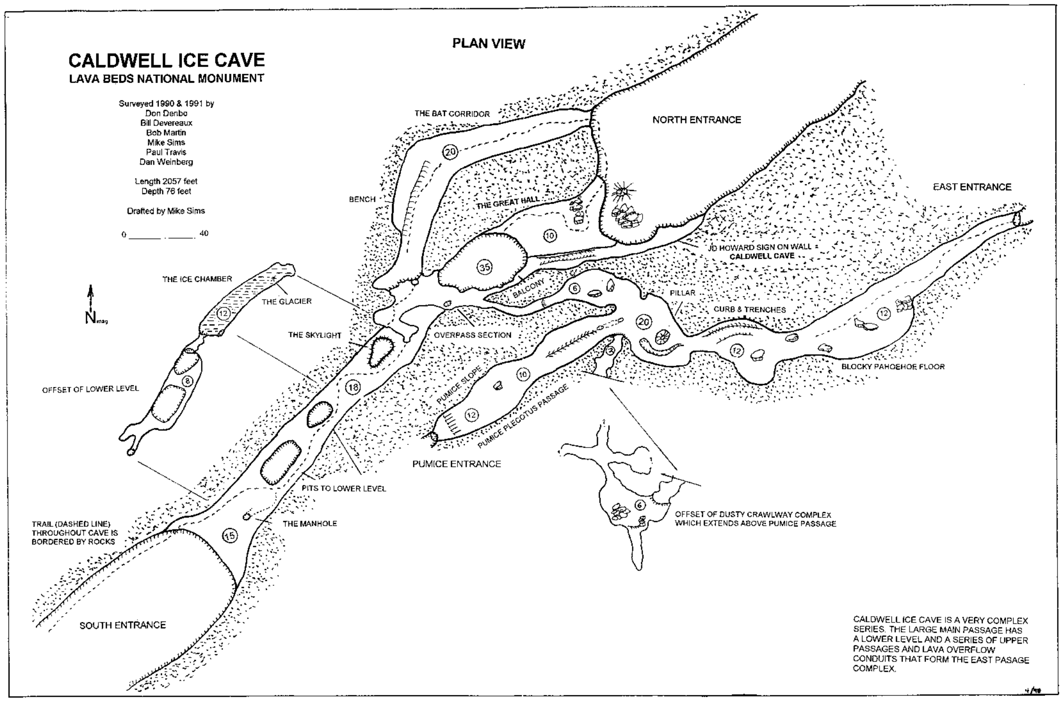
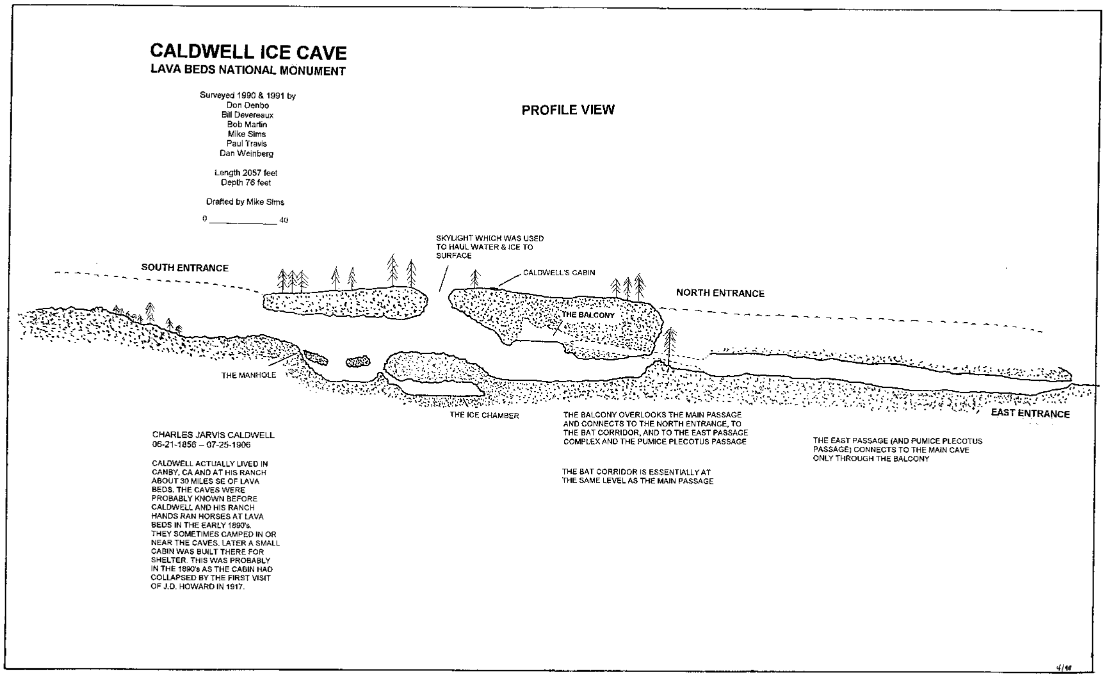


Figure 6. Relationship between oxygen isotope and hydrogen isotope ratios for Skull Cave and Crystal Cave samples. Both data sets fall near, but below the global meteoric water line ($\delta D=8x\delta^{18}O+10$). Linear fits to the data for Skull Cave give $\delta D=7.9(\pm0.40) \times \delta^{18}O +1.9(\pm4.4)$, for Crystal Cave $\delta D=7.5(\pm0.35) \times \delta^{18}O +0.97(\pm3.2)$.

Appendix: Maps of Caves Studied





CALDWELL ICE CAVE

LAVA BEDS NATIONAL MONUMENT

Surveyed 1990 & 1991 by
Don Denbo
Bill Devereaux
Bob Martin
Mike Sims
Paul Travis
Dan Weinberg

Length 2057 feet
Depth 76 feet

Drafted by Mike Sims

SKYLIGHT WHICH WAS USED TO HAUL WATER & ICE TO SURFACE

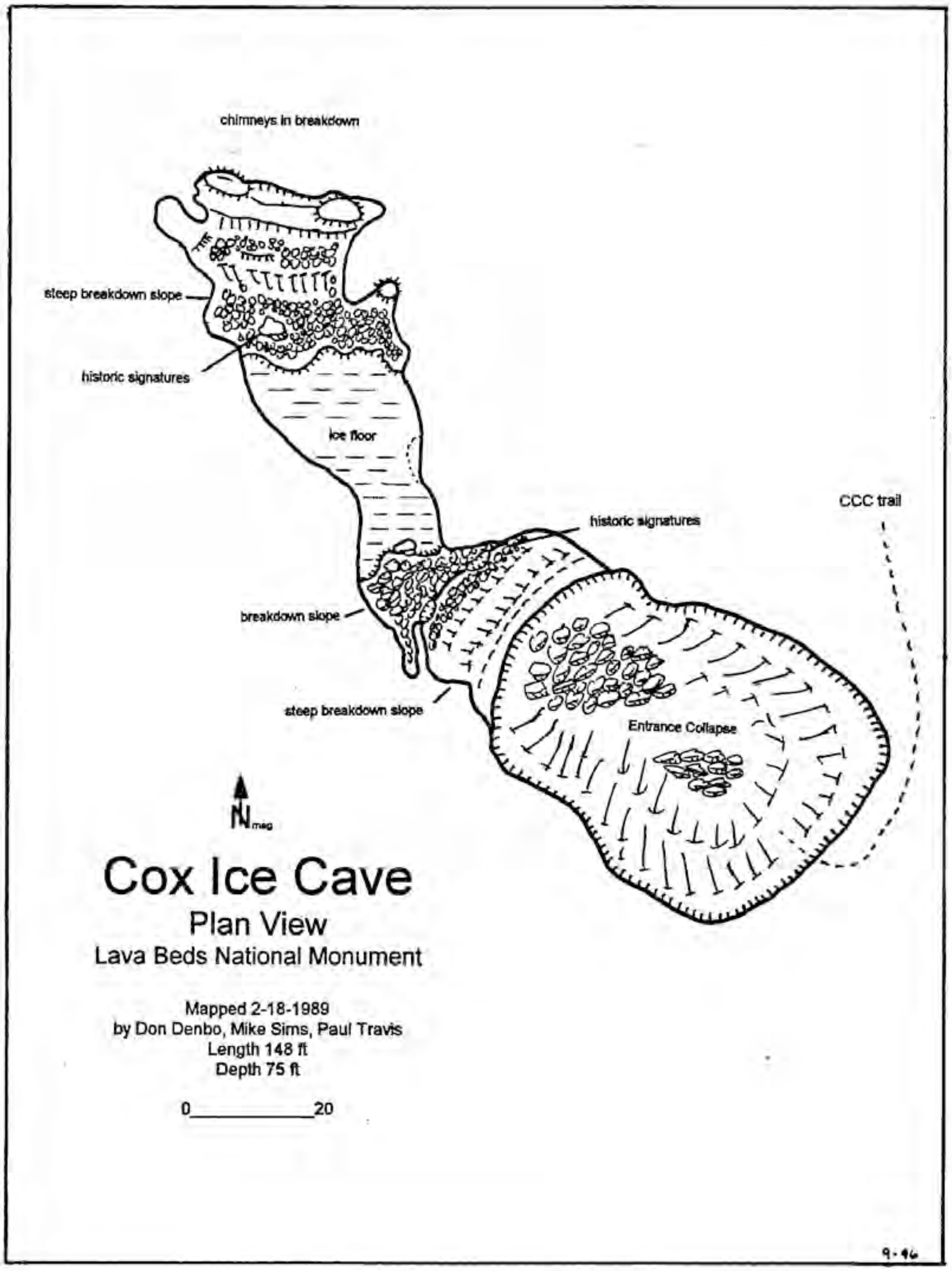
THE BALCONY OVERLOOKS THE MAIN PASSAGE AND CONNECTS TO THE NORTH ENTRANCE, TO THE BAT CORRIDOR, AND TO THE EAST PASSAGE COMPLEX AND THE PUMICE PLECOTUS PASSAGE

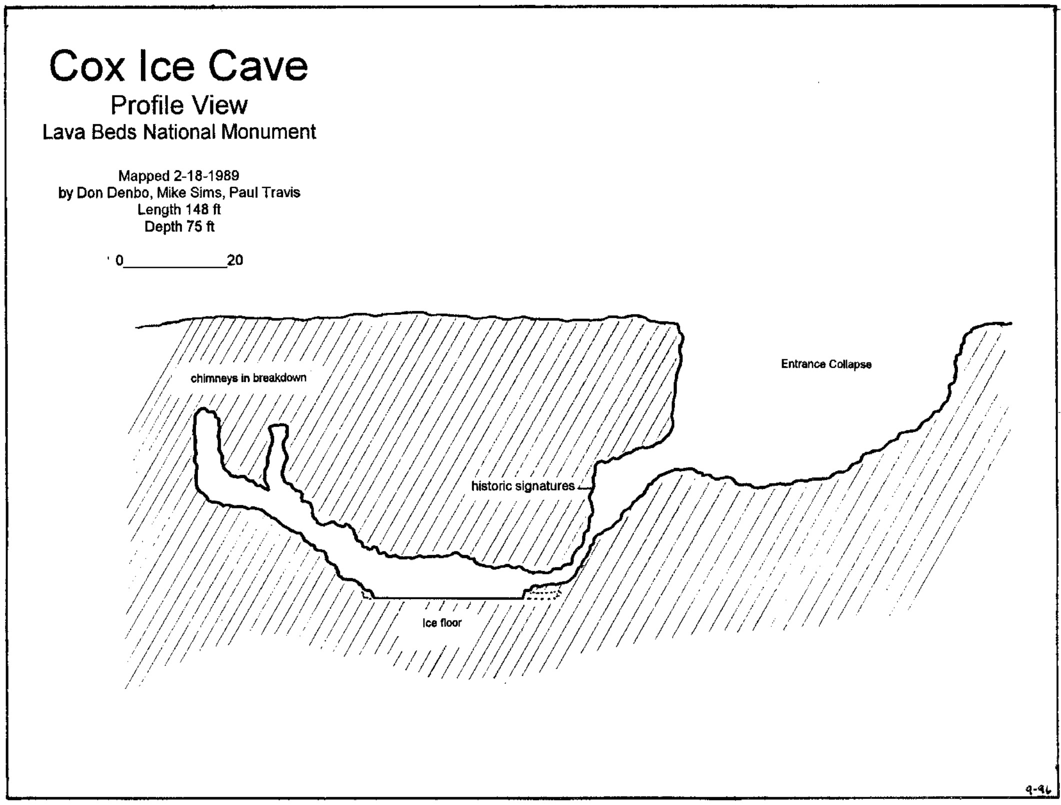
THE BAT CORRIDOR IS ESSENTIALLY AT THE SAME LEVEL AS THE MAIN PASSAGE

THE EAST PASSAGE (AND PUMICE PLECOTUS PASSAGE) CONNECTS TO THE MAIN CAVE ONLY THROUGH THE BALCONY

CHARLES JARVIS CALDWELL
06-21-1856 – 07-25-1906

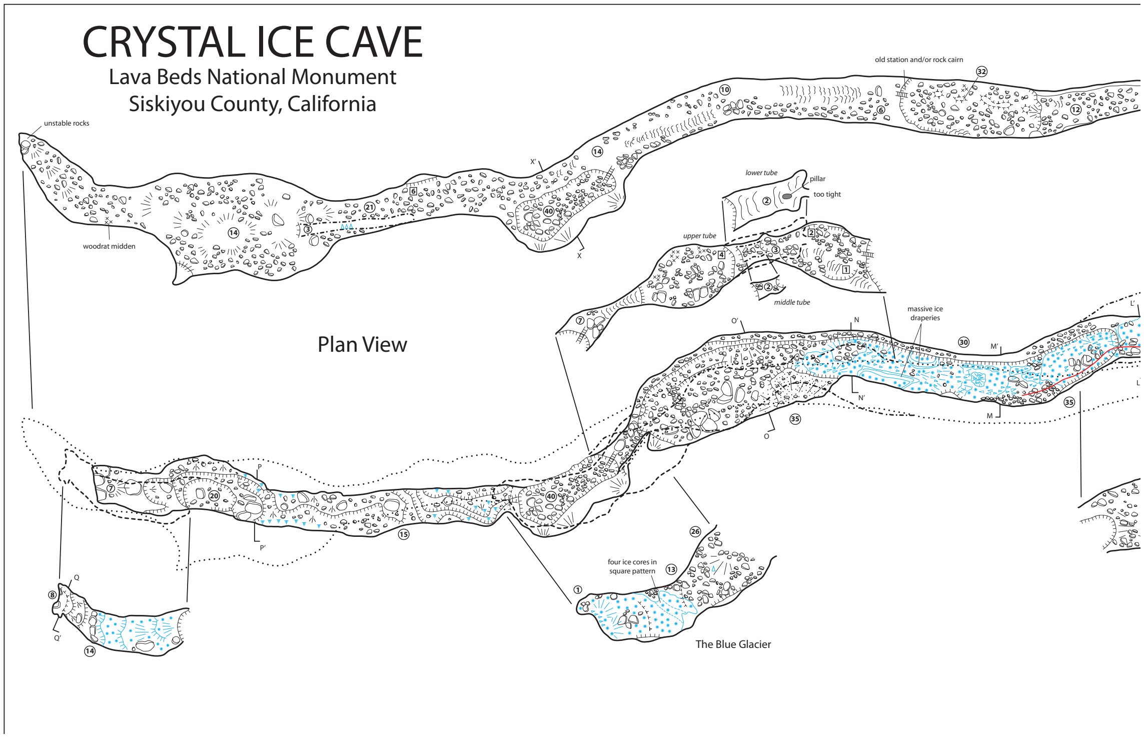
CALDWELL ACTUALLY LIVED IN CANBY, CA AND AT HIS RANCH ABOUT 30 MILES SE OF LAVA BEDS. THE CAVES WERE PROBABLY KNOWN BEFORE CALDWELL AND HIS RANCH HANDS RAN HORSES AT LAVA BEDS IN THE EARLY 1890's. THEY SOMETIMES CAMPED IN OR NEAR THE CAVES. LATER A SMALL CABIN WAS BUILT THERE FOR SHELTER. THIS WAS PROBABLY IN THE 1890's AS THE CABIN HAD COLLAPSED BY THE FIRST VISIT OF J.D. HOWARD IN 1917.

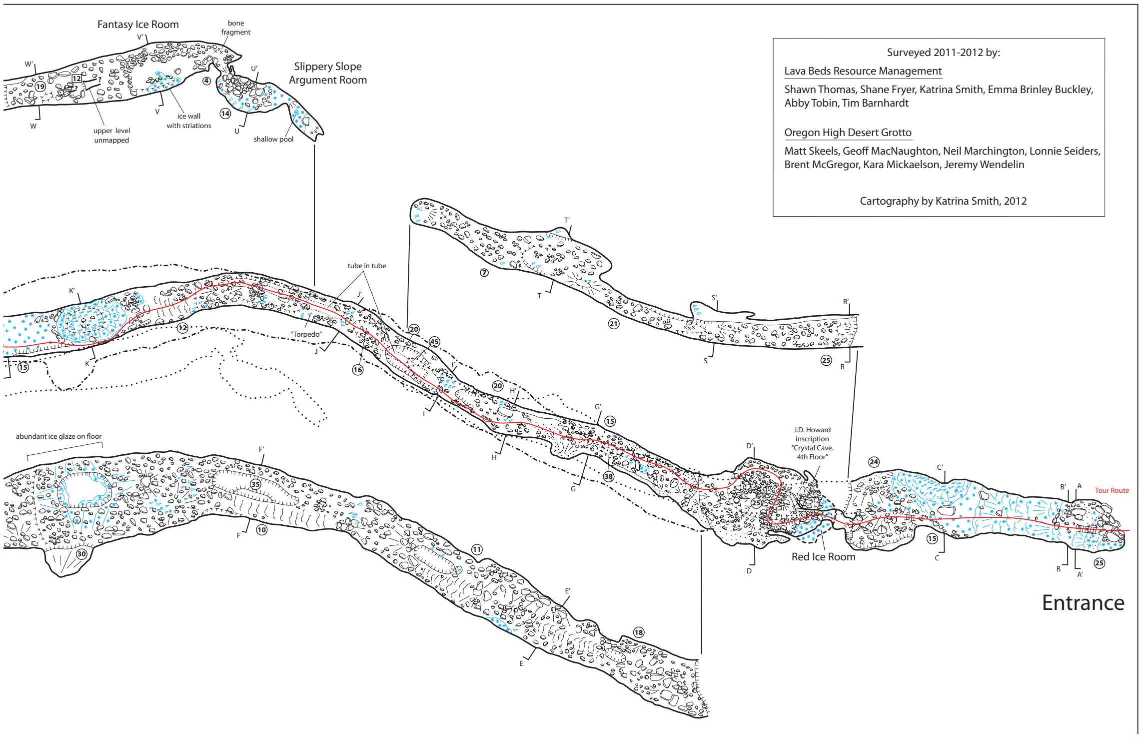

chimneys in breakdown
steep breakdown slope
historic signatures
ice floor
historic signatures
CCC trail
breakdown slope
steep breakdown slope
Entrance Collapse
N mag
Cox Ice Cave
Plan View
Lava Beds National Monument
Mapped 2-18-1989
by Don Denbo, Mike Sims, Paul Travis
Length 148 ft
Depth 75 ft
0
20
9-96


Cox Ice Cave
Profile View
Lava Beds National Monument
Mapped 2-18-1989
by Don Denbo, Mike Sims, Paul Travis
Length 148 ft
Depth 75 ft
0
20
chimneys in breakdown
Entrance Collapse
historic signatures
Ice floor
9-96

CRYSTAL ICE CAVE

Lava Beds National Monument
Siskiyou County, California





Surveyed 2011-2012 by:

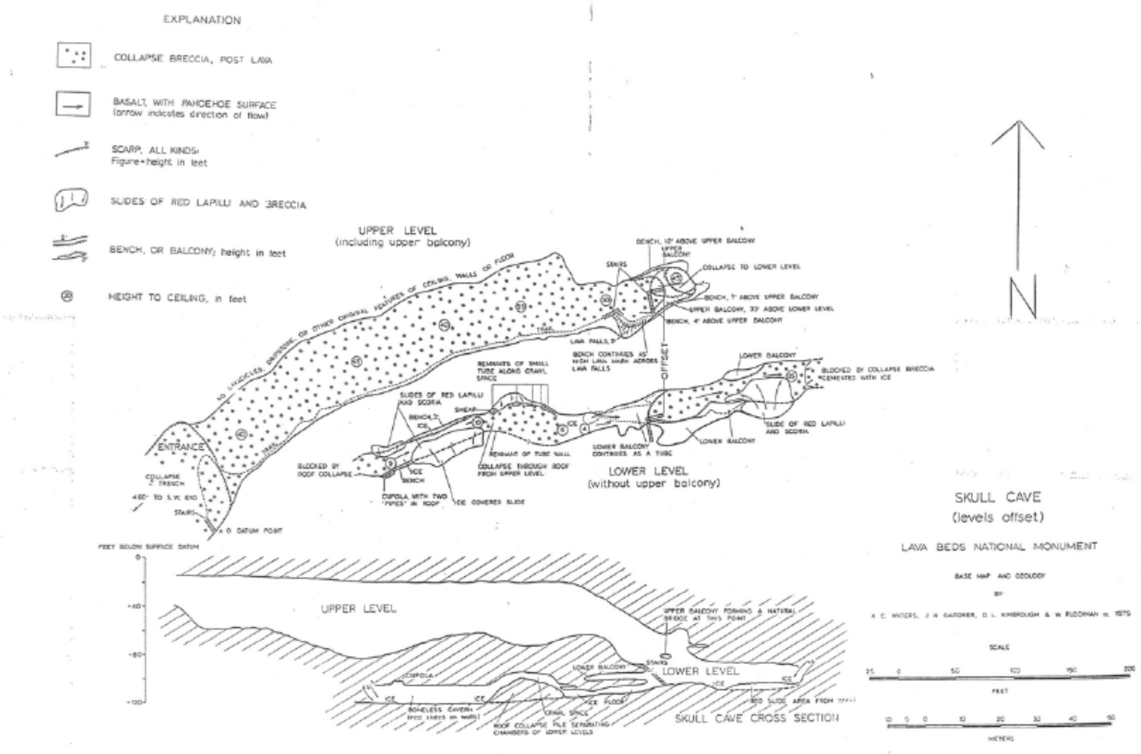
Lava Beds Resource Management

Shawn Thomas, Shane Fryer, Katrina Smith, Emma Brinley Buckley, Abby Tobin, Tim Barnhardt

Oregon High Desert Grotto

Matt Skeels, Geoff MacNaughton, Neil Marchington, Lonnie Seiders, Brent McGregor, Kara Mickaelson, Jeremy Wendelin

Cartography by Katrina Smith, 2012


EXPLANATION
COLLAPSE BRECCIA, POST LAVA
BASALT, WITH PAHOEHOE SURFACE (arrow indicates direction of flow)
SCARP, ALL KINDS; Figure = height in feet
SLIDES OF RED LAPILLI AND BRECCIA
BENCH, OR BALCONY; height in feet
HEIGHT TO CEILING, in feet
UPPER LEVEL
(including upper balcony)
NO LAVICICLES, DRIPSTONE, OR OTHER ORIGINAL FEATURES OF CEILING, WALLS OR FLOOR
TRAIL
ENTRANCE
COLLAPSE TRENCH
460' TO S.W. END
STAIRS
0 DATUM POINT
STAIRS
BENCH, 12' ABOVE UPPER BALCONY
UPPER BALCONY
COLLAPSE TO LOWER LEVEL
BENCH, 7' ABOVE UPPER BALCONY
UPPER BALCONY, 33' ABOVE LOWER LEVEL
BENCH, 4' ABOVE UPPER BALCONY
LAVA FALLS, 5'
BENCH CONTINUES AS HIGH LAVA MARK ACROSS LAVA FALLS
OFFSET
REMNANTS OF SMALL TUBE ALONG CRAWL SPACE
SLIDES OF RED LAPILLI AND SCORIA
SHEAR
BENCH, 3'
ICE
ICE
LOWER BALCONY
BLOCKED BY COLLAPSE BRECCIA CEMENTED WITH ICE
SLIDE OF RED LAPILLI AND SCORIA
LOWER BALCONY
LOWER BALCONY CONTINUES AS A TUBE
REMNANT OF TUBE WALL
COLLAPSE THROUGH ROOF FROM UPPER LEVEL
BLOCKED BY ROOF COLLAPSE
ICE
BENCH
CUPOLA WITH TWO "PIPES" IN ROOF
ICE COVERED SLIDE
LOWER LEVEL
(without upper balcony)
N
FEET BELOW SURFACE DATUM
0
-40
-80
-120
UPPER LEVEL
UPPER BALCONY FORMING A NATURAL BRIDGE AT THIS POINT
LOWER BALCONY
STAIRS
LOWER LEVEL
CUPOLA
ICE
ICE
ICE
ICE
ICE FLOOR
BONELESS CAVERN (red slides on walls)
CRAWL SPACE
ROOF COLLAPSE PILE SEPARATING CHAMBERS OF LOWER LEVELS
RED SLIDE AREA FROM WALL
SKULL CAVE CROSS SECTION
SKULL CAVE
(levels offset)
LAVA BEDS NATIONAL MONUMENT
BASE MAP AND GEOLOGY
BY
A. C. WATERS, J. R. GARDNER, D. L. KIMBROUGH & W. RUDDIMAN III, 1975
SCALE
25
0
50
100
150
200
FEET
10
5
0
10
20
30
40
50
METERS