Constraints on the timing of basin-forming impact events from excavated crustal rocks

Bill Cassata - Research Scientist
Lars Borg – Research Scientist
Nuclear & Chemical Sciences Division

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Lawrence Livermore National Laboratory

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Impact history of the Moon largely based on Ar-Ar ages

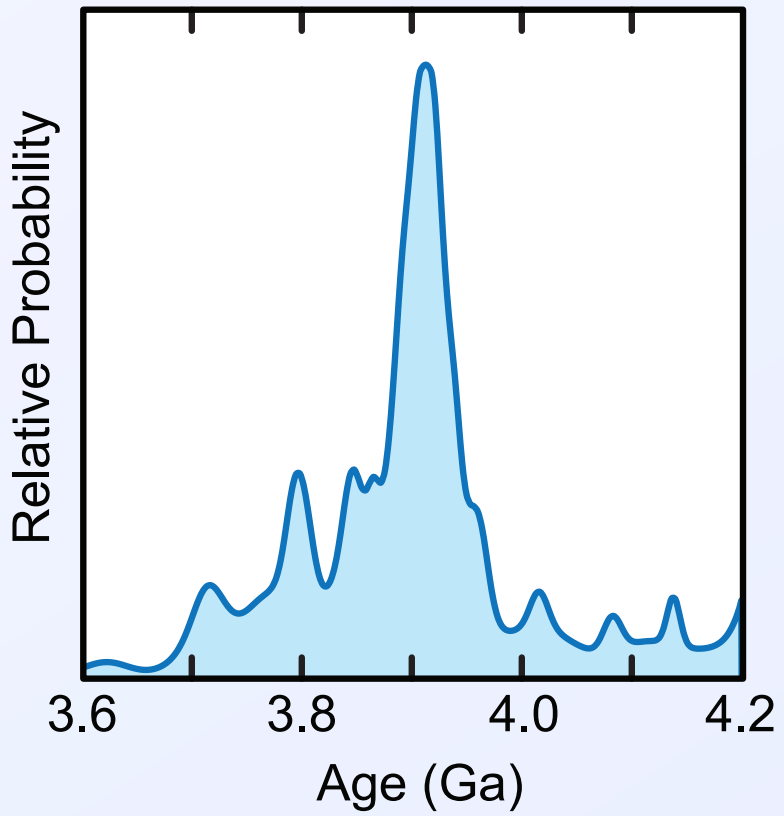
Preponderance of impact melt rocks in the Apollo collections formed ~3.8 – 4.0 Ga.

Two end-member explanations:

(1) Late Heavy Bombardment

(2) Sampling bias[e.g., 1-4]

- *geographically restricted landing sites*
- *superposition of younger ejecta*
- *resetting of old ejecta (preservation bias)*



[1,2]: Hartmann, 1975; 2003 [3]: Haskin et al., 1998 [4]: Chapman et al., 2007

Constraints on basin-forming impacts from crustal rocks

Many crustal rocks yield Ar-Ar ages considerably older than 3.9 Ga, but younger than their Sm-Nd, Rb-Sr, and U-Pb ages

- may provide additional constraints on early bombardment history of the Moon[e.g., 1-3]

Ar-Ar ages can be ambiguous:

(1) Excavation by basin-forming impact
- If the sample resided at sufficient depth in the crust to preclude quantitative retention of radiogenic Ar, may date impact.

(2) Conductive cooling in the crust
- secular, plutonic, metamorphic, etc.

(3) Resetting at surface in ejecta blanket
- May or may not be a basin-sized event

Select radioisotopic ages for 76535

System	Age (Ma)
Pb-Pb	4375 ± 1
Rb-Sr	4308 ± 45
^{147}Sm-^{143}Nd	4307 ± 11
^{146}Sm-^{142}Nd	$4297\ ^{+29}/_{-36}$
Ar-Ar	4230 ± 4[13]

Data from Borg et al. (2014) and this study. Uncertainties on Ar-Ar age reflect analytical and systematic (in brackets) uncertainties, including decay constant and standard age uncertainties.

[1]: Turner et al. (1973) [2]: Turner & Cadogan (1975) [3]: Garrick-Bethell et al. (2008)

Which crustal rocks date basin-forming impacts?

Thermal modeling can help us better understand the significance of Ar-Ar ages in exhumed crustal rocks.

Goal: Determine if the Ar-Ar ages of crustal rocks are associated with basin-forming impacts or other thermal phenomena (e.g., cooling in the crust)

(1) Detailed diffusion experiments using temperature-controlled, diode laser step-heating.

(2) Diffusion kinetics coupled with chronometric data and petrologic constraints on cooling rates and crustal residence depths to construct thermal histories

Samples discussed in this talk

Sample	Ar-Ar Age (Ma)	Depth (km)
76535	4230 ± 4 [13]	40-50[1]
78238	4215 ± 17 [21]	8-30[2]

Ar-Ar data from this study.

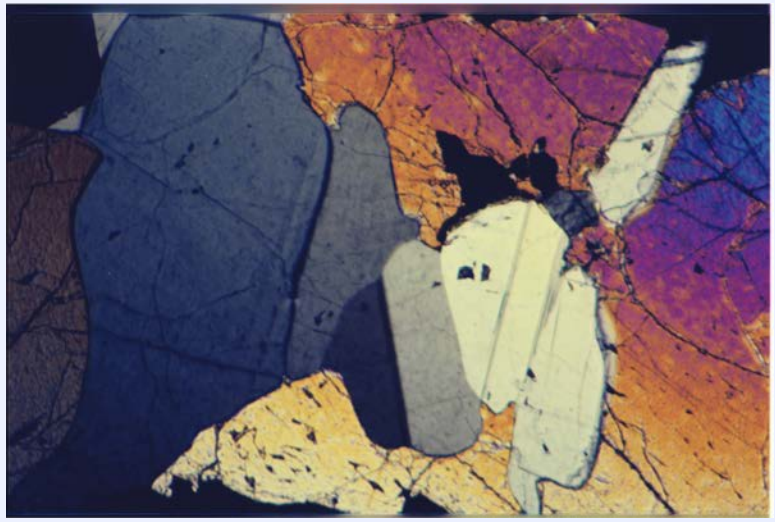
[1]: McCallum & Schwartz (2001) [2]: Jackson et al. (1975)

76535 – Sample Information

(1) Formed as cumulate, underwent subsolidus re-equilibration at ~40-50 km depth
- equilibrium compositions of mineral phases (McCallum & Schwartz, 2001)

(2) Cooled slowly in crust to 700 – 400 °C
- mineral textures, phase relations of co-existing metals (Gooley et al., 1974)

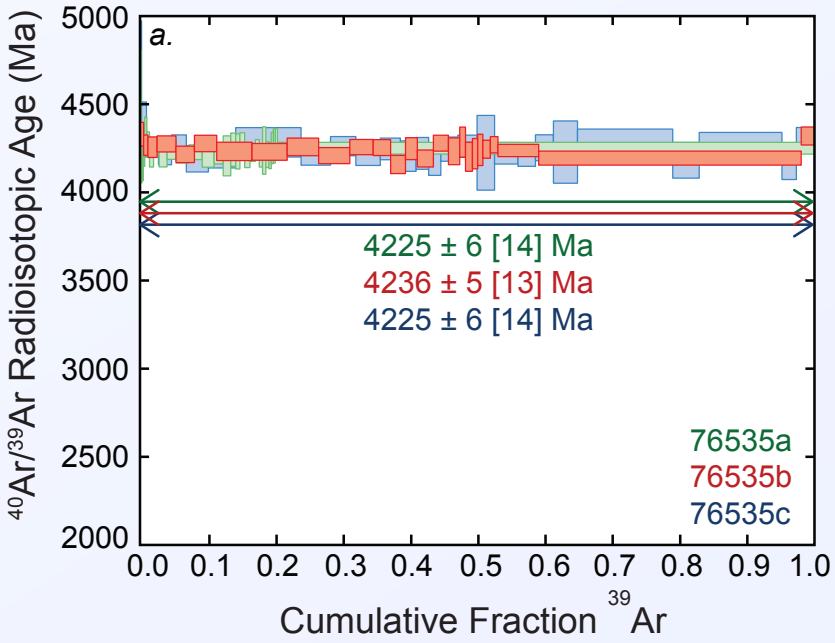
(3) Cooled rapidly from 500 °C (~0.04 C/yr)
- ordering in pyx. (McCallum et al., 2006) and plag. domain structure (Nord, 1976)

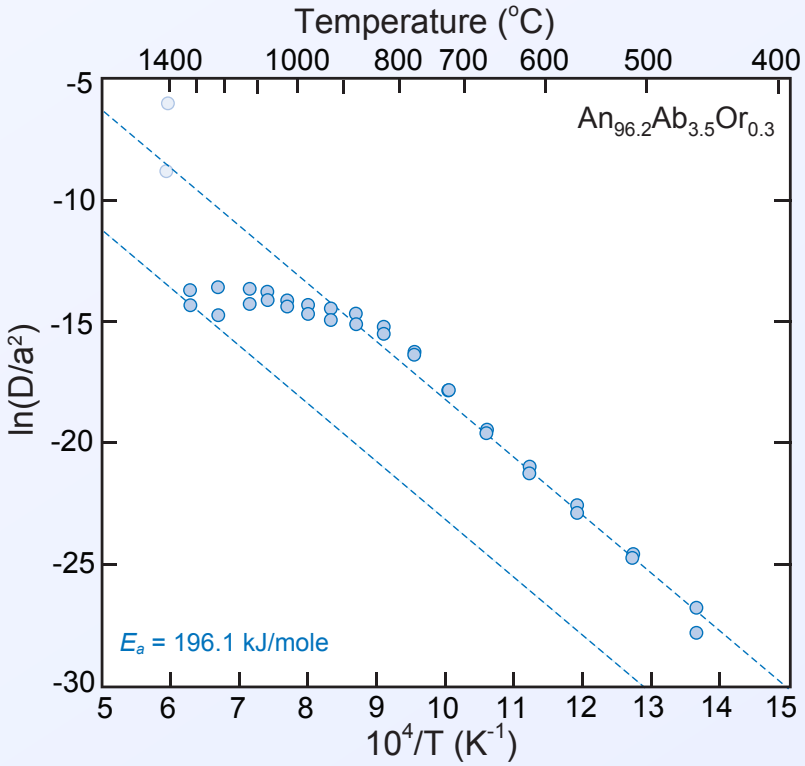


76535 – Chronology and Diffusion Kinetics

Three aliquots yield 100% concordant plateaus defining an age of **4230 ± 4 [13] Ma**

- Indistinguishable from previous Ar-Ar ages[1-4], but younger than Sm-Nd, Pb-Pb, Rb-Sr





Diffusion parameters are typical of high-Ca plagioclase with a range in diffusion domain/sub-grain dimensions

Does the Ar-Ar age may reflect excavation, conductive cooling in the crust, or near-surface resetting following an impact event?

[1]: Husain & Schaeffer (1975) [2]: Huneke & Wasserburg (1975) [3]: Bogard et al. (1975) [4]: Garrick-Bethell et al. (2009)

76535 – Cooling or exhumation age from Ar-Ar?

How well is Ar retained during crustal residence at depth?

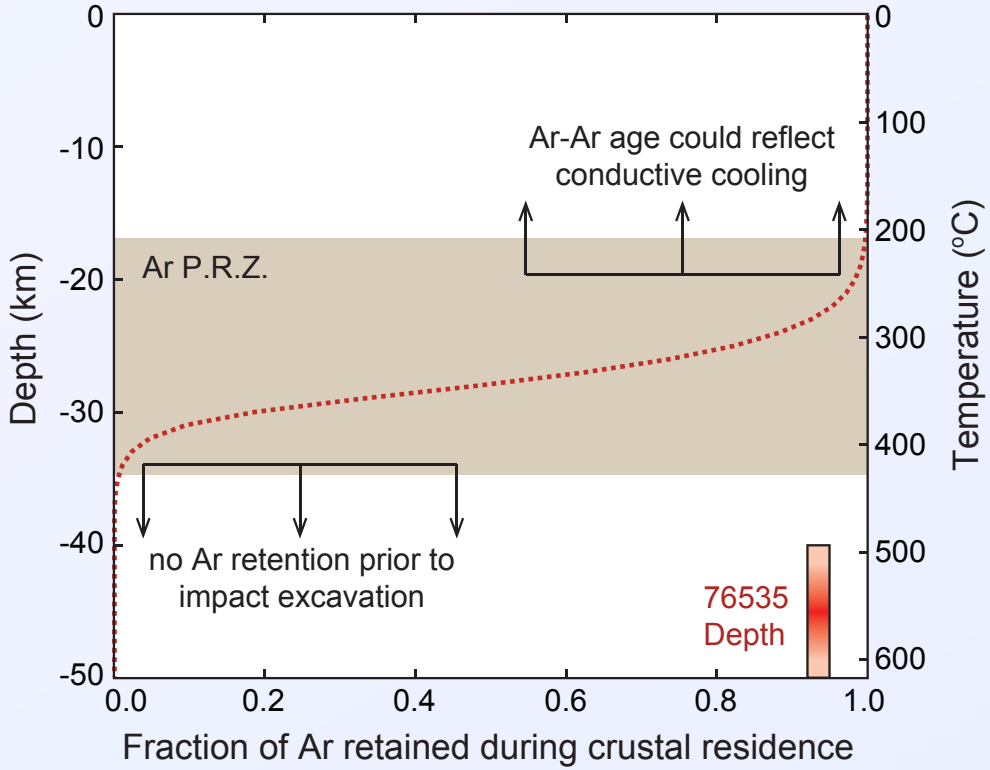
Depth of crustal residence is 40 – 50 km (McCallum & Schwartz, 2001)
Crustal residence temperature is 490 – 615 °C (assuming DT/dx = 12.3 °C/km)

(1) *Diffusion kinetics **are not** consistent with age constraining cooling in crust.*
- requires crustal residence at <20 km

(2) *Diffusion kinetics **are** consistent with age constraining excavation*[1]
- crater diameter of >650 – 850 km

(3) It is also possible that sample was exhumed prior to 4230 ± 13 Ma, and was then reset in an ejecta blanket at 4230 ± 13 Ma.

What size impact event would be required to reset the K-Ar system?



[1]: McCallum et al. (2006) [2]: Garrick-Bethell et al. (2008) ArPRZ based on 100 Ma residence, diffusion kinetics of large domain

Thermal modeling of ejecta blankets

Resetting of K-Ar system in ejecta blankets depends on t-T conditions

- Ejecta thickness as a function of distance & crater diameter from Housen et al. (1983) [Eq. 1]
- Ejecta temperature as a function of crater diameter from Abramov & Mojzsis (2012) [Fig. 1]
  - T variations with distance may exist. Fernandes & Artemieva (2012) indicates hotter at greater distance

Eq. (1) Ejecta thickness

$$t = 0.0078R\left(\frac{r}{R}\right)^{-2.61}$$

Fig. (1) Ejecta temperature

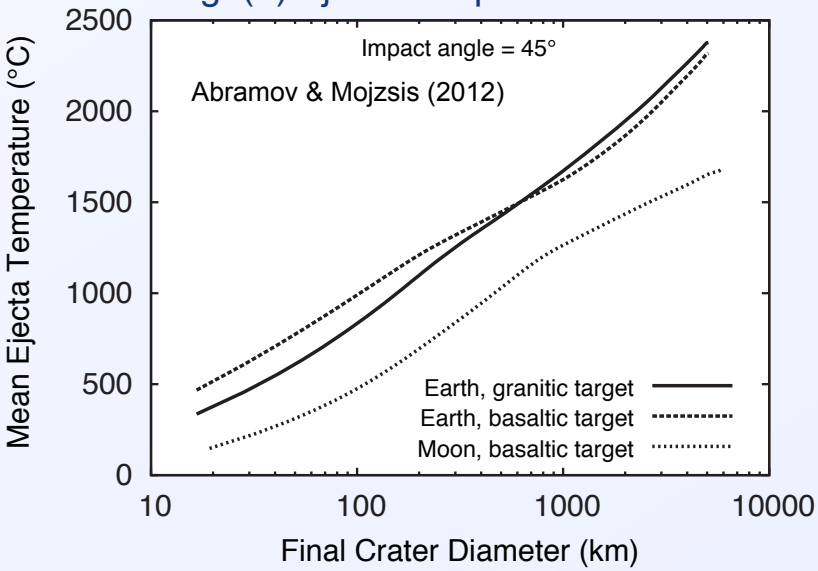
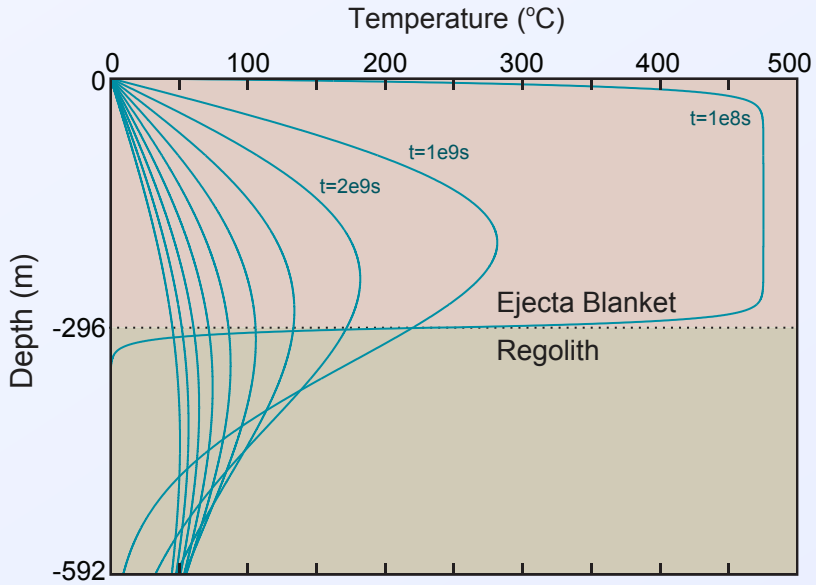
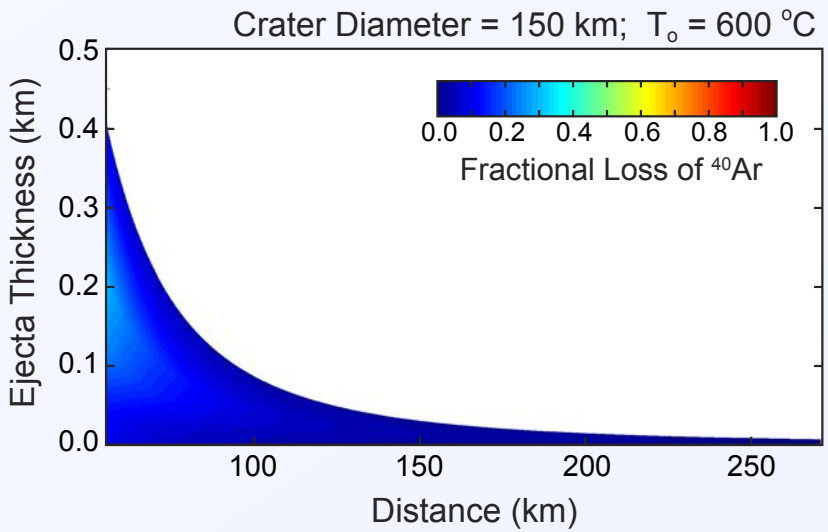


Fig. (2) Thermal Model – conductive cooling

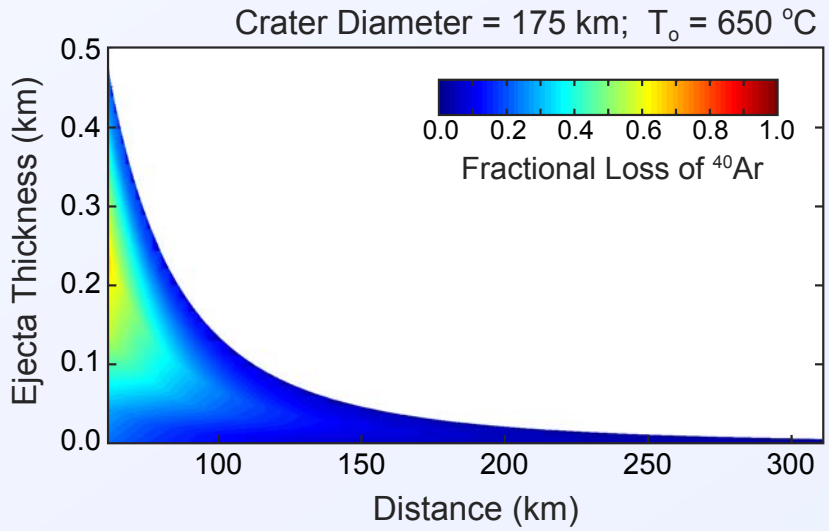


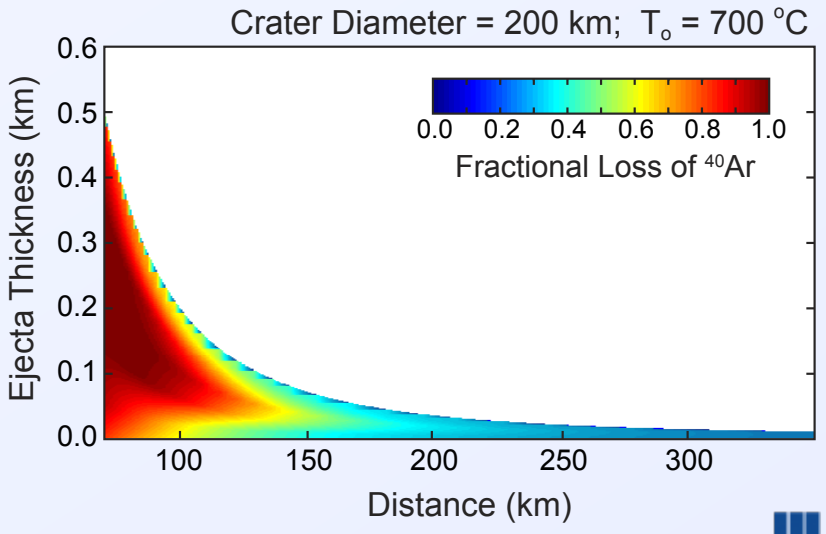
76535 – Thermochronometry (cont.)



Ejecta blanket from crater with D >175 km likely required to reset K-Ar clock in 76535.

- temperatures (>650 °C) are greater than indicated by ordering in pyroxene (~500 °C)[1]





[1]: McCallum et al. (2006)

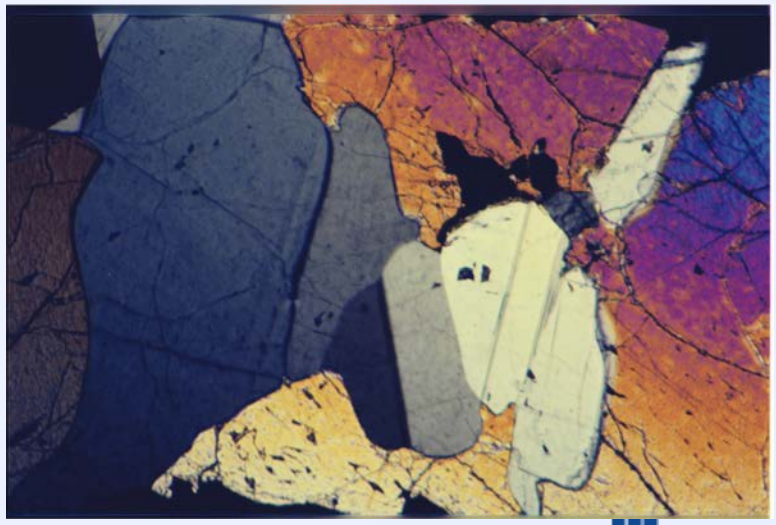
76535 – Two possible thermal histories

(1) 76535 was excavated from 40 - 50 km depth at 4230 ± 13 Ma (D *>650 - 850 km)*
- *most consistent with petrographic constraints on thermal history*
- *suggested by previous authors based on various lines of reasoning*[e.g., 1-3]

(2) 76535 was excavated from 40 - 50 km depth prior to 4230 ± 13 Ma **&** a subsequent impact event producing a crater with D >175 km occurred at 4230 ± 13 Ma

Age of 76535 does not reflect cooling in the crust, with excavation occurring later.

An impact event producing a crater with D >650 km occurred between 4230 ± 13 and 4307 ± 11 Ma & an impact event with D >175 km occurred at 4230 ± 13 Ma

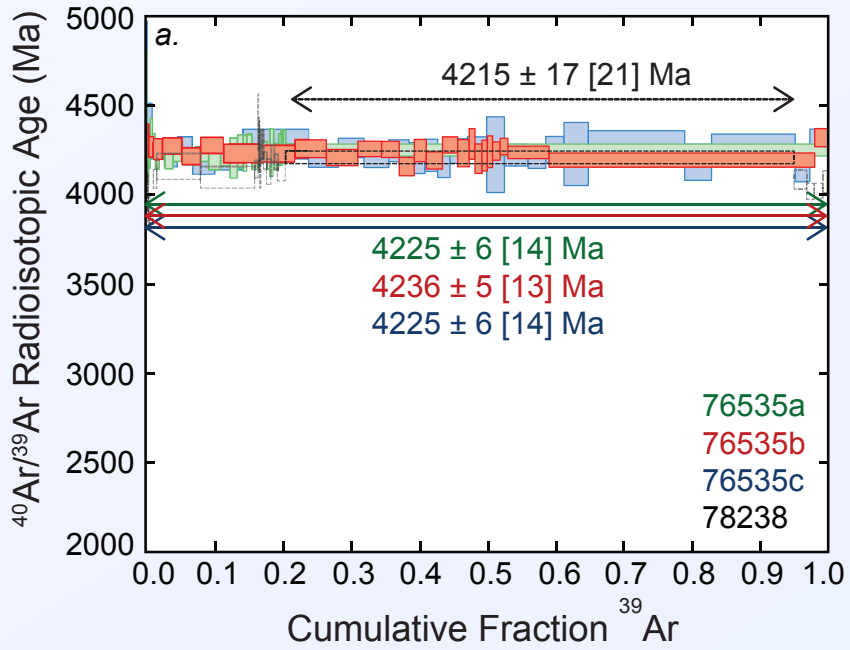


[1]: Nord, 1976 [2]: McCallum et al. (2006) [3]: Garrick-Bethell et al. (2008)

78238 – Sample Information

Shocked (300 – 500 kbar)[1,2] norite – plagioclase converted to maskelynite
Derived from depth of 8 - 30 km depth in the crust (Jackson et al., 1975)

Plateau age of **4215 ± 17 [21] Ma** - indistinguishable from 76535
- Consistent with recent Ar-Ar age on 78235 (4210 ± 27 Ma; Fernandes et al., 2013)[1]
- Younger than recent Sm-Nd, Rb-Sr, and Pb-Pb ages



Select radioisotopic ages for 78238

System	Age (Ma)
Pb-Pb	4333 ± 59
Rb-Sr	4359 ± 24
^{147}Sm-^{143}Nd	4334 ± 34
Ar-Ar	4215 ± 17[21]

Data from Edmunson et al. (2009) and this study

[1]: recalculated using the decay constant and standard calibration of Renne et al. (2013)

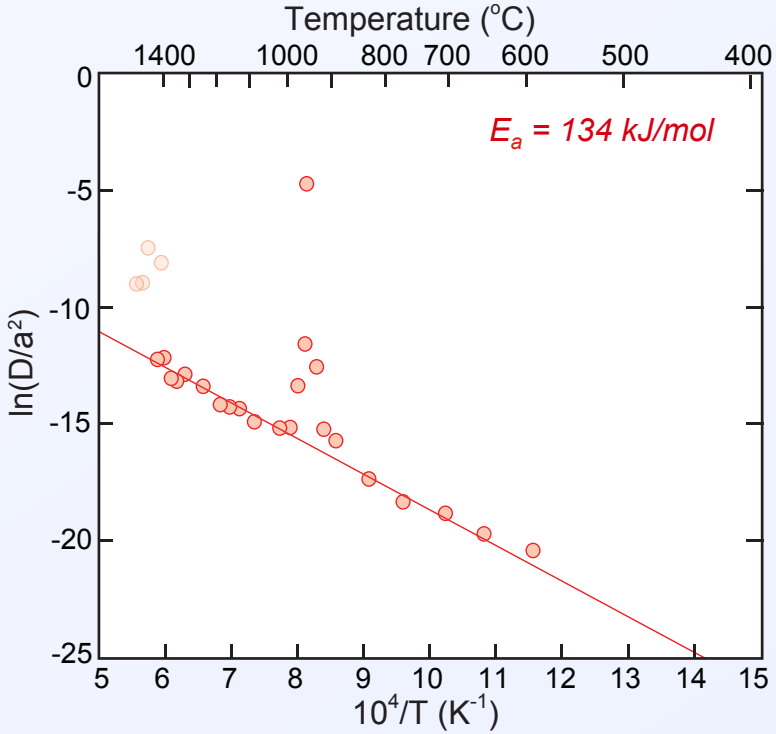
78238 – Thermochronometry

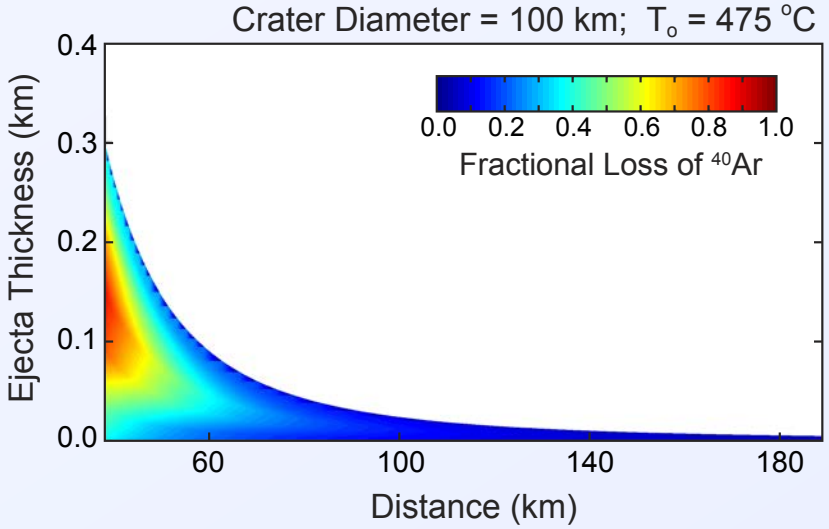
Sample may have resided above the ArPRZ

- age may reflect conductive cooling in the crust

Would the K-Ar system have been reset during excavation from 8 – 30 km depth?

- crater diameter required for excavation from 8 km: >105 km[1]





K-Ar system not necessarily reset during excavation – Age may reflect conductive cooling in the crust or smaller impact event.

Diffusion parameters are typical of maskelynite

[1]: Assuming $h_{excavation} = 0.1*D_t$ and $D(D_t)$ from Melosh (1989)

Conclusions

Crustal rocks record major impact events before 4.2 Ga. (e.g., Turner et al., 1973)

Diffusion kinetics reported herein provide constraints on open system behavior prior to and following exhumation from depth.
- diffusion kinetics are sample-specific, and vary considerably within feldspars[1]
- no broadly applicable set of plagioclase diffusion parameters for thermal modeling[1]

Impact events that excavate from 10-12 km depth produce ejecta blankets that will likely reset the K-Ar system in plagioclase and maskelynite
- overprint conductive cooling ages acquired in the crust

Without constraints on depths of crustal residence, Ar-Ar ages are ambiguous and size of impact event cannot be inferred – crater D may only be 125 – 175 km.
- combined petrographic and thermochronometric studies would be useful

Future Direction: Ar-Ar thermochronometry of pyroxenes
- ***Spans critical gap in closure temperature space (600 – 800 °C)[2]***
- ***Can help distinguish conductive cooling from impact excavation / resetting***

[1]: Cassata & Renne (2013) [2]: Cassata et al. (2011)