



U.S. Department of Energy  
Office of Civilian Radioactive Waste Management



# Climate Change and Yucca Mountain Unsaturated Zone Hydrology

Presented to:

**U.S. Nuclear Waste Technical Review Board Panel  
on the Natural System**

Presented by:

**James B. Paces  
U.S. Geological Survey**

**March 9-10, 2004  
Las Vegas, Nevada**

# 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 ( $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ ) and chlorine-36 (low resolution; limited to last pluvial cycle)
  - Secondary hydrogenic minerals



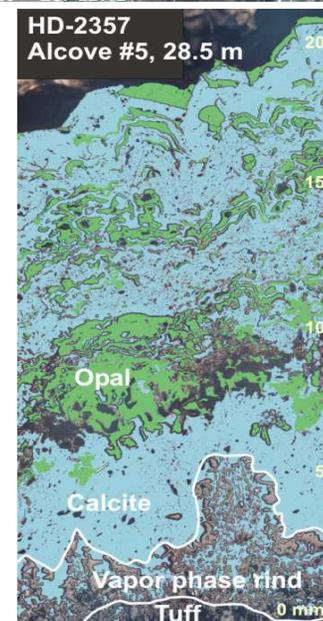
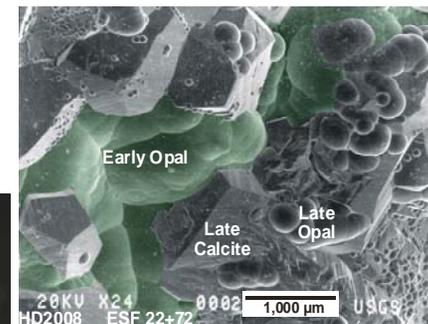
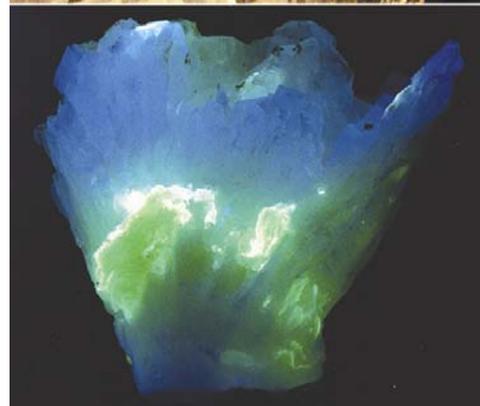
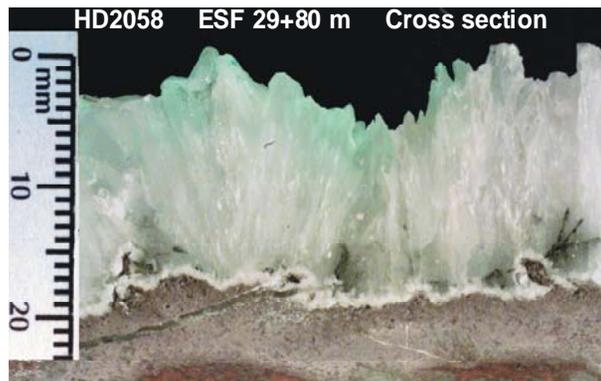
# Importance of Unsaturated Zone Hydrogenetic Minerals

- 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

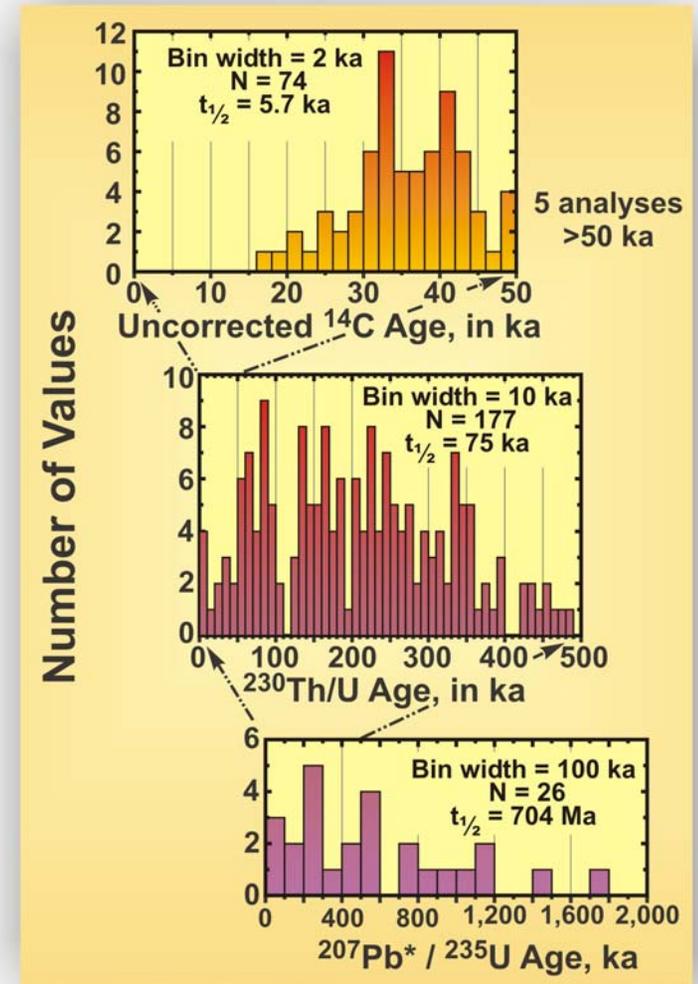
- Records of past climate require reliable geochronological framework
- Minerals can be dated by natural radioactive decay

Material	Concentration	Dating method	Dating range	Amount of material used (mg)
Opal (SiO <sub>2</sub> •nH <sub>2</sub> O)	10 to 500 ppm U	<sup>230</sup> Th/U	~1 to 400 ka	~0.001 to 10's
		<sup>234</sup> U/ <sup>238</sup> U	100 to 1,500 ka	~0.001 to 10's
		<sup>207</sup> Pb/ <sup>235</sup> U	0.1 to 12.7 Ma	0.1 to 10's
Calcite (CaCO <sub>3</sub> )	~0.01-1 ppm U	<sup>230</sup> Th/U	~1 to 400 ka	~50 to 200
	12 wt% C	<sup>14</sup> C	0 to 50 ka	10 to 20 mg



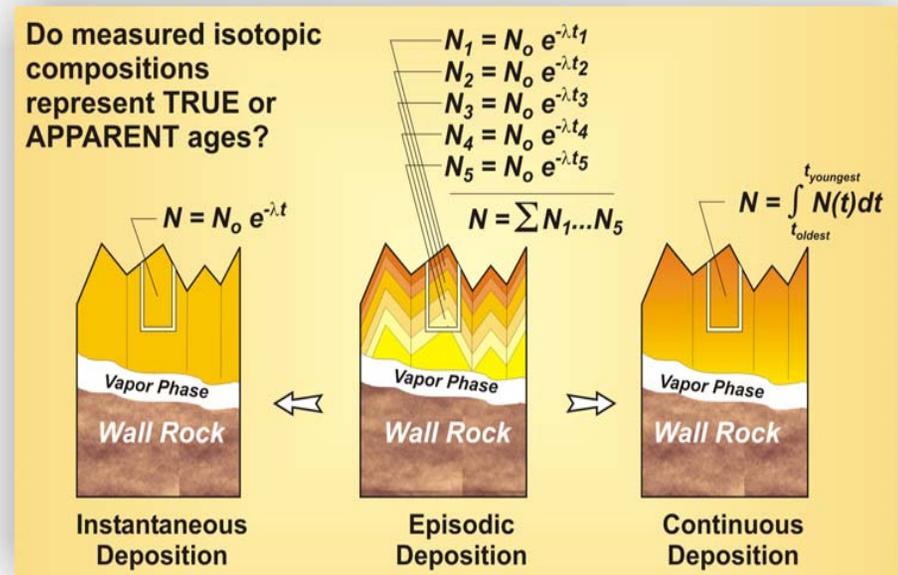
# Initial Dating of Outermost Surfaces

- Outer surfaces of nearly all UZ mineral coatings have Pleistocene  $^{14}\text{C}$  and  $^{230}\text{Th}/\text{U}$  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

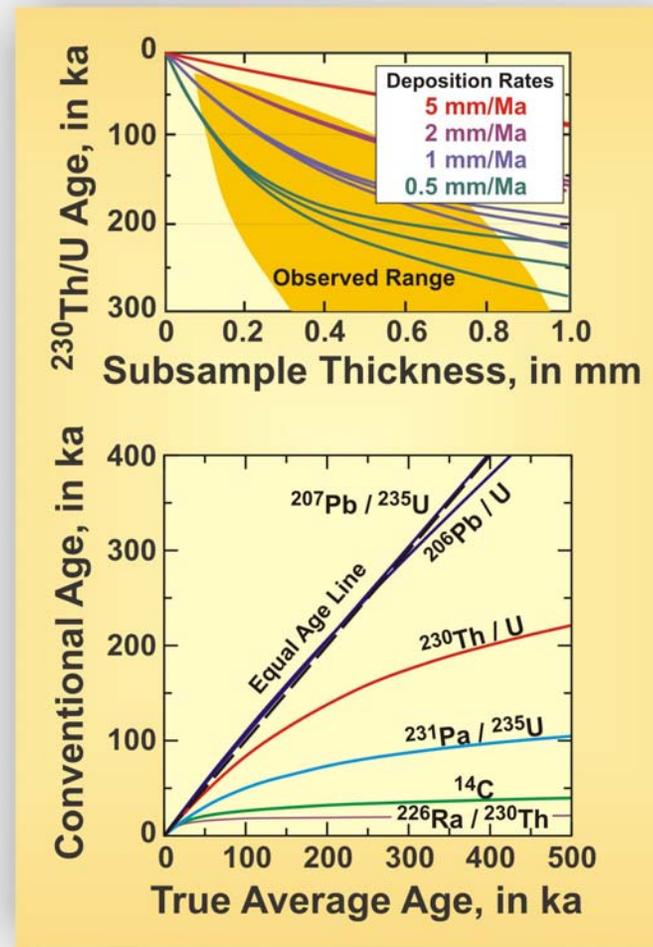


# Numerical Model of Continuous Deposition

- 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

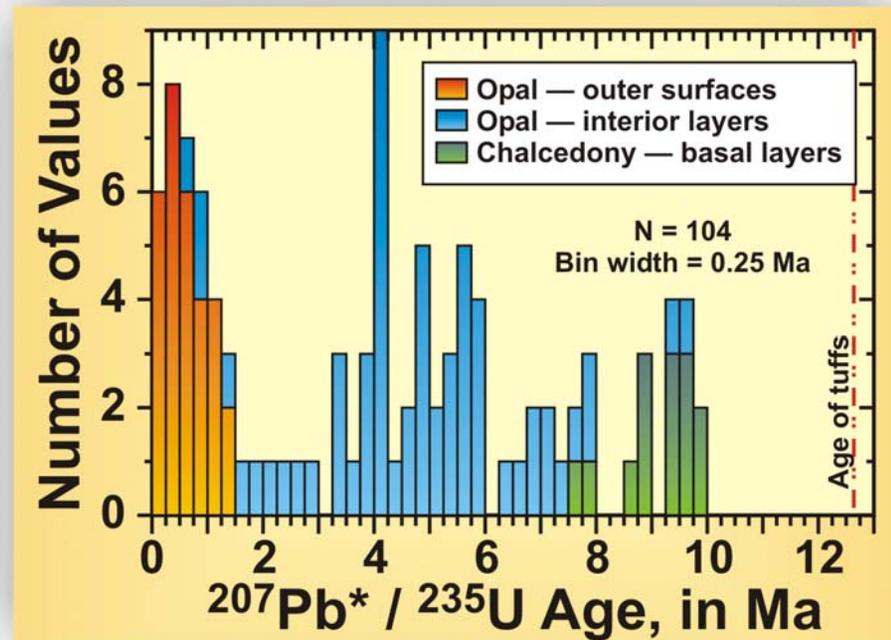
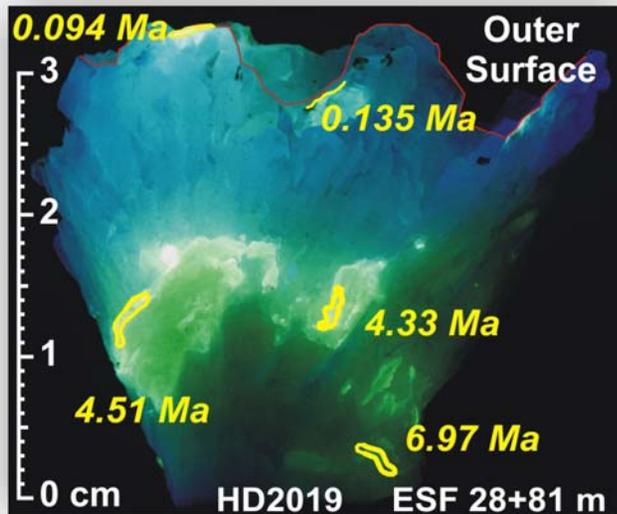
- **Conclusions**

- 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

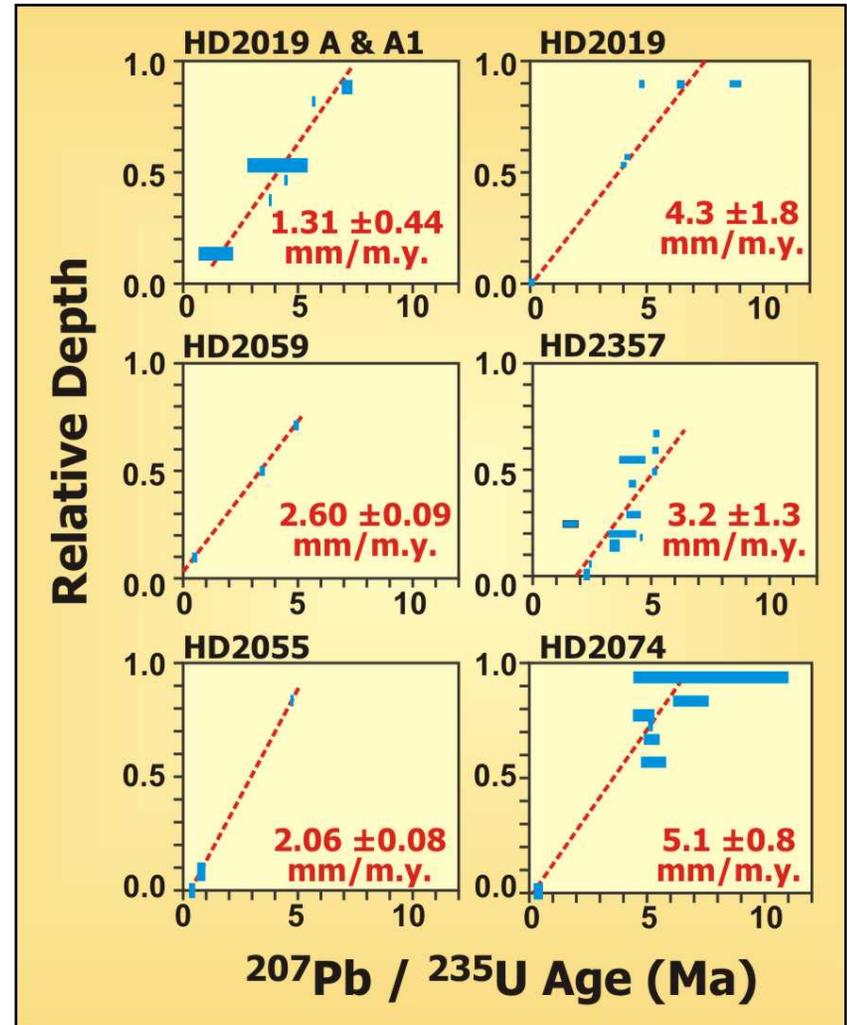
- Growth histories extended by dating of interior layers
  - U-Pb dates are usually concordant with microstratigraphy
  - Basal layers range from 4 to 10 Ma
  - Used to calculate long-term average growth rate



# U-Pb Dating of Interior Layers

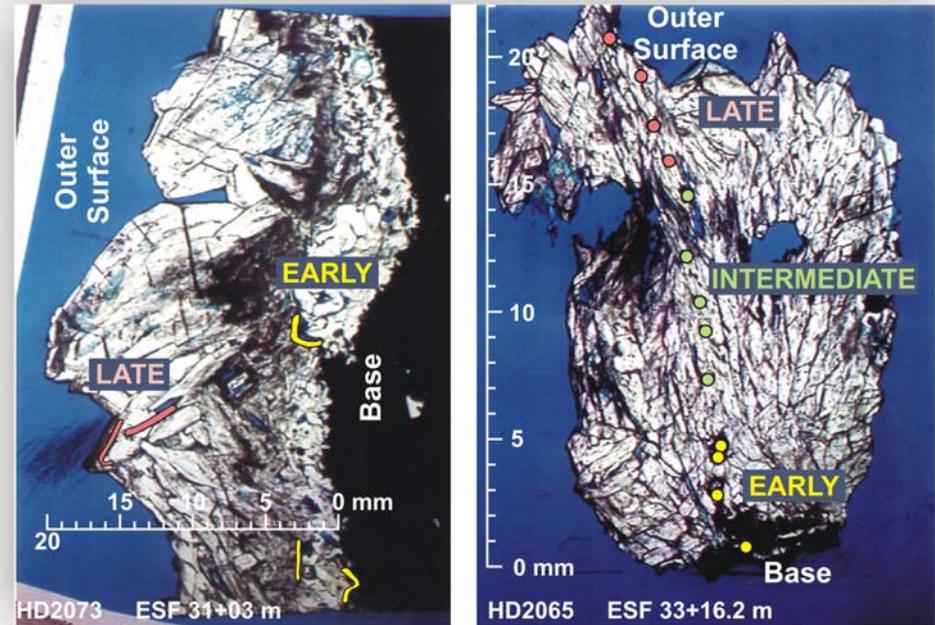
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- Depth-age relations indicate average Tertiary growth rates between 1 and 5 mm/m.y.
- Growth rates are  $10^3$  to  $>10^6$  slower than published speleothem growth rates
- Long-term average growth rates are generally consistent for different parts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



# Isotope Variations in Mineral Coatings

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



Typical Values

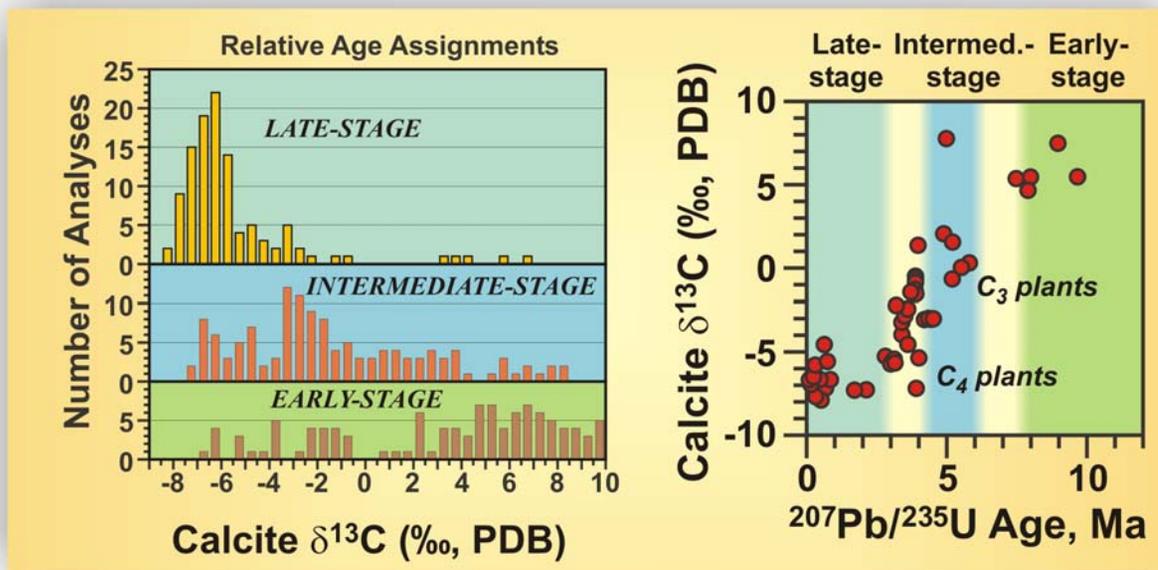
Isotope	Early-stage	Late-stage
$\delta^{13}\text{C}$	+6 ‰	-6 ‰
$\delta^{18}\text{O}$	+10 ‰	+18 ‰
$\delta^{87}\text{Sr}$	+1.8 ‰	+4.5 ‰



# $\delta^{13}\text{C}$ Variations in Mineral Coatings

- Changes in  $\delta^{13}\text{C}$  interpreted to reflect shifts in local flora

Time period	Climate	Dominant flora	Photo-synthetic pathway	Soil calcite $\delta^{13}\text{C}$ (‰)
Tertiary	Wetter, milder	Grasses	$\text{C}_4$	+2 to -5
Quaternary	Drier, seasonal	Shrubs, succulents	Mixed $\text{C}_3$ and $\text{C}_4$	-5 to -8

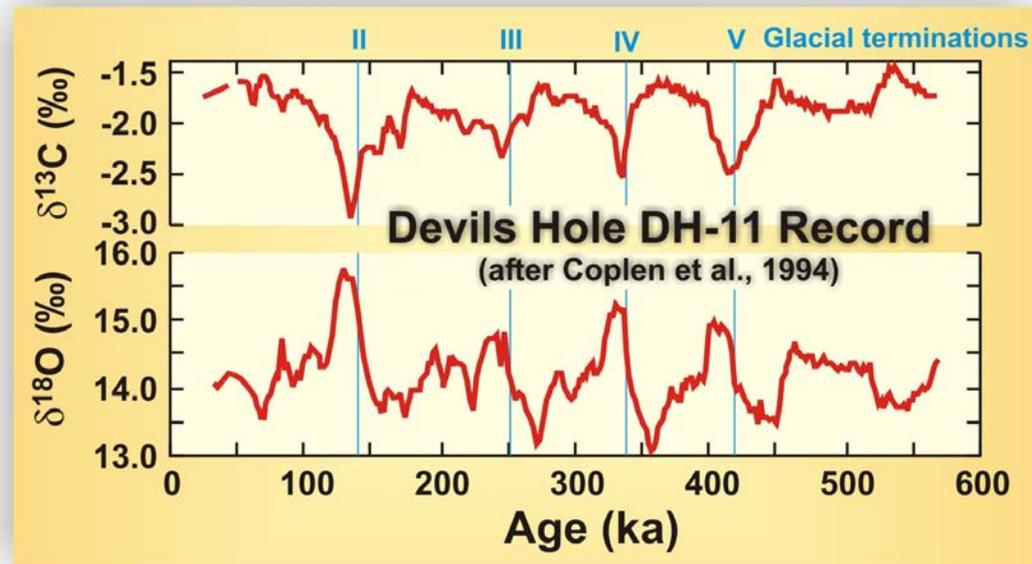


Transition between 2 and 3 Ma correlates with a major shift in climate conditions throughout northern hemisphere



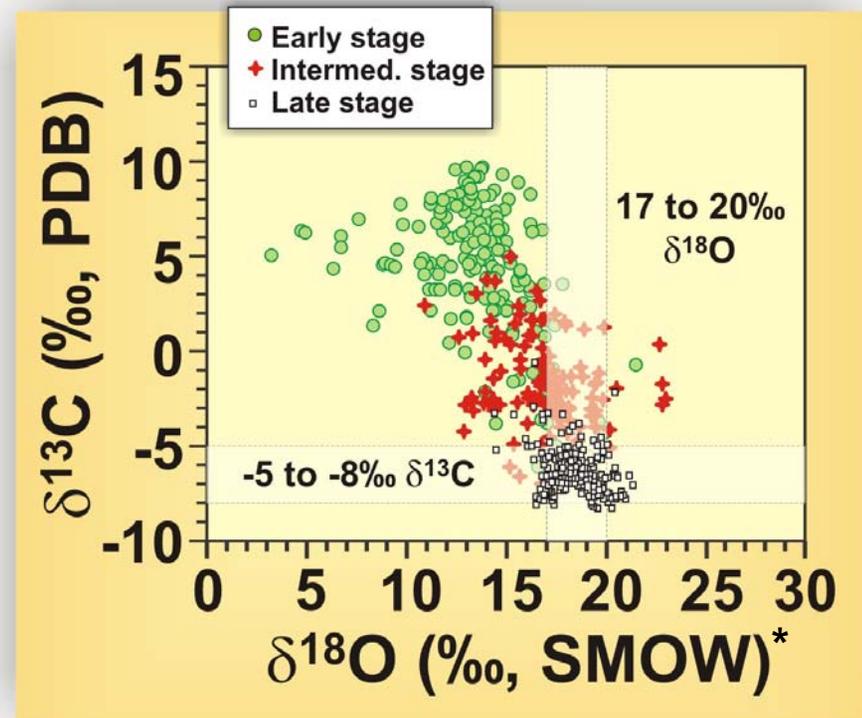
# Quaternary Stable Isotope Records

- **600,000-year record of Devils Hole SZ water compositions (Winograd et al. 1992)**
  - $\delta^{18}\text{O}$ : 13‰ to 16‰
    - ◆ Reflects changes in mean annual temperature
  - $\delta^{13}\text{C}$ : -3‰ to -1.5‰
    - ◆ Reflects changes in vegetation
- **$\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  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 ( $\sim 3\text{‰}$ ) similar to variations at Devils Hole
  - Correlation between  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  is not obvious; however, temperature-depth relations may account for some  $\delta^{18}\text{O}$  variation
- Interpreted to indicate
  - No obvious control of Pleistocene climate on percolating UZ water
  - Calcite deposition is not restricted to single climate state

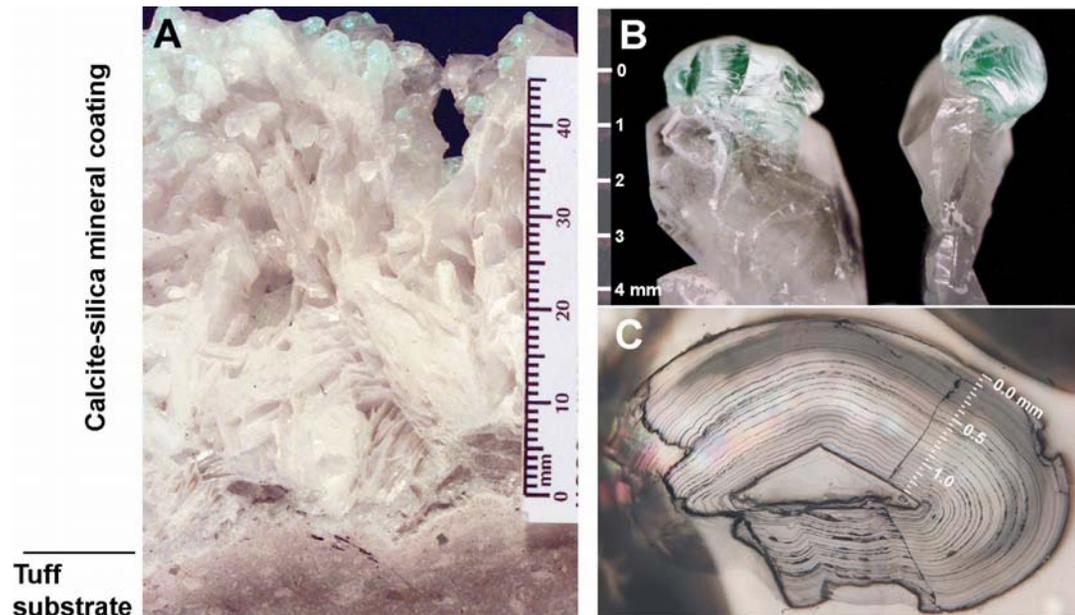


SMOW = standard mean ocean water



# 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  $\mu\text{m}$ )
- 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)

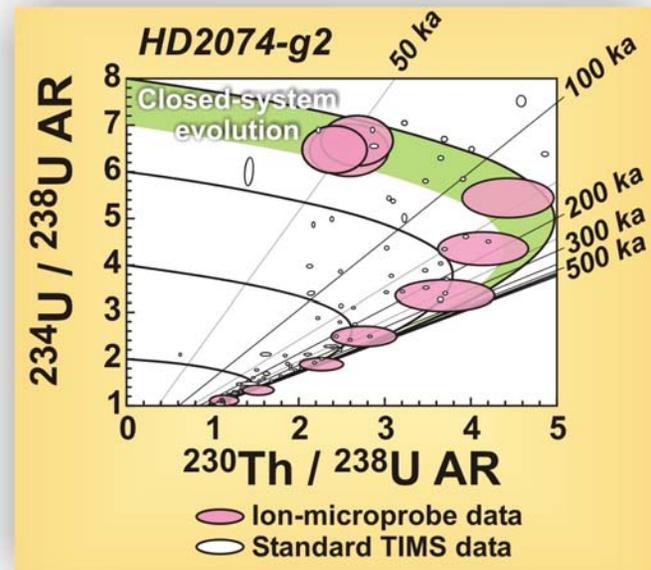


# Ion-Microprobe Dating

- **Secondary ionization mass spectrometry (SIMS)**
  - Primary oxygen ion beam focused to  $\sim 40 \mu\text{m}$  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

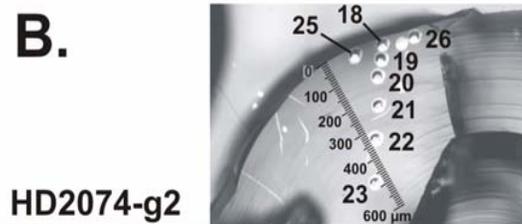
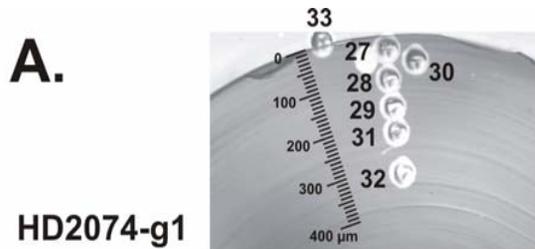


USGS-Stanford SHRIMP-RG

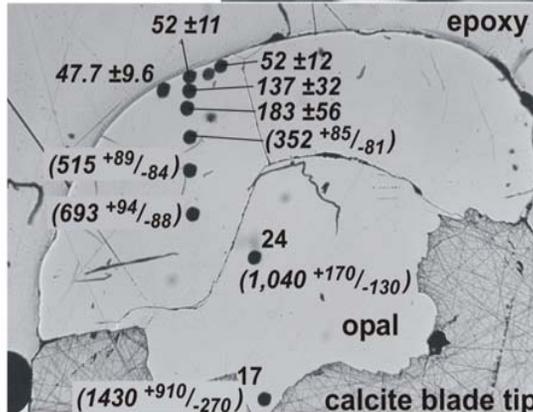
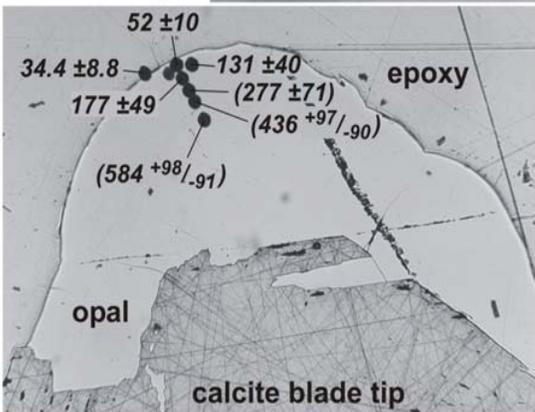


# Ion-Microprobe Results

- 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

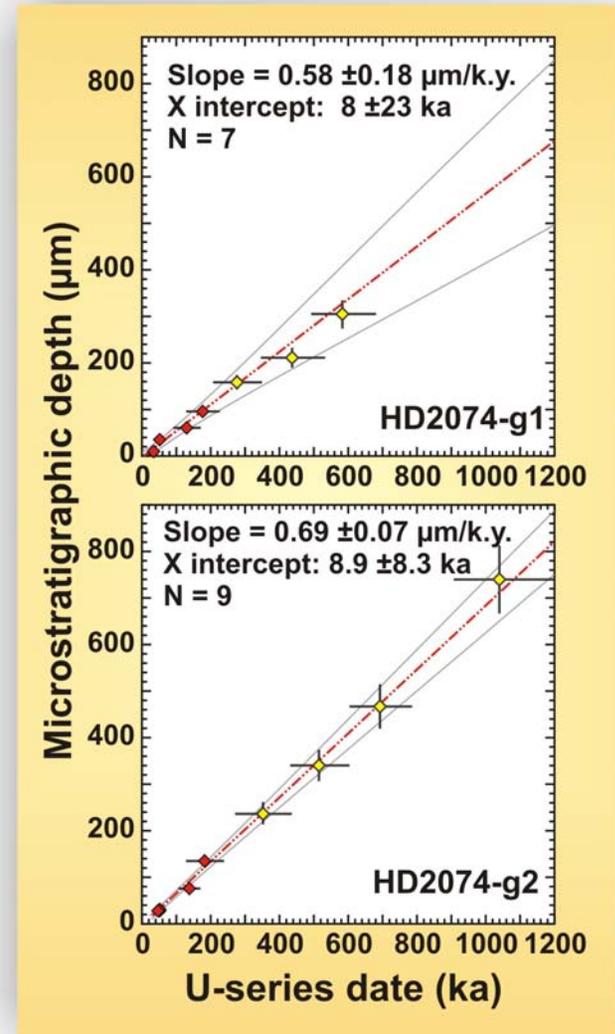


Reflected light images



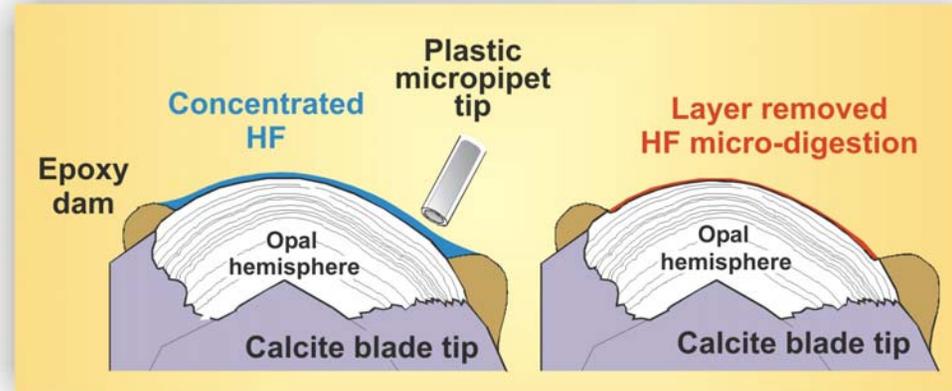
# Ion-Microprobe Growth Rates

- Age-depth relations indicate average growth rates of 0.6 to 0.7  $\mu\text{m}/\text{k.y.}$  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  $\mu\text{m}/\text{k.y.}$  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  $^{234}\text{U}/^{238}\text{U}$  than whole-hemisphere digestion**

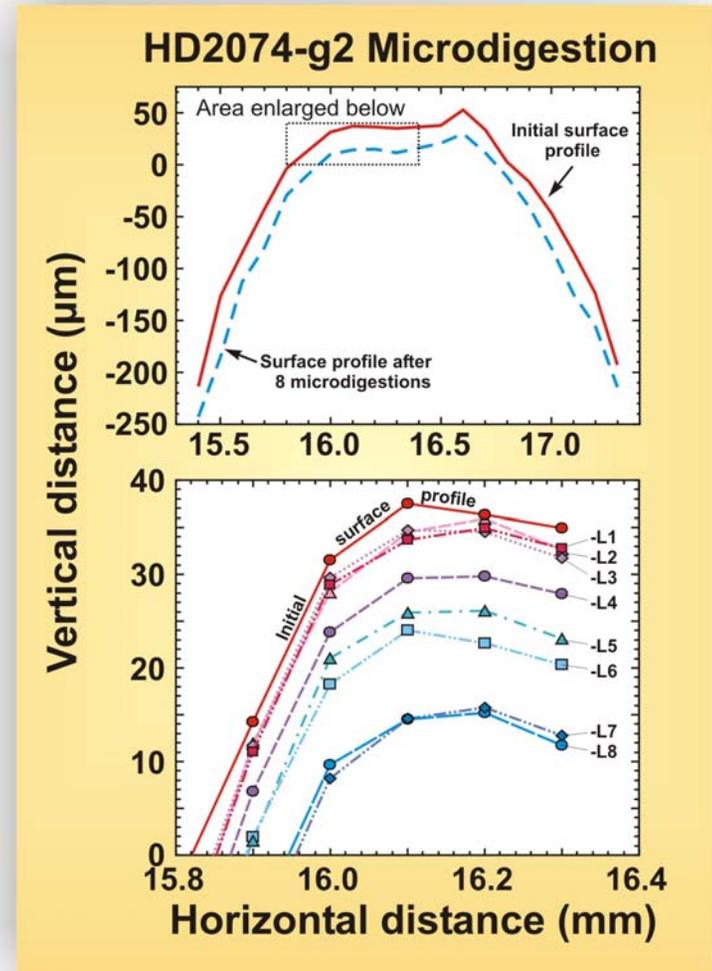


Sample HD2074	Thickness ( $\mu\text{m}$ )	$^{230}\text{Th}/\text{U}$ date (ka)	Initial $^{234}\text{U}/^{238}\text{U}$ AR
Whole-hemisphere digestion	~1,000	150 – 230	2.7 – 4.2
Single micro-digestion	<5	4.0 – 11.6	6.1 – 7.0



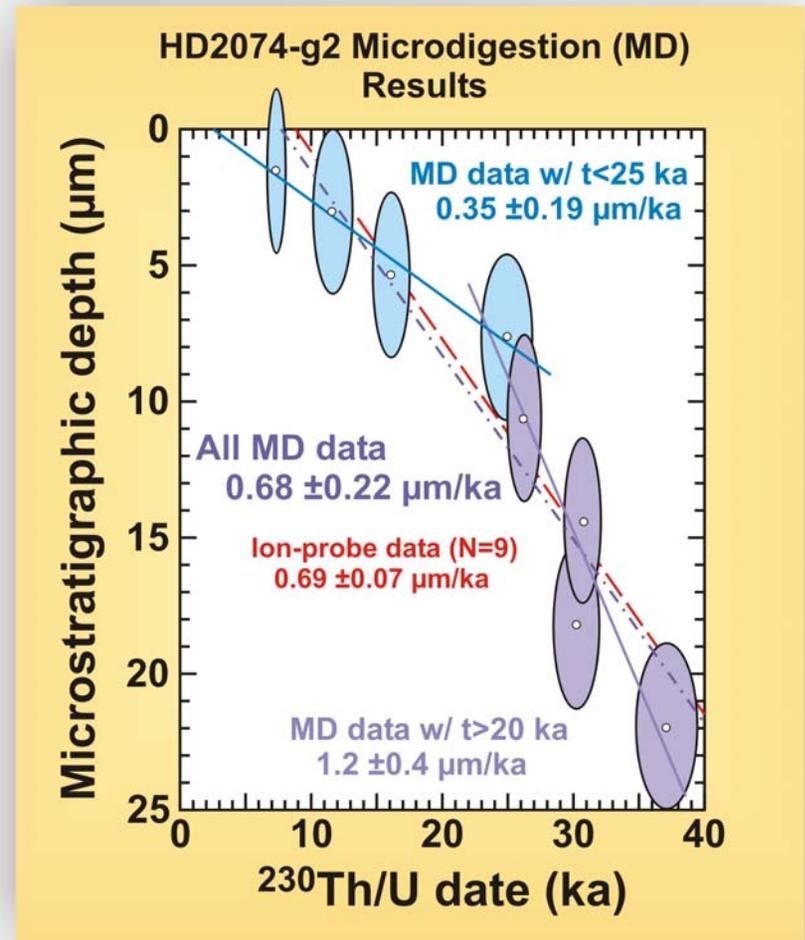
# Sequential Microdigestion

- 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  $\mu\text{m}$  of opal were removed in 8 separate digestion steps
  - Each digestion step removed 1.5 to 4  $\mu\text{m}$  of opal



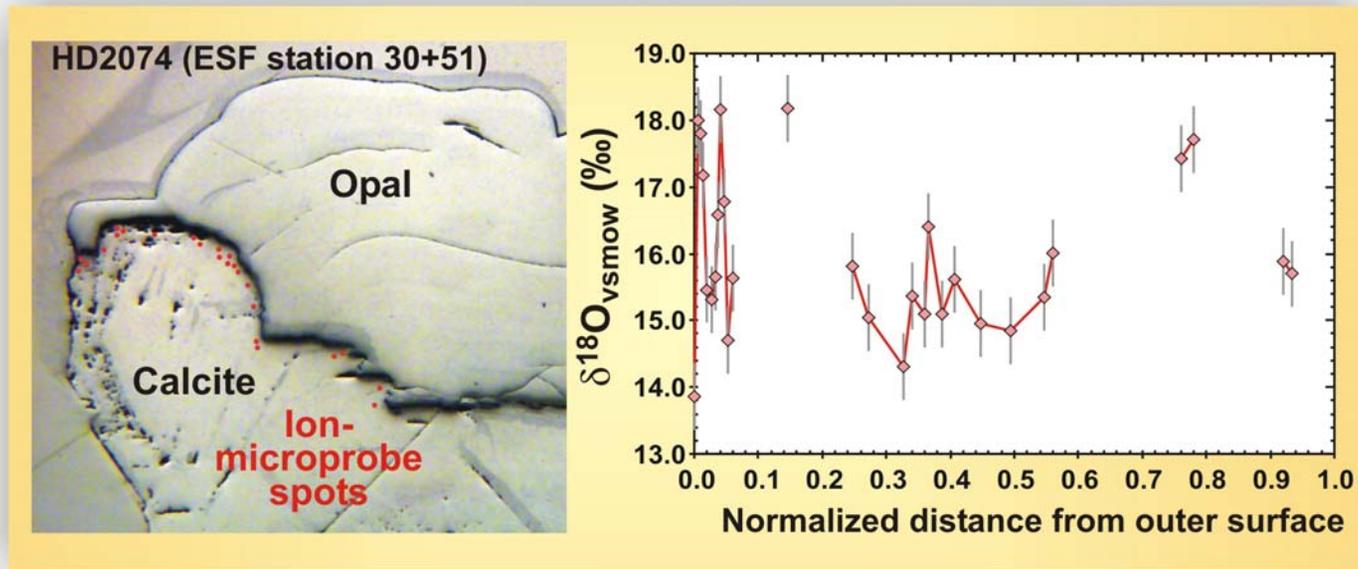
# Sequential Microdigestion Results

- $^{230}\text{Th}/\text{U}$  ages increase with depth from  $7.3 \pm 0.7$  ka to  $37.1 \pm 2.3$  ka
- Age-depth relations for all 8 microdigestions yield an average growth rate of  $0.68 \pm 0.22 \mu\text{m}/\text{k.y.}$
- 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  $\delta^{18}\text{O}$  in late-stage calcite
- Presence of a Pleistocene climate signal?
  - Profiles across outer parts of calcite blades show 3 to 4‰ range in  $\delta^{18}\text{O}$ , similar to conventional analyses of UZ calcite
  - Possible systematic patterns of  $\delta^{18}\text{O}$  variation with time



~30  $\mu\text{m}$ -diameter spot analyses across outer 2 mm of opal-tipped calcite blade

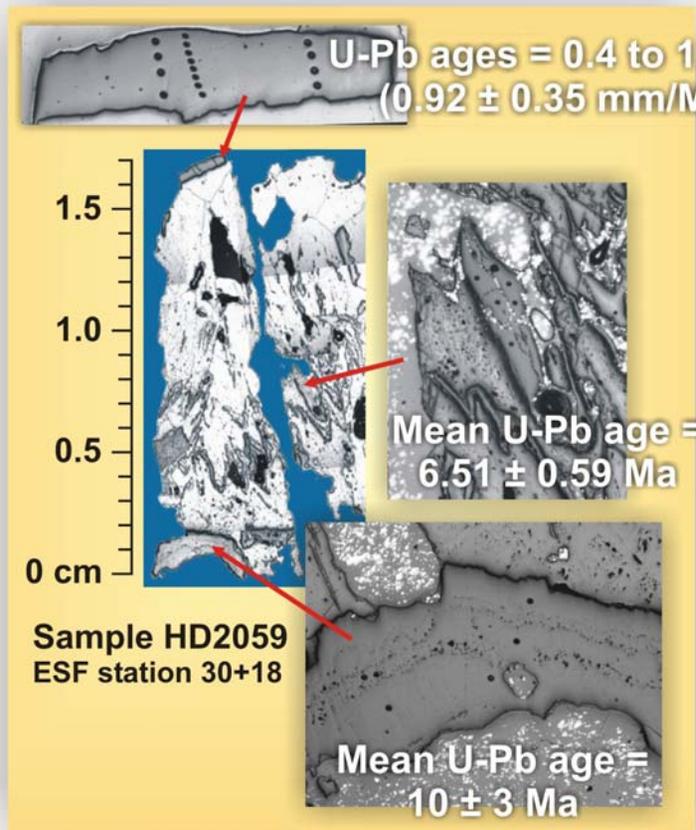


# Additional Ion-Microprobe Studies

(Continued)

## Development of U-Pb dating by ion microprobe

- Collaboration with A. Nemchin, Curtin University, Western Australia



- As with U-series,  $2030 \mu\text{m}$  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 ( $2.0 \pm 0.2$  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  $\delta^{13}\text{C}$  compositional shift in UZ calcite is consistent with a climate-controlled shift in flora
- **Slow, uniform growth rates ( $\sim 1 \mu\text{m/k.y.}$ ) 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  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  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

