Climate Change and Yucca Mountain Unsaturated Zone Hydrology

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Two Scales of Past Climate Variation at Yucca Mountain

- **Transition from Tertiary to Quaternary climates**
  - Miocene and Pliocene conditions were wetter and milder
  - Quaternary conditions were drier, and more seasonal
  - Transition 2 to 4 m.y. ago
- **Variations in Quaternary climate**
  - ~100,000-year cycles related to glaciation in the northern hemisphere
  - In southern Nevada, cycles consisted of:
    - Colder, wetter pluvials
    - Intermediate/monsoonal periods
    - Warmer, drier interpluvials

Future Climate Variation

- **Estimates of climate change in next 500,000 years**
  - **Based on analysis of orbital parameters and analog sites**
  - **Six glacial cycles with conditions similar to previous cycles**

Climate state	% of time	Mean annual temperature (°C)	Mean annual precipitation (mm)	Mean net infiltration (mm/yr)
Glacial	19	0 – 9	250 – 510	?
Intermediate	68	9 – 10	200 – 430	2 – 38
Monsoon	3	13 – 17	125 – 400	12 – 25
Interglacial (modern)	13	13 – 14	120 – 180	0.4 – 12

Sources of information: Spaulding 1985; Forester et al. 1999; Thompson 1999; Sharpe 2003 (Yucca Mountain (YM) Site Description); Flint/Hevesi 2003 (YM Site Description)

Records of Climate Change

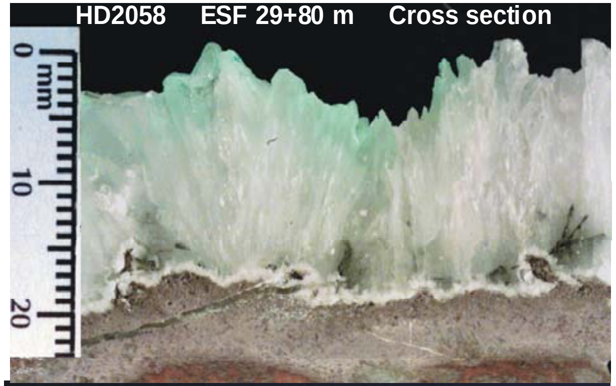
- Surface records (temperature and precipitation)
  - Paleolimnology (sedimentological, paleontological, geochemical)
  - Paleobotany (packrat middens, pollen)
  - Sedimentology (weathering, calcrete formation, eolian and fluvial activity)
- Saturated zone (SZ) records
  - Paleohydrographs (regional groundwater table fluctuations)
    - Discharge deposits (Amargosa and elsewhere)
    - Brown's Room (Ash Meadows) deposits
  - Paleorecharge compositions
    - Variations in meteoric water composition (Devils Hole)
- Unsaturated zone (UZ) records
  - Pore water ($\delta^{18}O$, $\delta^{2}H$) and chlorine-36 (low resolution; limited to last pluvial cycle)
  - Secondary hydrogenic minerals

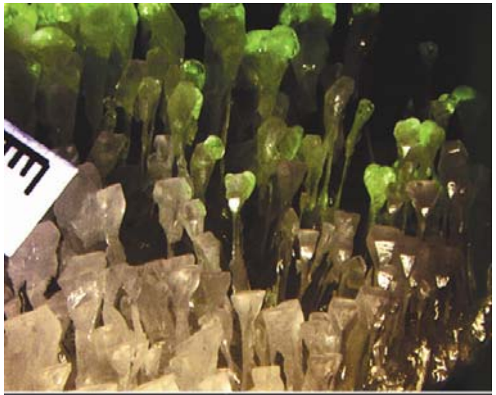
Importance of Unsaturated Zone Hydrogenic Minerals

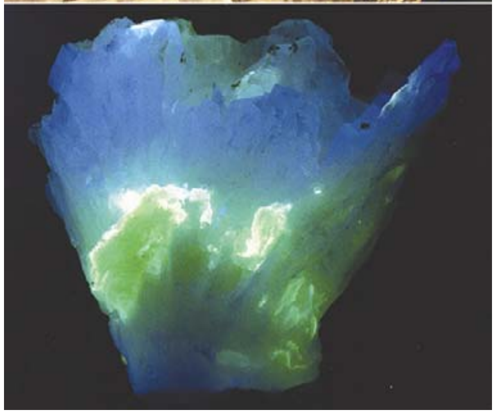
- Represent a >10 m.y.-long record of deposition from water percolating through UZ fracture network
- Two types of information related to climate change
  - Growth rates
    - Controlled by liquid and gas fluxes that can respond to climate-induced variations in infiltration
  - Compositions (isotopic and chemical)
    - Reflect climate-related changes in the compositions of percolating water at time of deposition

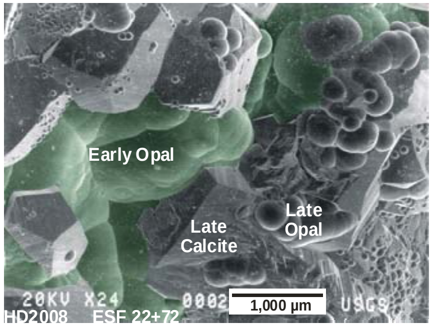
Secondary Hydrogenic Minerals

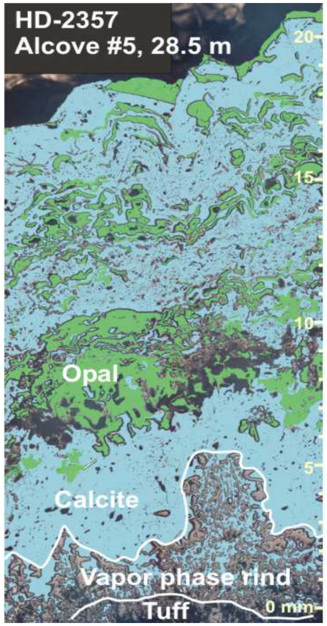
- Secondary mineral coatings are distributed sporadically throughout the UZ on fracture footwalls and cavity floors
- Coatings are dominantly calcite with less abundant silica phases (opal, chalcedony)











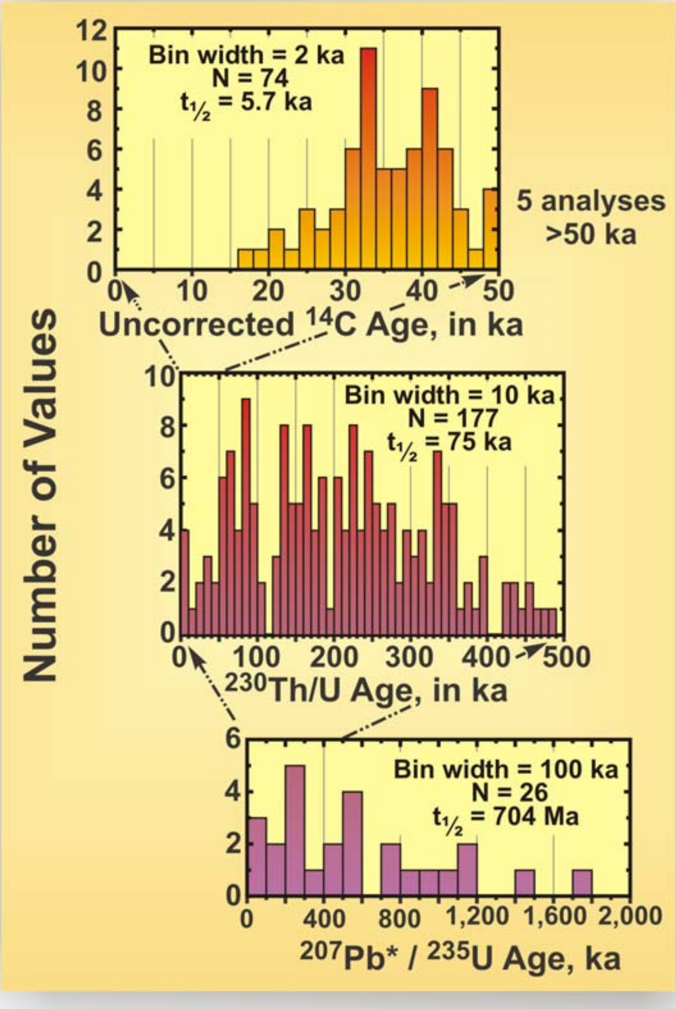
Dating Secondary Fracture Minerals

- **Records of past climate require reliable geochronological framework**
- **Minerals can be dated by natural radioactive decay**

Material	Concentration	Dating method	Dating range	Amount of material used (mg)
Opal ($SiO_2 \cdot nH_2O$)	10 to 500 ppm U	$^{230}Th/U$	~1 to 400 ka	~0.001 to 10's
		$^{234}U/^{238}U$	100 to 1,500 ka	~0.001 to 10's
		$^{207}Pb/^{235}U$	0.1 to 12.7 Ma	0.1 to 10's
Calcite ($CaCO_3$)	~0.01-1 ppm U	$^{230}Th/U$	~1 to 400 ka	~50 to 200
	12 wt% C	^{14}C	0 to 50 ka	10 to 20 mg

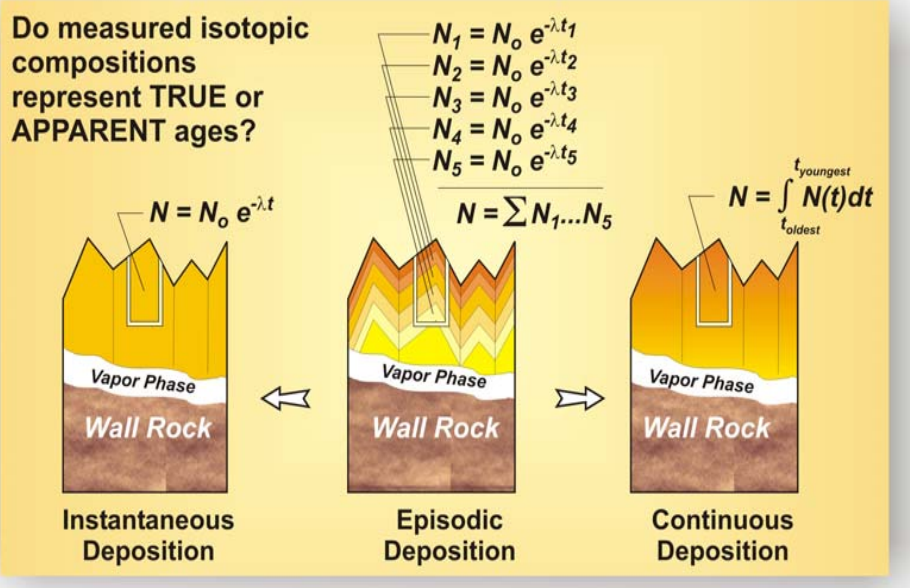
Initial Dating of Outermost Surfaces

- Outer surfaces of nearly all UZ mineral coatings have Pleistocene ^{14}C and $^{230}Th/U$ ages
- Problematic aspects:
  - Wide range of ages for subsamples from the same outer surface
  - Youngest ages from the thinnest subsamples
  - Isotopic systems with larger half-lives yield older ages
  - Unexpected behavior for U-series isotope systematics



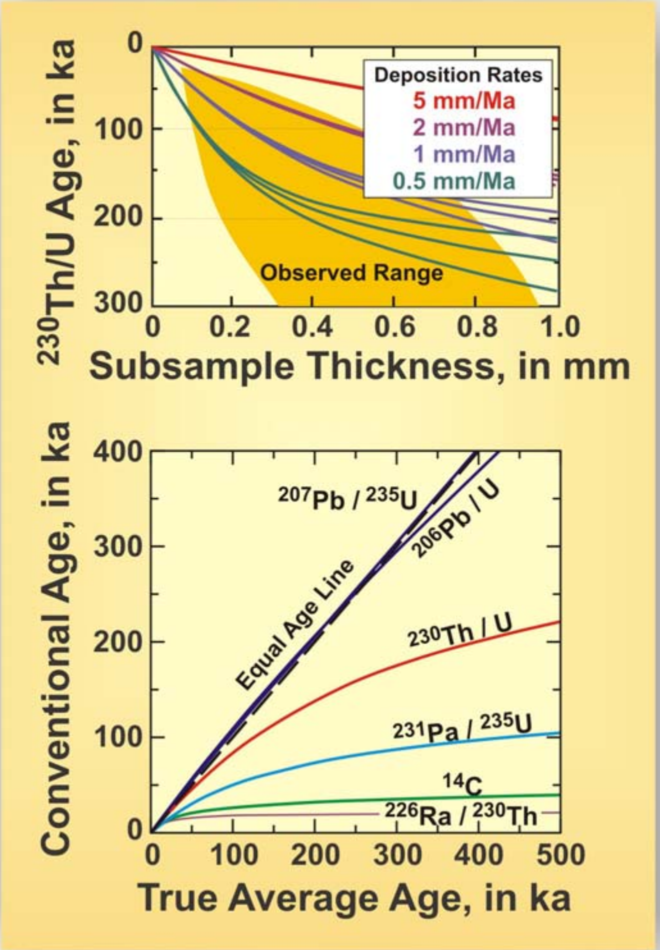
Conceptual Models of Mineral Deposition

- **Instantaneous, episodic, or continuous mineral growth**
- **Dating results depend on relations between layering, subsample thickness, and rates of radioactive decay**
  - **Slow growth rates can result in sub-samples consisting of mixtures of older and younger material**
  - **Effect on calculated age is even more substantial when the rate of growth approaches the rate of radioactive decay**



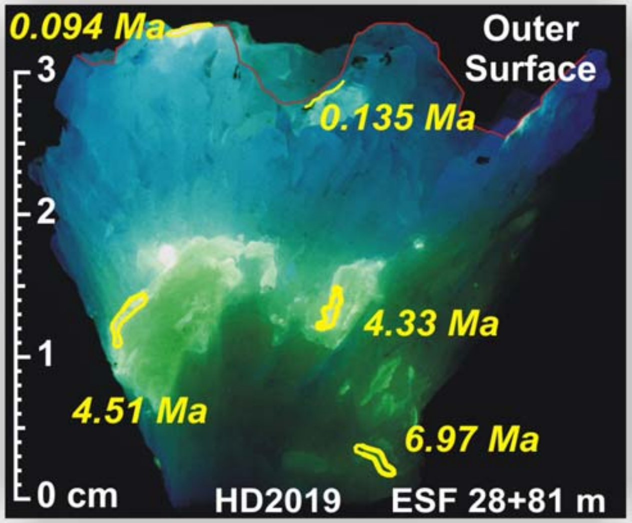
Numerical Model of Continuous Deposition

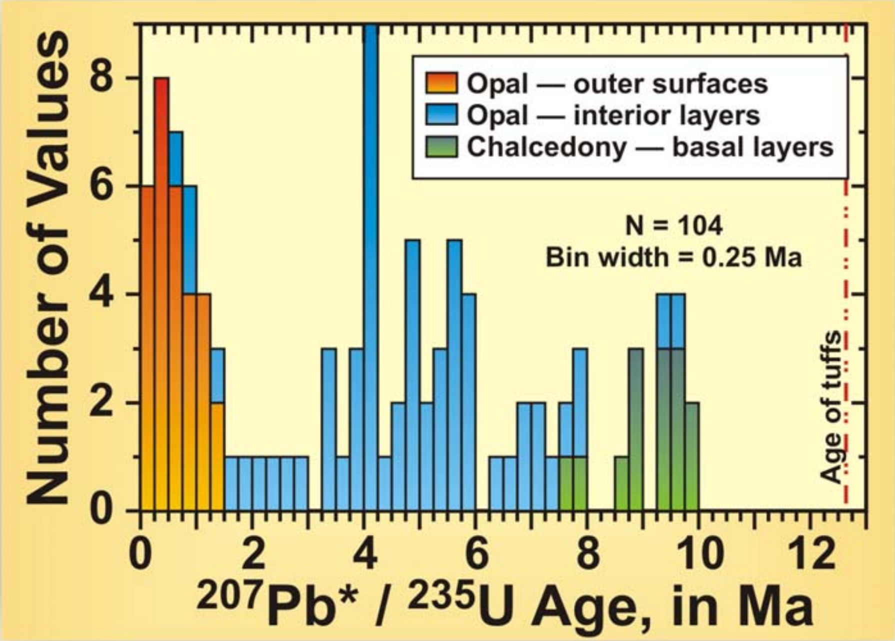
- Predicts a number of features observed in fracture mineral data sets:
  - Positive correlations between age and subsample thickness
  - Growth rates slower than ~5 mm/m.y.
  - Discordant ages between different isotopic systems
  - U-series systematics that mimic observed patterns
- Conclusions
  - Measured isotopic compositions are mixtures of older and younger material
  - Thinnest samples yield calculated ages closest to true ages



U-Pb Dating of Interior Layers

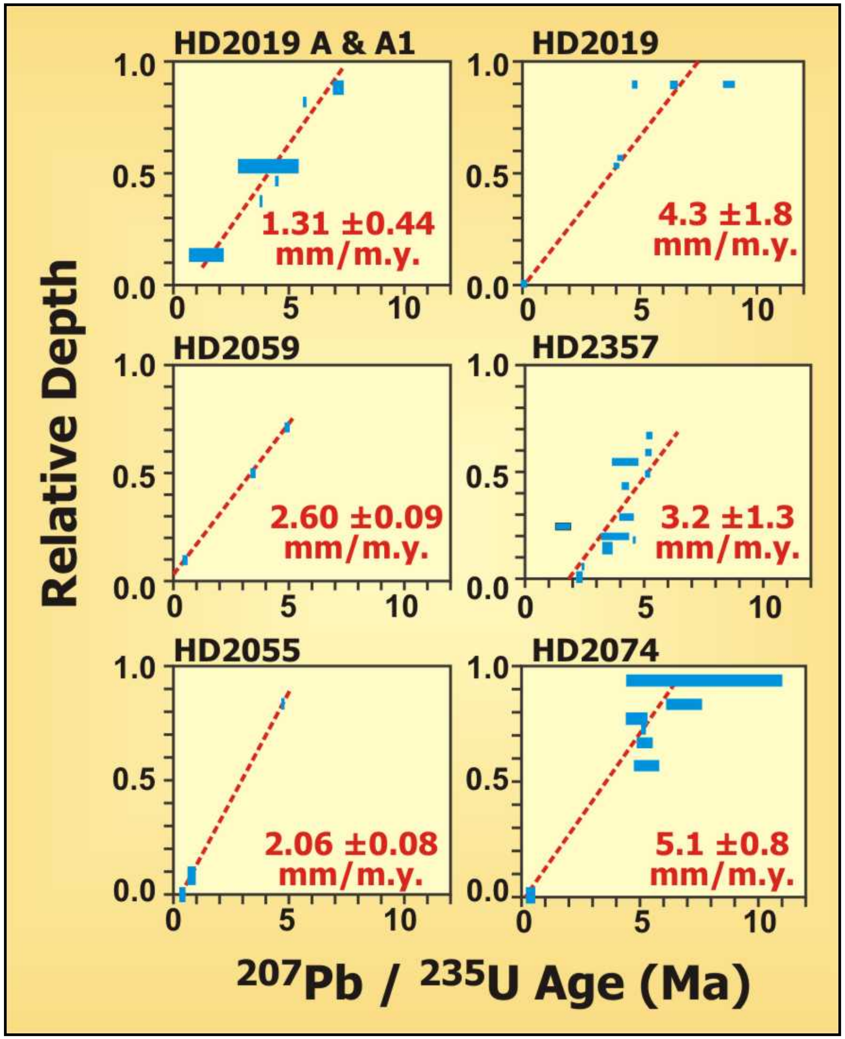
- **Growth histories extended by dating of interior layers**
  - **U-Pb dates are usually concordant with microstratigraphy**
  - **Basal layers range from 4 to 10 Ma**
  - **Used to calculate long-term average growth rate**





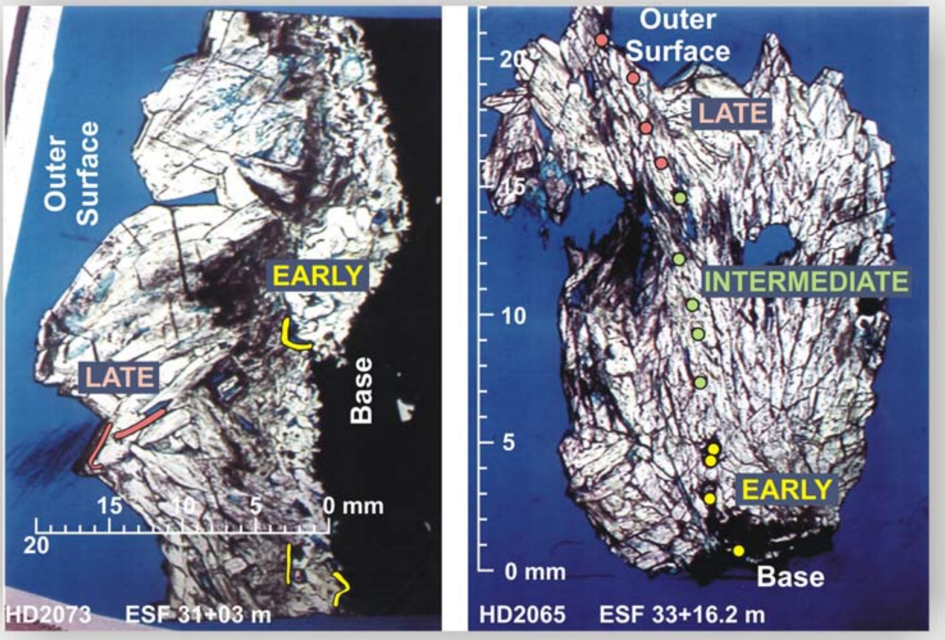
U-Pb Dating of Interior Layers
(Continued)

- Depth-age relations indicate average Tertiary growth rates between 1 and 5 mm/m.y.
- Growth rates are 10^3 to $>10^6$ slower than published speleothem growth rates
- Long-term average growth rates are generally consistent for different parts of a single mineral coating



Isotope Variations in Mineral Coatings

- **Profiles across individual coatings show patterns of $\delta^{18}O$, $\delta^{13}C$, and $\delta^{87}Sr$ variation with microstratigraphy**
- **Relative ages can be assigned by micro-stratigraphic position**
- **U-Pb ages for interior layers form a framework allowing interpretation of observed isotope variations**



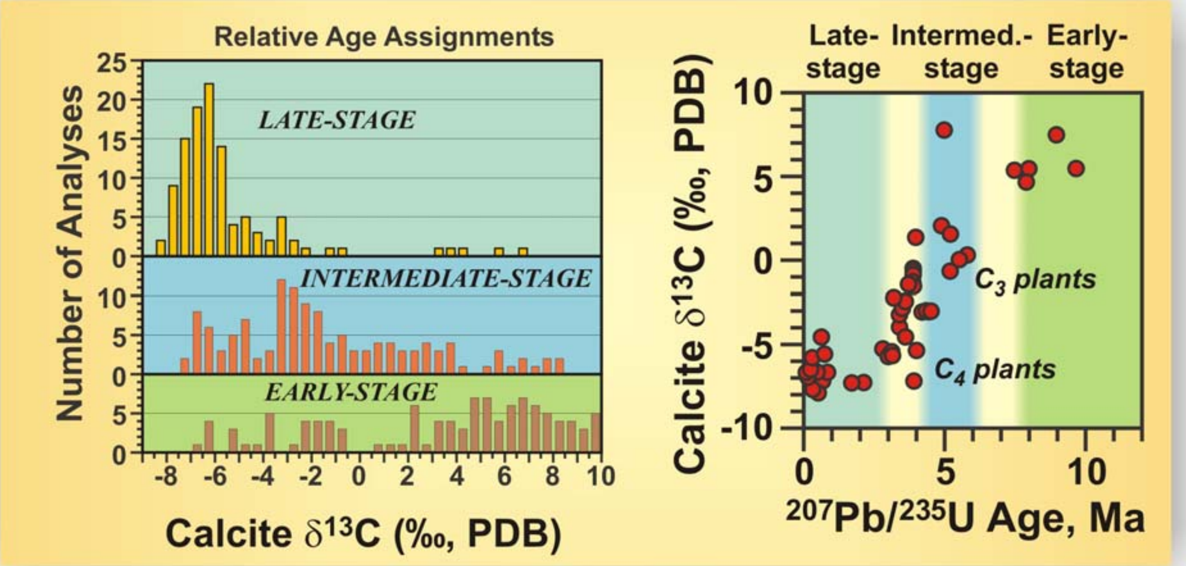
Typical Values

Isotope	Early-stage	Late-stage
$\delta^{13}C$	+6 ‰	-6 ‰
$\delta^{18}O$	+10 ‰	+18 ‰
$\delta^{87}Sr$	+1.8 ‰	+4.5 ‰

δ^{13}C Variations in Mineral Coatings

- **Changes in δ^{13}C interpreted to reflect shifts in local flora**

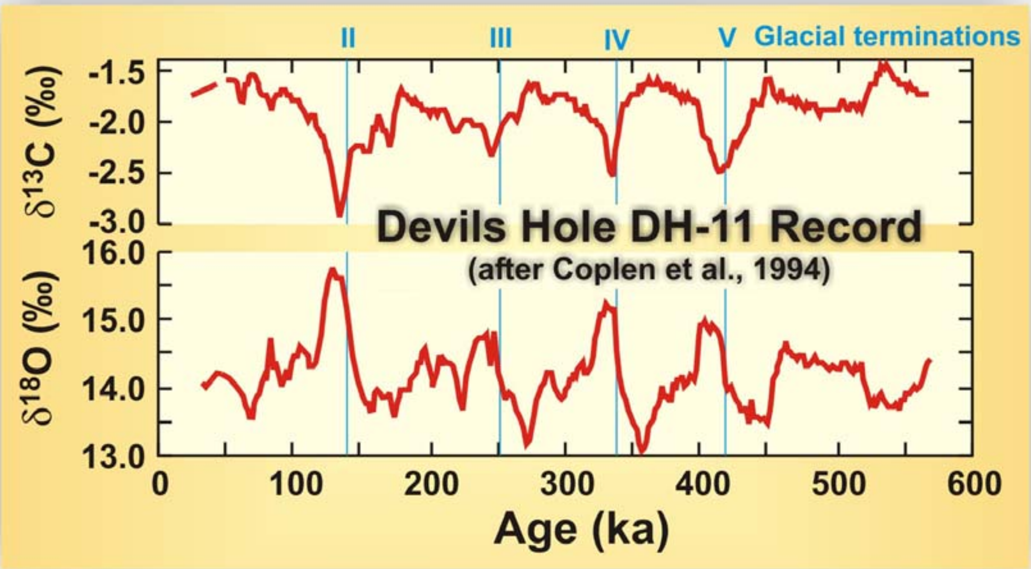
Time period	Climate	Dominant flora	Photo-synthetic pathway	Soil calcite δ^{13}C (‰)
Tertiary	Wetter, milder	Grasses	C_4	+2 to -5
Quaternary	Drier, seasonal	Shrubs, succulents	Mixed C_3 and C_4	-5 to -8



Transition between 2 and 3 Ma correlates with a major shift in climate conditions throughout northern hemisphere

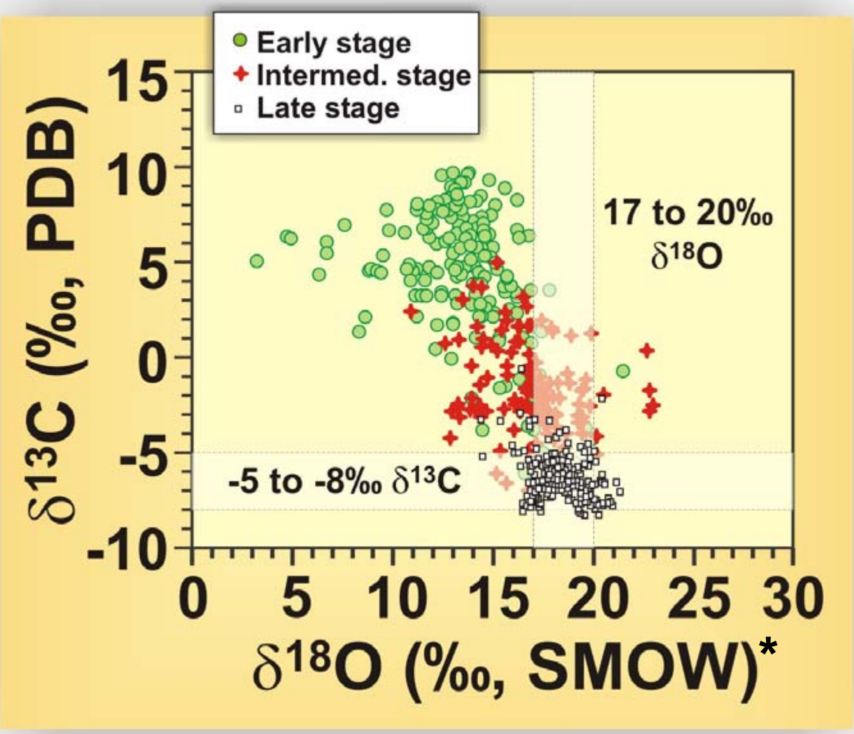
Quaternary Stable Isotope Records

- **600,000-year record of Devils Hole SZ water compositions (Winograd et al. 1992)**
  - **$\delta^{18}O$: 13‰ to 16‰**
    - **Reflects changes in mean annual temperature**
  - **$\delta^{13}C$: -3‰ to -1.5‰**
    - **Reflects changes in vegetation**
- **$\delta^{18}O$ and $\delta^{13}C$ signals show strong negative correlation**



Stable Isotopes in Late-Stage Unsaturated Zone Calcite

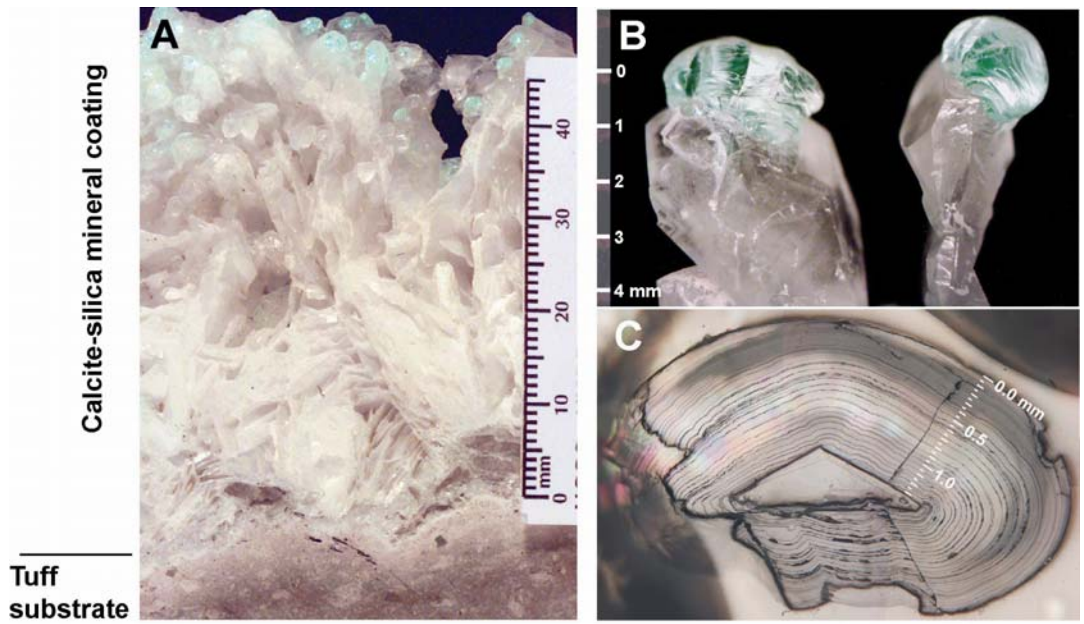
- Late-stage UZ calcite (last 2 – 3 m.y.) has a total range of values (~3 ‰) similar to variations at Devils Hole
  - Correlation between $\delta^{18}O$ and $\delta^{13}C$ is not obvious; however, temperature-depth relations may account for some $\delta^{18}O$ variation
- Interpreted to indicate
  - No obvious control of Pleistocene climate on percolating UZ water
  - Calcite deposition is not restricted to single climate state



SMOW = standard mean ocean water

Micro-Records of Quaternary Climate

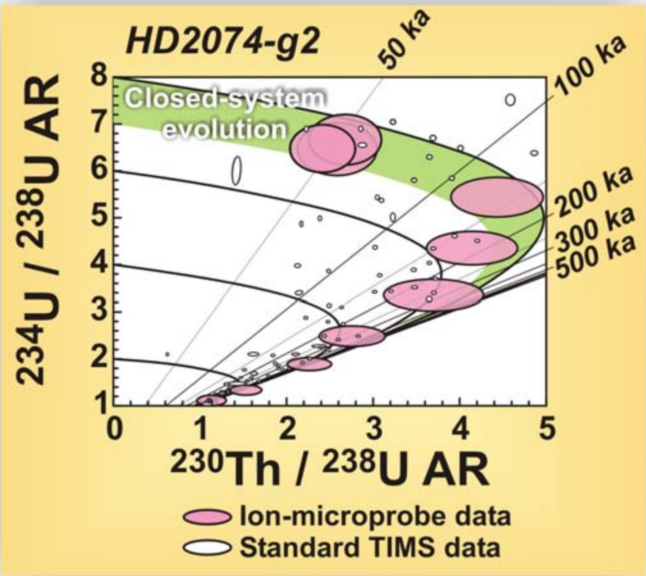
- **Evaluation of Quaternary climate variations require age resolutions at 1,000-year time scales**
- **Slow growth rates require sampling resolution finer than previous efforts (100s of *μ*m)**
- **Two approaches:**
  - **Ion microprobe**
  - **In situ micro-digestion**
- **Sample HD2074:**
  - **Thick coating on lithophysal cavity floor**
  - **Exploratory Studies Facility station 30+51 (TSw)**
  - **~270 m below land surface (repository horizon)**



Ion-Microprobe Dating

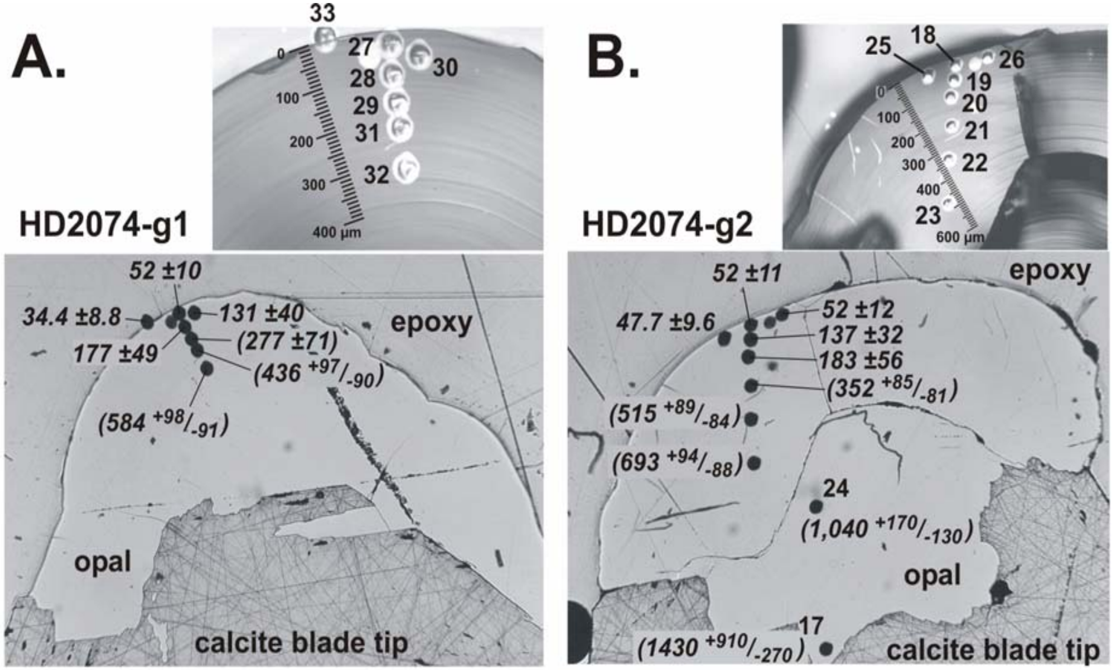
- **Secondary ionization mass spectrometry (SIMS)**
  - **Primary oxygen ion beam focused to ~40 μm spot size - generates secondary U and Th ion beam from opal target**
- **Compared to standard methods**
  - **Lose precision due to small intensity of ion beams**
  - **Gain accuracy due to finer spatial resolution**

USGS-Stanford SHRIMP-RG



Ion-Microprobe Results

- **Depth traverses for two separate opal hemispheres**
  - **Outermost spots consistently yield dates of ~50 ka**
  - **Partial overlap of outer surface yields younger date: indicates spots are mixtures of older- and younger-aged material**
  - **Inner layers become progressively older with depth (to 1.4 m.y.)**

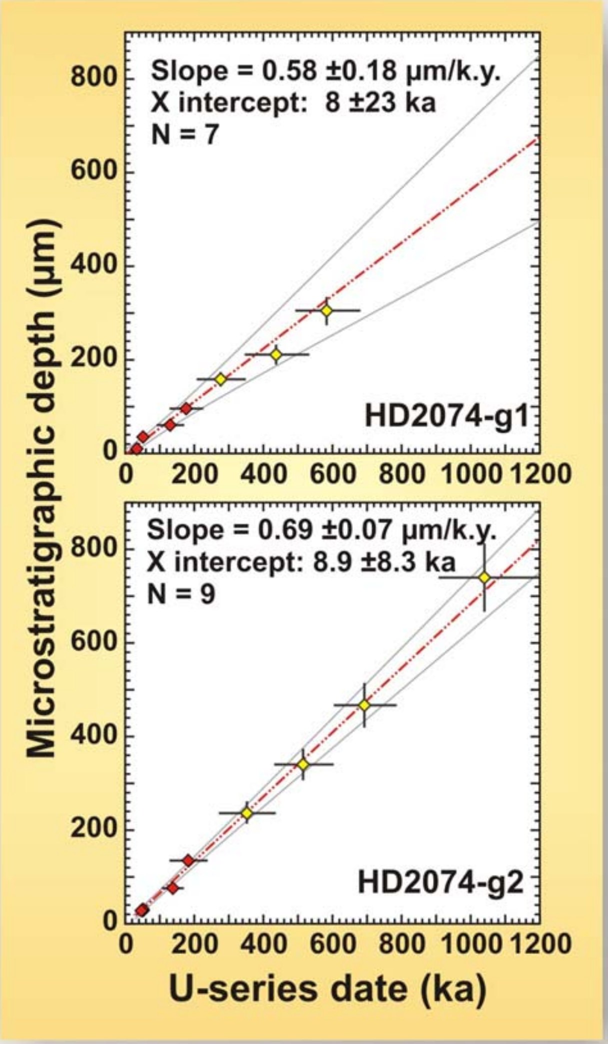


Transmitted light images

Reflected light images

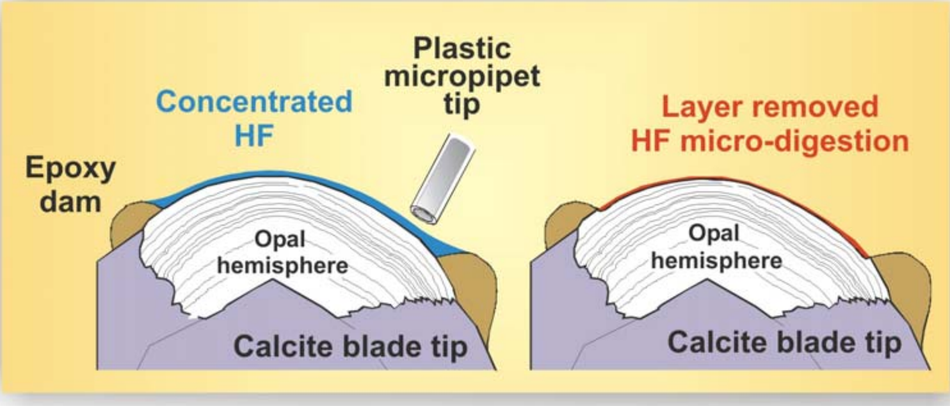
Ion-Microprobe Growth Rates

- **Age-depth relations indicate average growth rates of 0.6 to 0.7 *µ*m/k.y. over the last 1.5 m.y.**
- **No discernable variation in growth rates with time, given spatial and analytical resolution**
- **Growth rates calculated for Pleistocene opal are lower than those determined from U-Pb data across whole coating (5 *µ*m/k.y. for HD2074)**
  - **Consistent with a shift to increased aridity and decreased percolation flux**



Microdigestion-Thermal Ionization Mass Spectrometry Dating

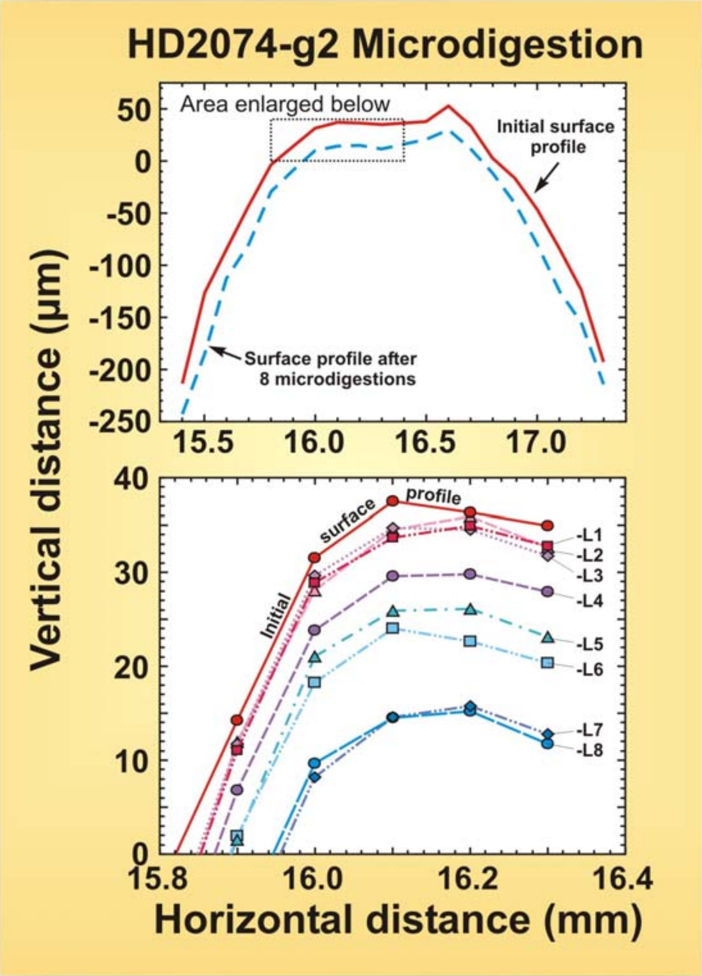
- **In situ digestion of outermost opal layers**
  - Acid confined by wax dam or embedding in epoxy
  - Acid removed after 2 to 10 minutes along with thin layer of dissolved opal
  - Solution is spiked and analyzed by thermal ionization mass spectrometry (TIMS)
- **Results give younger ages and higher initial $^{234}U/^{238}U$ than whole-hemisphere digestion**



Sample HD2074	Thick-ness (μm)	^{230}Th/U date (ka)	Initial $^{234}U/^{238}U$ AR
Whole-hemisphere digestion	~1,000	150 – 230	2.7 – 4.2
Single micro-digestion	<5	4.0 – 11.6	6.1 – 7.0

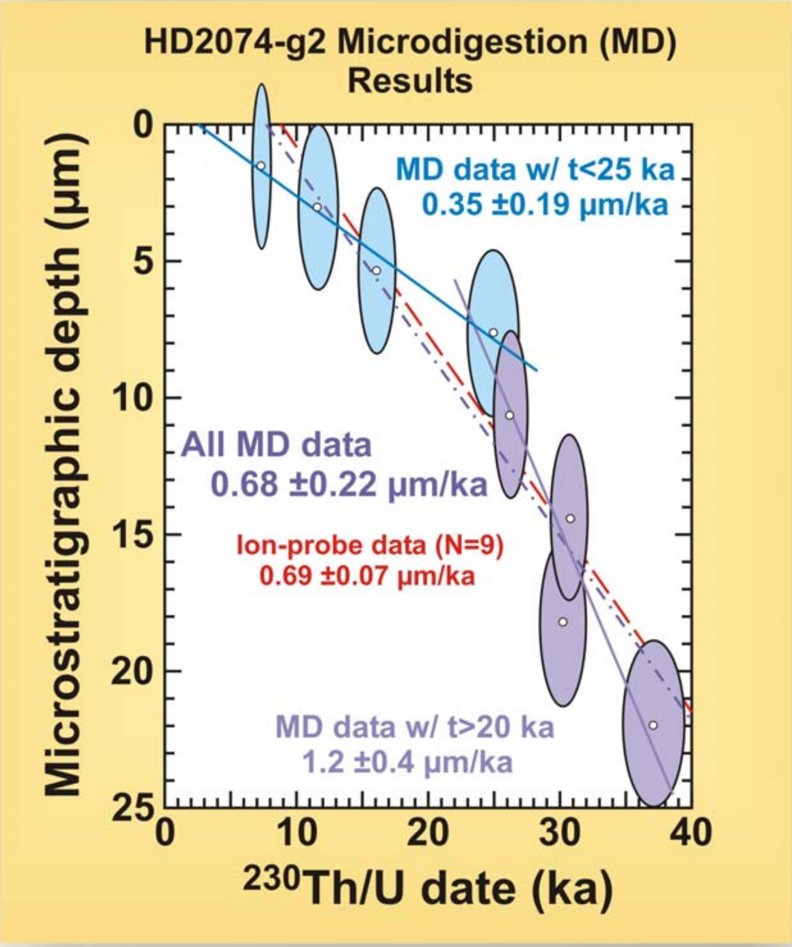
Sequential Microdigestion

- Microdigestion method can be used to analyze progressively deeper layers within a single hemisphere
- Use identical hemisphere dated previously by ion microprobe (HD2074-g2)
- For HD2074-g2, 22 μm of opal were removed in 8 separate digestion steps
  - Each digestion step removed 1.5 to 4 μm of opal



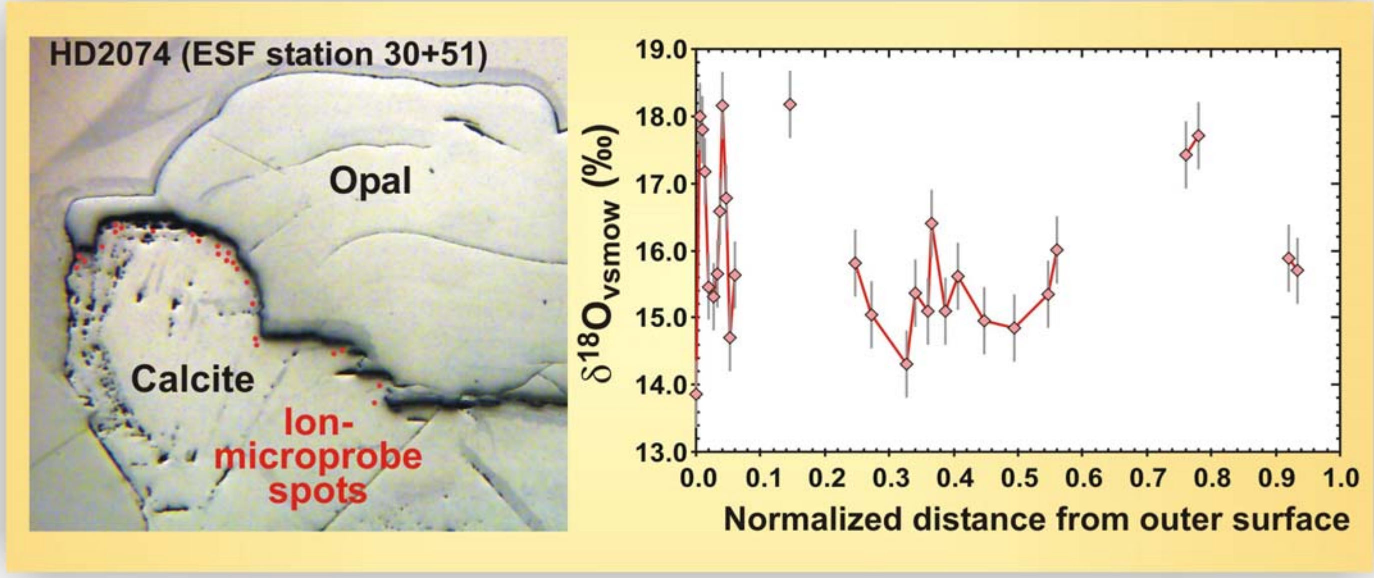
Sequential Microdigestion Results

- ^{230}Th/U ages increase with depth from 7.3 ±0.7 ka to 37.1 ± 2.3 ka
- Age-depth relations for all 8 microdigestions yield an average growth rate of 0.68 ±0.22 *μ*m/k.y.
- Data may define two different slopes with an inflection around 25 ka
- Regressions indicate a non-zero age for outermost opal



Additional Ion-Microprobe Studies

- Initial efforts to analyze $\delta^{18}O$ in late-stage calcite
- Presence of a Pleistocene climate signal?
  - Profiles across outer parts of calcite blades show 3 to 4‰ range in $\delta^{18}O$, similar to conventional analyses of UZ calcite
  - Possible systematic patterns of $\delta^{18}O$ variation with time



~30 *μ*m-diameter spot analyses across outer 2 mm of opal-tipped calcite blade

Additional Ion-Microprobe Studies
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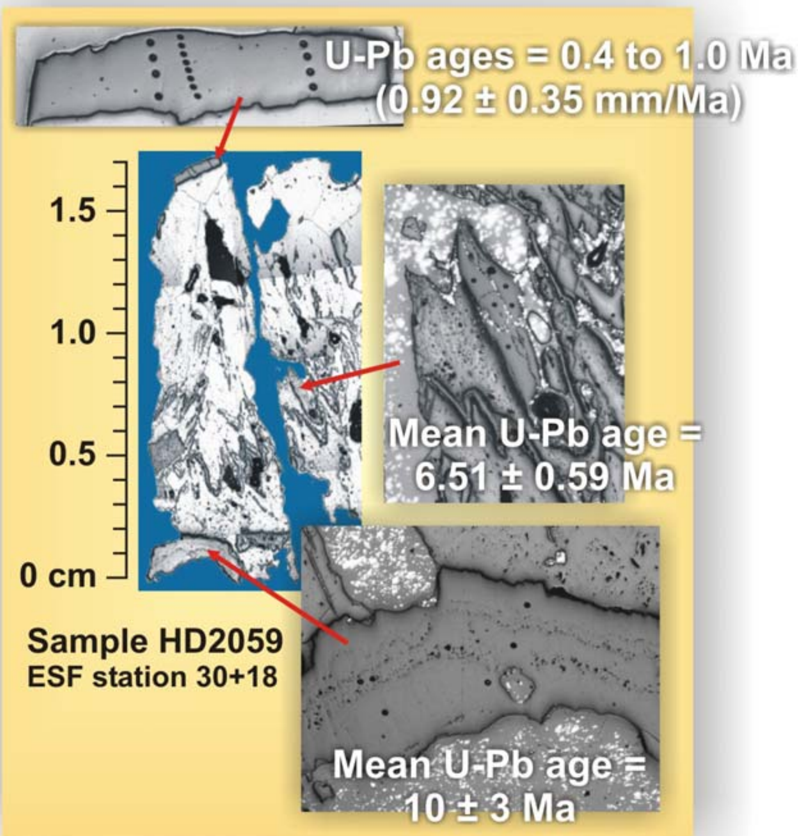
- **Development of U-Pb dating by ion microprobe**
  - **Collaboration with A. Nemchin, Curtin University, Western Australia**



- **As with U-series, 2030 μm spot diameters result in less precise but more accurate U-Pb ages**
- **U-Pb ages for HD2059 outer opal sheet yield a Pleistocene growth rate of 0.92 mm/m.y.**
- **Older U-Pb ages for deeper layers**
- **Growth rate for entire 17 mm-thick coating is higher (2.0 ± 0.2 mm/m.y.)**

Conclusions - I

- **Mineral record reflects the gradual climate shift to more arid Quaternary conditions**
  - **Average Pleistocene UZ mineral growth rates (<1 mm/m.y.) are systematically lower than Tertiary growth rates (1–5 mm/m.y.)**
  - **Timing and δ^{13}C compositional shift in UZ calcite is consistent with a climate-controlled shift in flora**
- **Slow, uniform growth rates (~1 μm/k.y.) are consistent with a UZ hydrogeologic system that**
  - **Is buffered from extreme events and short-term hydraulic fluctuations**
  - **Shows long-term hydrologic stability**
- **Late-stage calcite has δ^{13}C and δ^{18}O compositions that span the range expected for Pleistocene meteoric water**
  - **Implies that deposition was not limited to only part of the Quaternary climate cycle**

Conclusions - II

- **Very high degrees of spatial resolution are necessary to resolve Pleistocene climate signals**
- **Microdigestion dating implies that UZ percolation is not completely buffered from long-term Pleistocene climate change**
  - **Above-average growth rates (increased flux) may be present during full-pluvial climate states (37 to 20 ka)**
  - **Below-average growth rates (decreased flux) may be present during intermediate climate states (25 to 7 ka)**
- **Interpluvial (modern) percolation flux may be too low to exceed seepage threshold**
  - **Depositional hiatus over last few thousand years**
    - **Middle Holocene ages for outermost microdigestions**
    - **Age intercepts for depth-age regressions between 3 and 10 ka**