Exploring the Law of Detrital Zircon in Alaska's Cook Inlet: LA-ICPMS and CA-TIMS Geochronology of Jurassic Forearc Strata

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Abstract

A sedimentary rock cannot be older than its youngest zircon. This premise—the law of detrital zircon—permits maximum depositional age (MDA) determinations, but geochronologic dates are complicated by uncertainty. We conducted U–Pb laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) and chemical abrasion-thermal ionization mass spectrometry (CA-TIMS) of detrital zircon in forearc basin strata of southern Alaska to assess the accuracy of several MDA approaches. Six samples from Middle–Upper Jurassic units are generally replete with youthful (i.e., near stratal age) zircon and underwent three rounds of analysis: 1) LA-ICPMS of ~115 grains, with one date per zircon; 2) LA-ICPMS of the ~15 youngest grains identified in round 1, acquiring two additional dates per zircon; and 3) CA-TIMS of the ~5 youngest grains identified by LA-ICPMS.

Youngest single-grain LA-ICPMS dates are all younger than—and rarely overlap at 2σ uncertainty with—the CA-TIMS MDAs, indicating that random statistical fluctuations during analysis and subtle Pb-loss render these youngest LA-ICPMS dates poorly suited to characterizing the age of the densely sampled youthful populations. Youngest kernel density estimation modes are typically several m.y. older than the CA-TIMS MDAs, with the full probability distributions incorporating truly older dates. Weighted means of round 1 dates that define youngest statistical populations are our preferred LA-ICPMS constraints, as this high-*n* approach extracts a normally distributed sub-sample from the youngest tail of each full density estimation—thus tying these determinations to statistical fluctuations during analysis—and yields the best overall coincidence with the CA-TIMS MDAs.

CA-TIMS dating of the youngest detrital zircon grains identified by LA-ICPMS is indispensable for critical chronostratigraphic applications, eliminating laser-induced matrix effects, mitigating and evaluating Pb-loss, and resolving complexities of interpreting lower precision, normally distributed LA-ICPMS dates. Finally, numerous CA-TIMS MDAs in this study are younger than Bathonian(?)–Callovian and Oxfordian faunal correlations suggest and underscore the need for additional high-precision radioisotopic constraints to refine the Middle–Late Jurassic geologic time scale.

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A companion study is also available here: http://doi.org/10.14509/30180

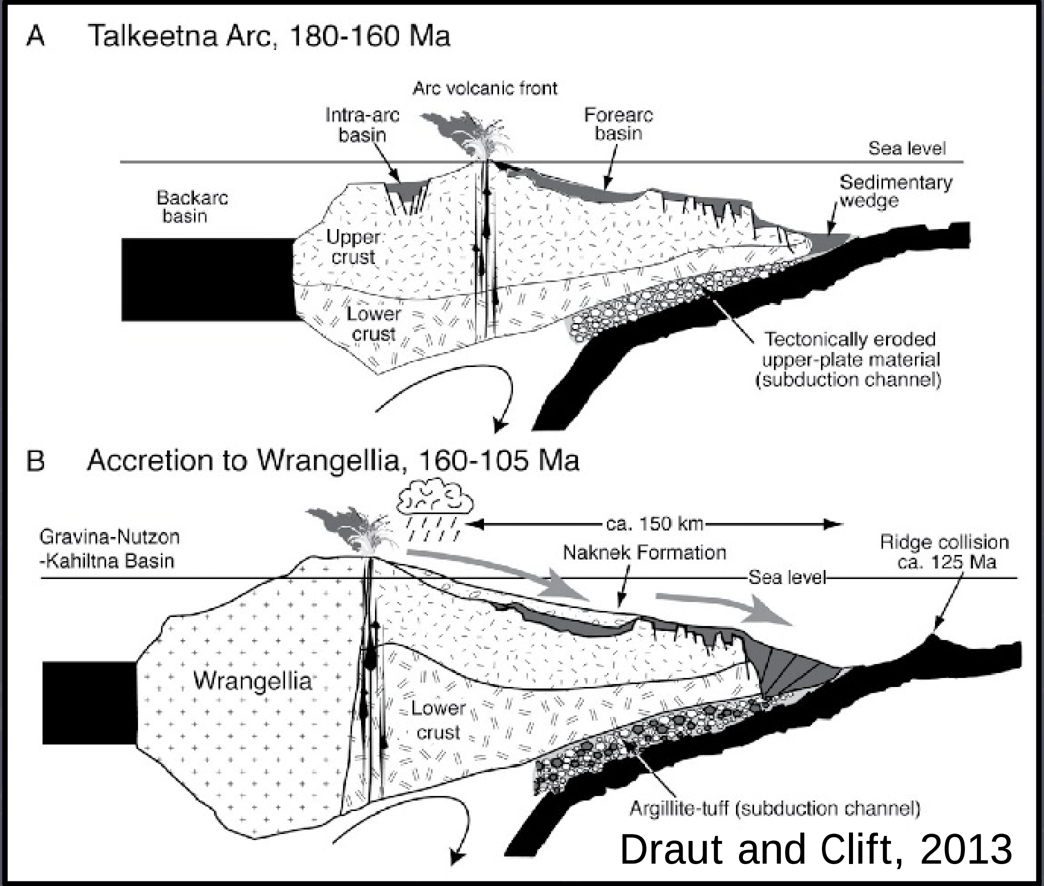
Premise and Framework

- Law of detrital zircon (Gehrels, 2014): A sedimentary rock cannot be older than its youngest zircon (Houston and Murphy, 1965)
  - Permits maximum depositional age (MDA) determinations
- LA-ICPMS is ubiquitous in DZ studies
  - Fast, affordable, with moderate precision
  - Pb-loss, matrix effects, and analytical uncertainties present challenges
- CA-TIMS is not ubiquitous in DZ studies

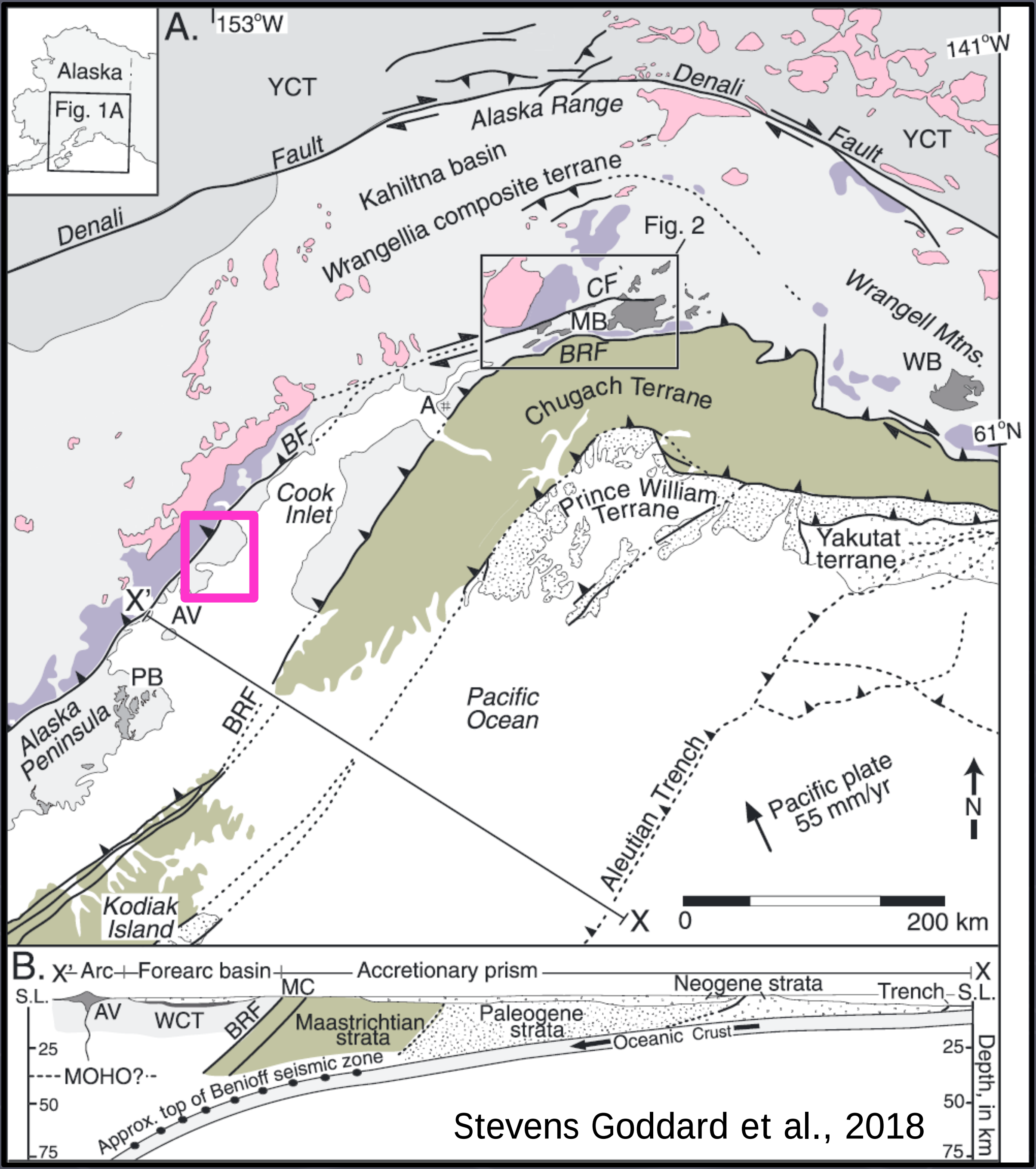
Geochronologic applications of the LDZ are complicated by uncertainty. Determining the true age of the youngest DZ is key to establishing accurate MDAs. We analyzed six Jurassic forearc basin sandstones—which are replete with youthful (i.e., near stratal age) zircon—in several rounds of LA-ICPMS and CA-TIMS U–Pb geochronology to evaluate best practices for establishing MDAs.

Geologic Setting—Cook Inlet Forearc Basin

- Southern Alaska: Arc–forearc–accretionary wedge
- Cook Inlet forearc basin: Nearly 200 m.y. history
- Jurassic Cook Inlet forearc basin: Coupled to Talkeetna oceanic island arc (e.g., Clift et al., 2005)



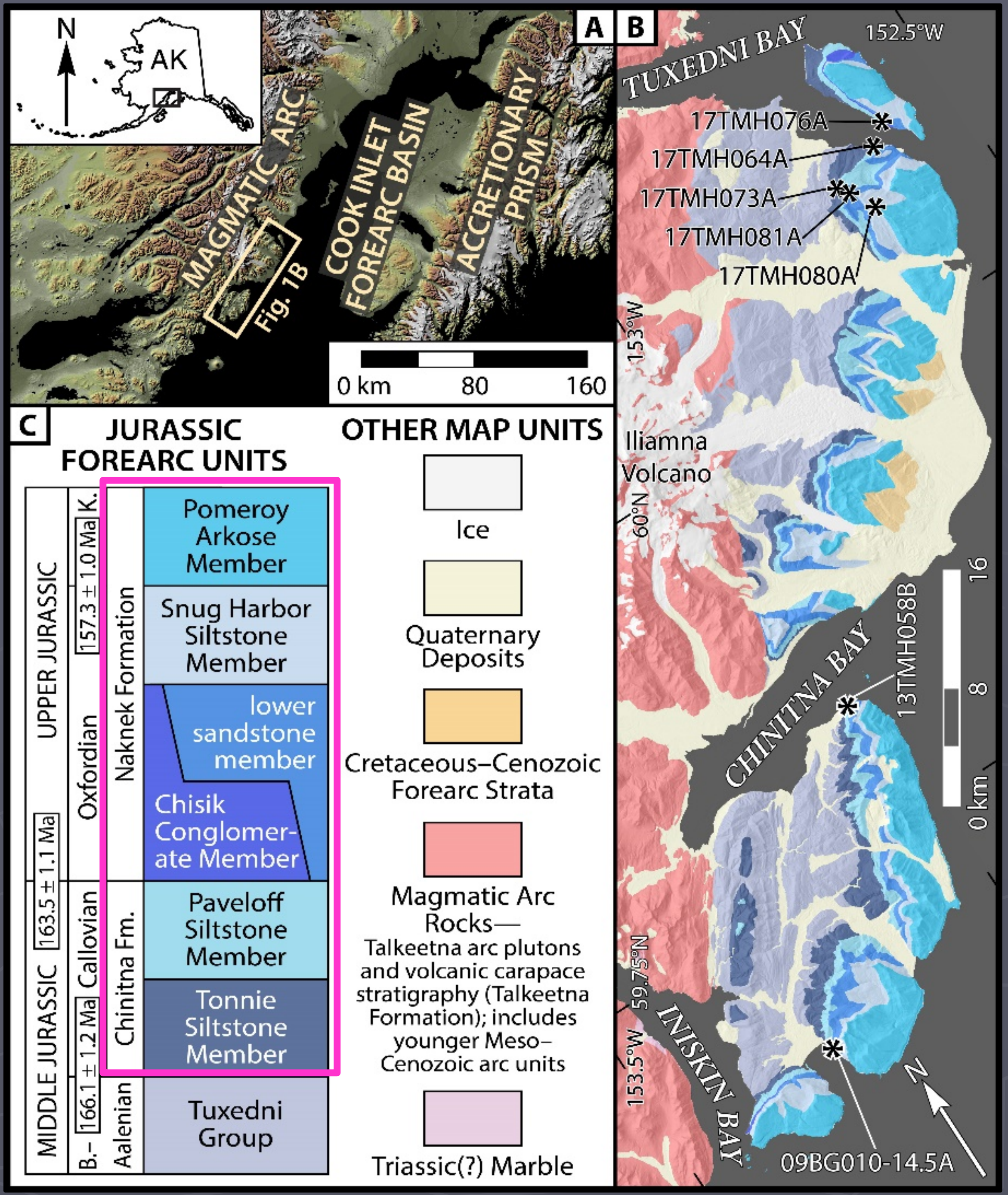
Draut and Clift, 2013



Stevens Goddard et al., 2018

Geologic Setting—Cook Inlet Forearc Basin

- Naknek Formation
  - Pomeroy Arkose
  - Snug Harbor Siltstone
  - Lower sandstone
  - Chisik Conglomerate
- Chinitna Formation
  - Paveloff Siltstone
  - Tonnie Siltstone
- Tuxedni Group
- Talkeetna Formation



Impetus for This Study—Jurassic DZ MDAs in Southern Alaska

- Recent DZ studies in southern Alaska yielded Naknek and Chinitna constraints that are notably younger than biostratigraphic correlations suggest
  - Finzel and Ridgway, 2017 (*Lithosphere*)
  - Reid et al., 2018 (*GSA Special Paper 540*)
  - Stevens Goddard et al., 2018 (*Tectonics*)

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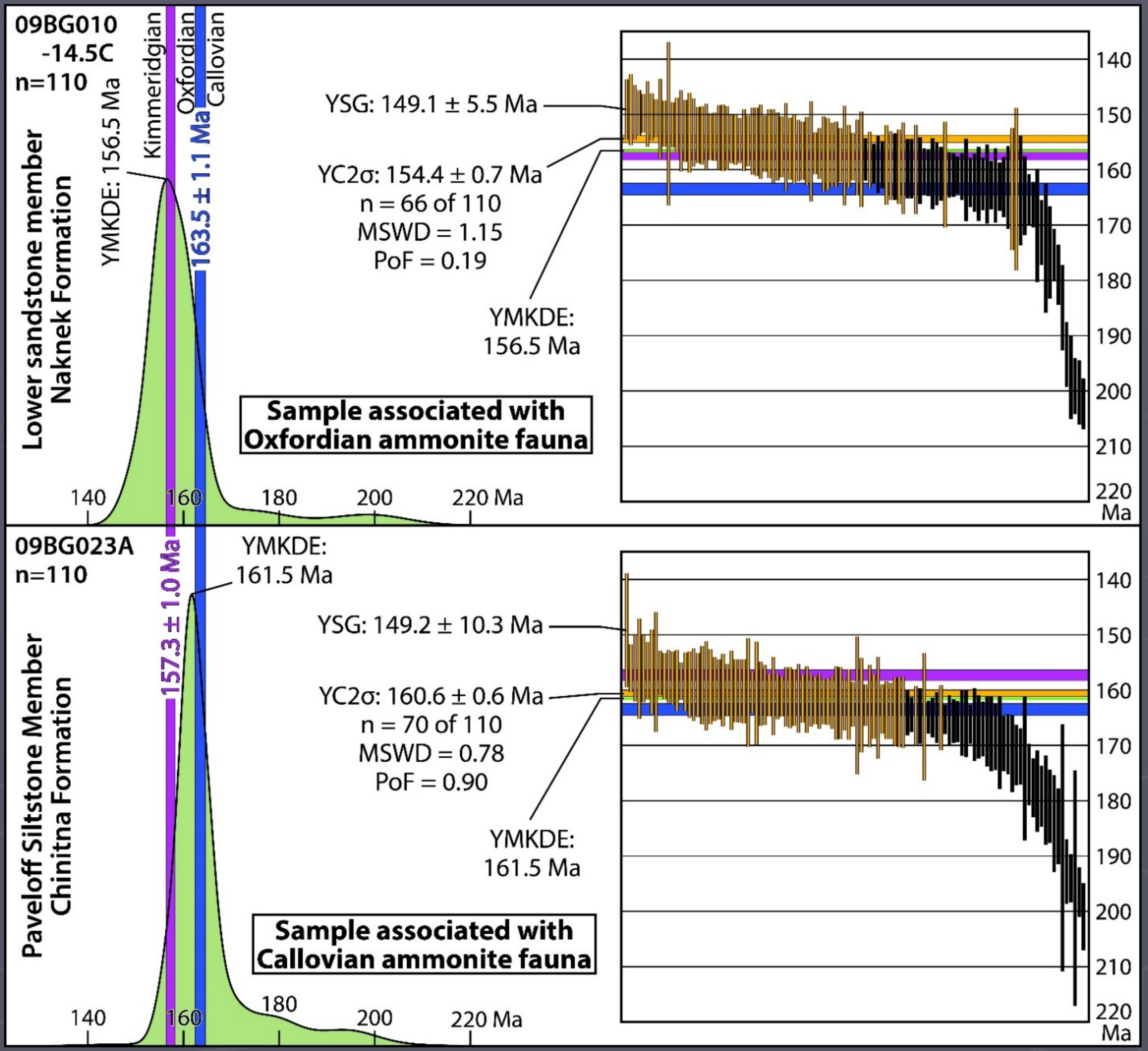
  - Stevens Goddard et al., 2018 (*Tectonics*)
  - Herriott et al., 2019 (*DGGS PIR*)

- Four variables:
  - 1) Biostratigraphy: Callovian and Oxfordian ammonite faunas are seemingly robust
  - 2) Time scale: Few radioisotopic dates for Middle and Late Jurassic (Gradstein and others, 2012)
  - 3) Geochronologic uncertainty: Pb-loss? Matrix-effects imparting too-young bias?
  - 4) Which MDA determination? *The challenge is common but underscored here by a too-young "problem" that can be either amplified or diminished by selecting one MDA or another.*



Experimental Design

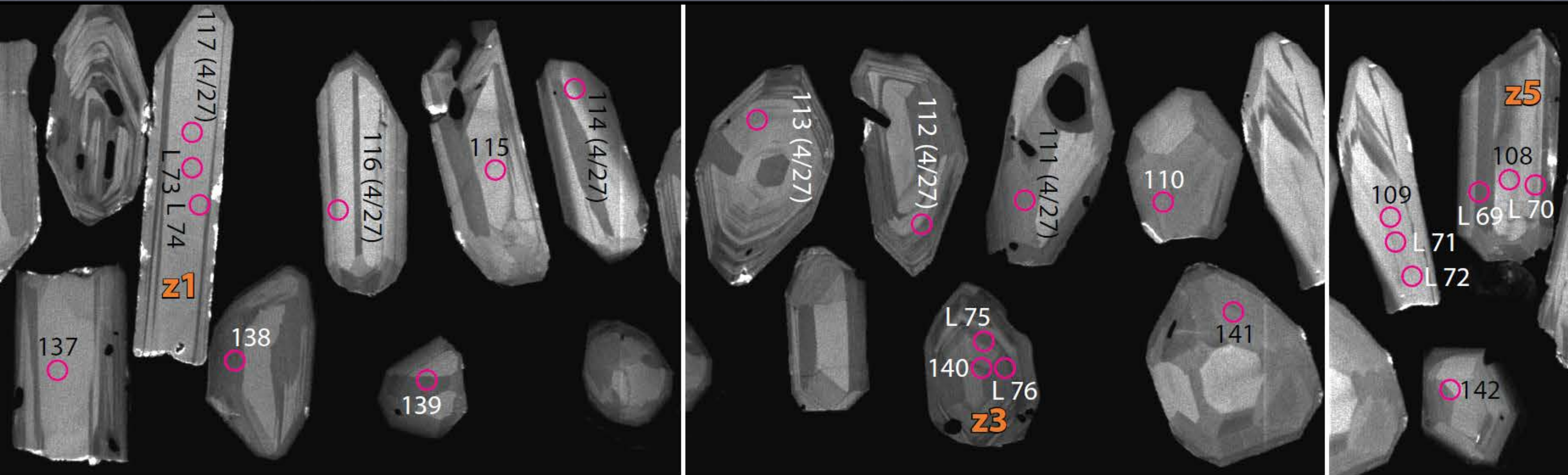
LA-ICPMS:

- Round 1: ~115 grains, with one date per zircon
- Round 2: Multiple analyses of ~15 youngest grains identified in round 1, acquiring two additional dates per zircon

CA-TIMS:

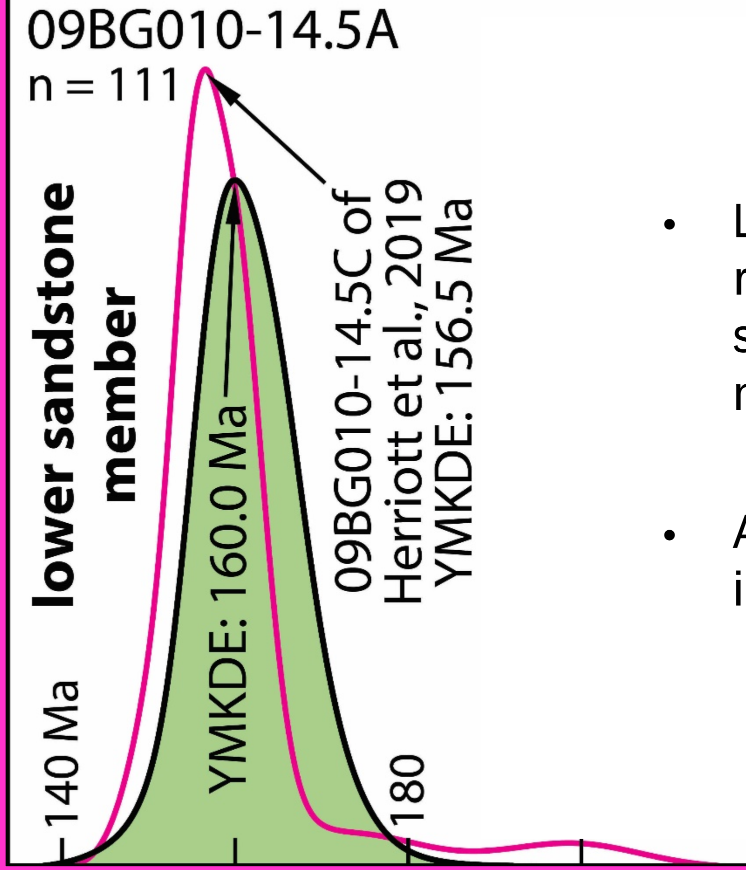
- Round 3: ~5 youngest grains identified by LA-ICPMS, with n=3 and PoF>0.05

Note: We thermally annealed references and unknowns prior to LA-ICPMS; chemical abrasion followed LA-ICPMS



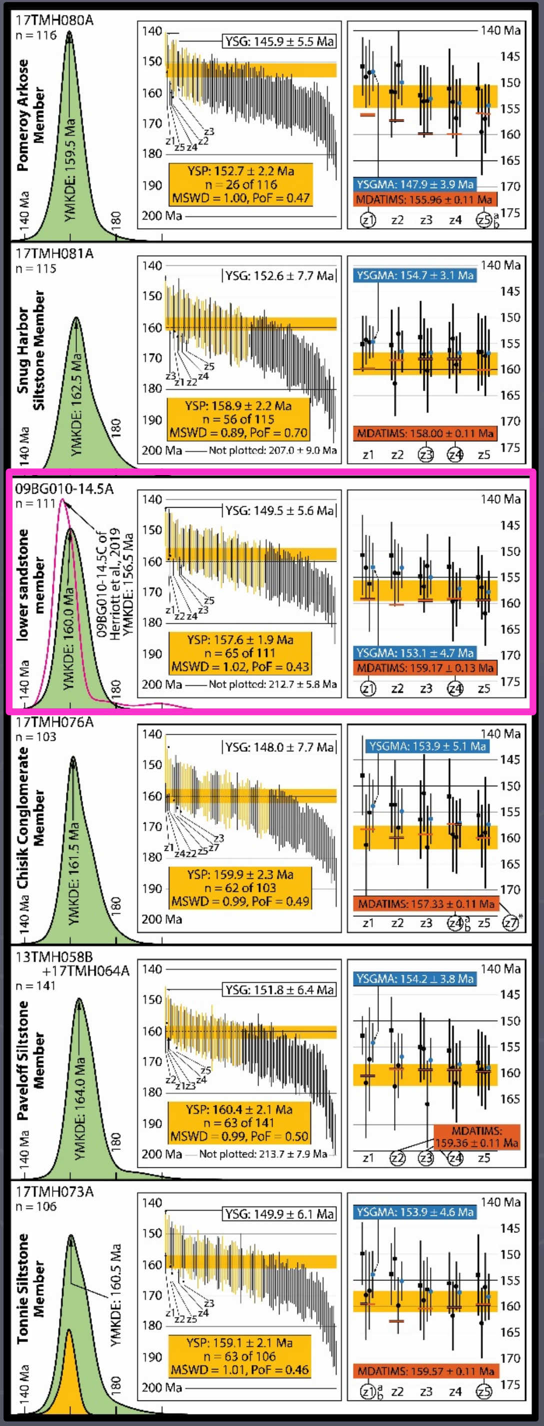
Results

- Nearly entirely Jurassic dates
- Unimodal date distributions
- Average per sample U values are low (77–112 ppm)
    - No correlation or subtly increasing U toward older dates
- All R1 dates and R2 WMs are younger than their associated (i.e., same zircon) CA-TIMS dates; ~60% of date pairs overlap at 2σ
- CA-TIMS dates (n=34) are concordant



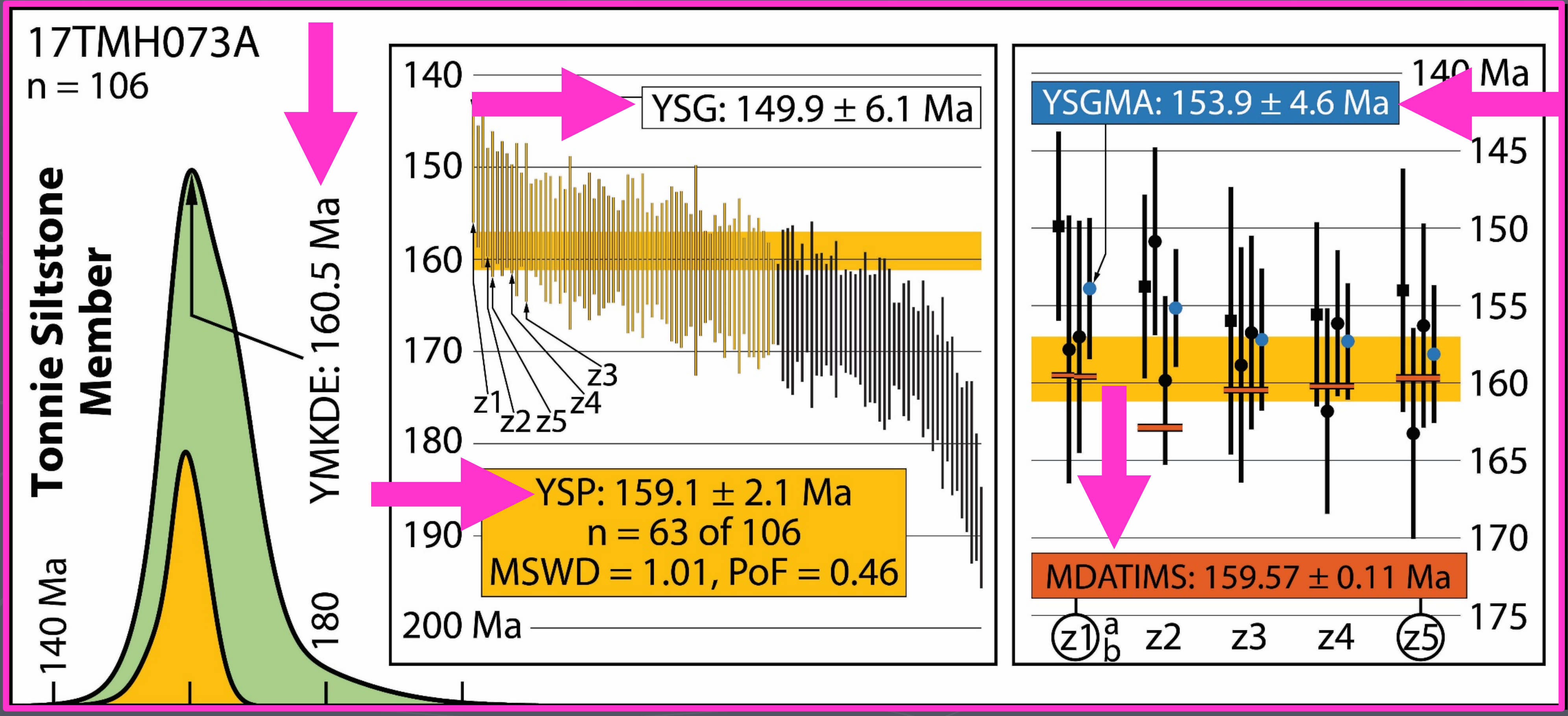
Systematic Uncertainty

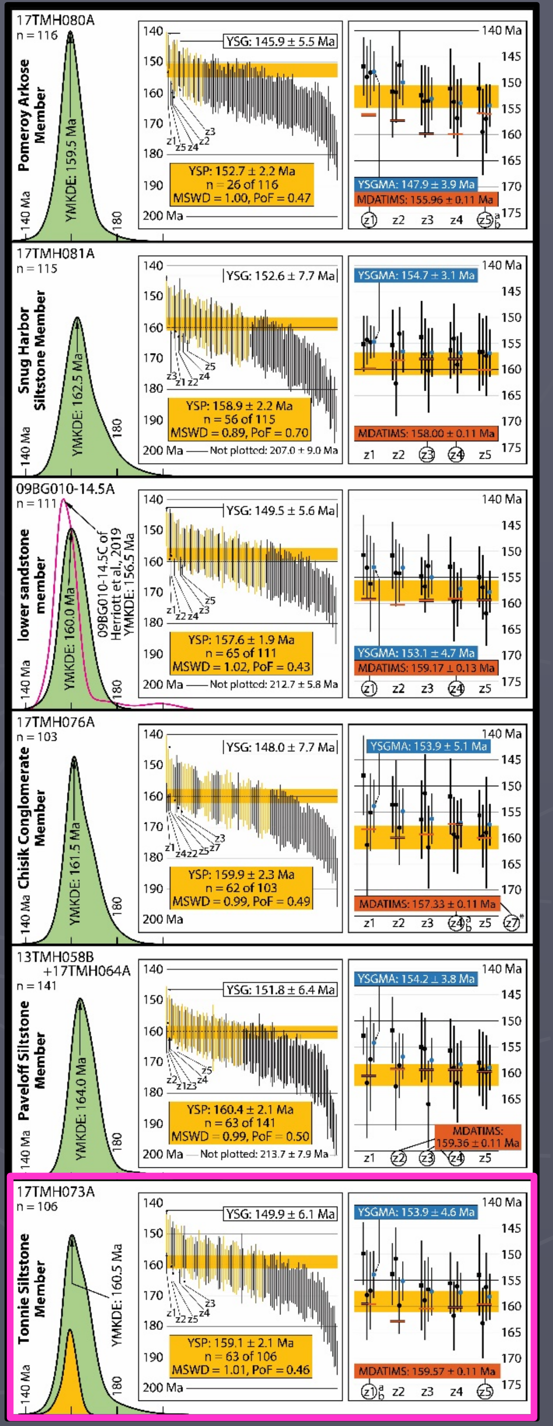
- Laboratory reported confidence intervals principally reflect analytical precision and reproducibility of standard materials, and repeat measurements do not mitigate sample-specific systematic uncertainty
- Always consider potential for systematic bias of data, including laser-induced matrix effects
    - Thermally anneal references and unknowns (e.g., *Chemical Geology*: Allen and Campbell, 2012; Sliwinski et al., 2017; see also Mattinson, 2005)



Maximum Depositional Constraints

- YSG (Dickinson and Gehrels, 2009, *EPSL*): Youngest R1 zircon date
- YSGMA (e.g., this study): Youngest R1+R2 WM date (n=3; PoF>0.05)
- YMKDE (cf. Dickinson and Gehrels, 2009, *EPSL*): Youngest mode of kernel density estimation
- YSP (Coutts et al., 2019, *GSF*): Youngest WM date of R1 sub-sample with MSWD ~1.00
- CA-TIMS (e.g., this study): Youngest CA-TIMS WM date (2σ overlap, PoF>0.05)





Maximum Depositional Dates (MDDs) and Ages (MDAs)

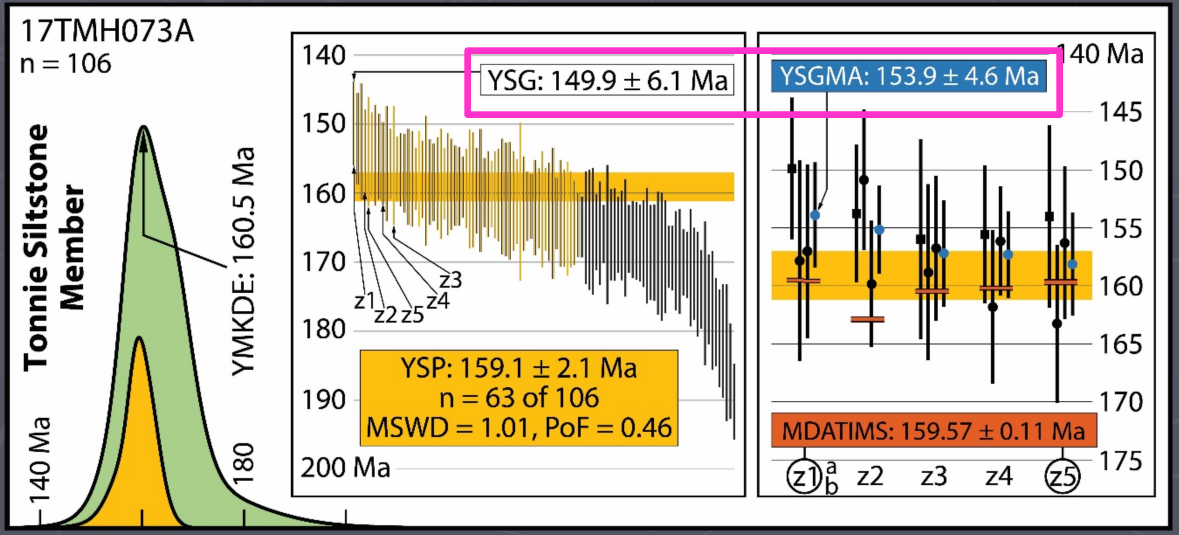
YSG and YSGMA—Single Grain MDDs:

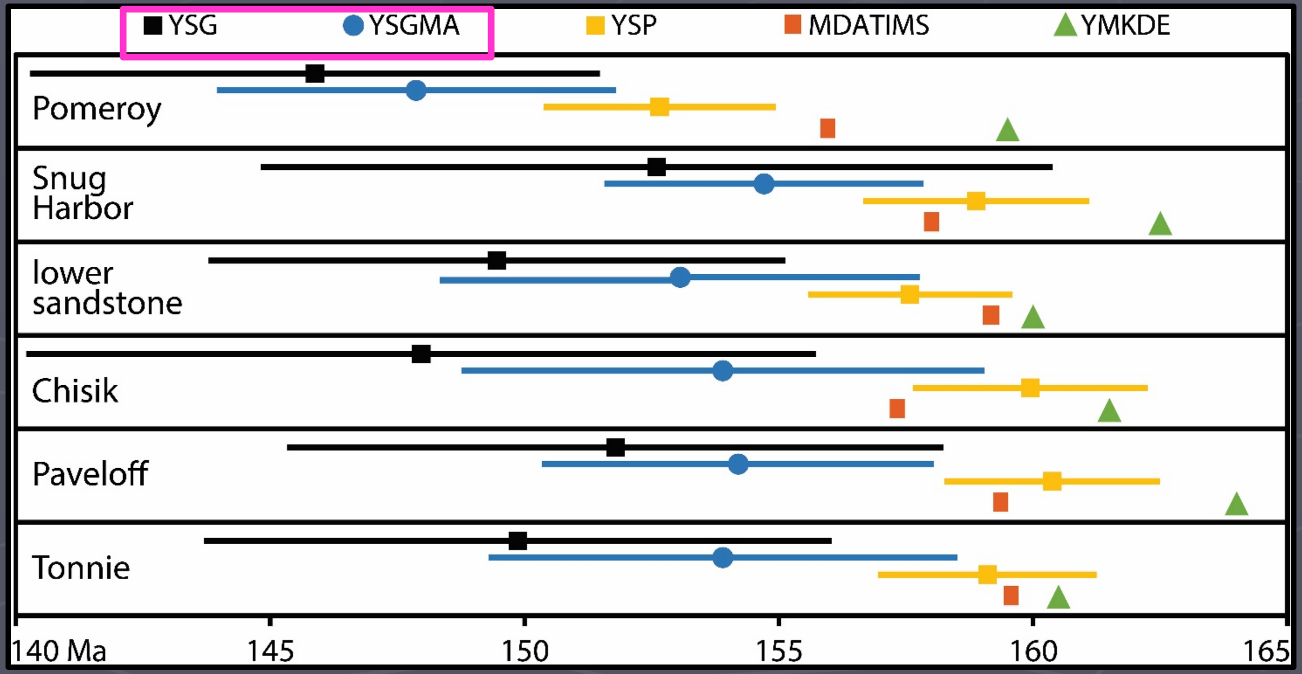
- Too young, with two likely sources of bias:
  - 1) Selectively sampling the low probability tail of normally distributed data tied to random statistical fluctuations during analysis
  - 2) Pb-loss
- YSGMA determinations are older than the YSG results, indicating a low probability tail bias for YSGs
- Consistent residual young bias—attributable to Pb-loss—remains in YSGMA relative to CA-TIMS MDAs

MDDs: YSG < YSGMA < YSP < YMKDE

MDAs based on CA-TIMS dates

YSP best coincidence with CA-TIMS MDAs





Maximum Depositional Dates (MDDs) and Ages (MDAs)

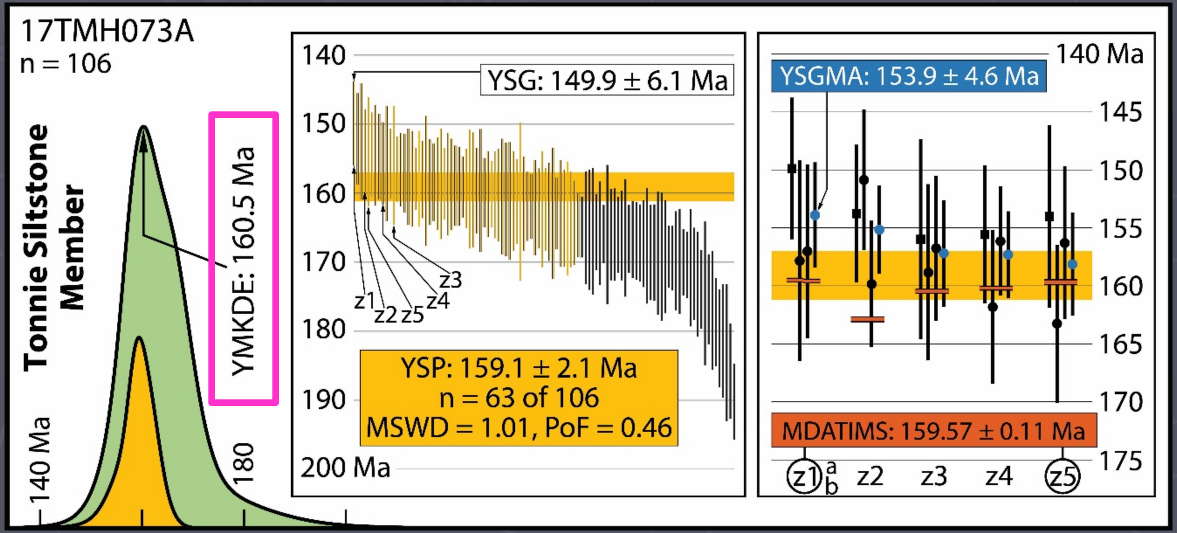
YMKDE:

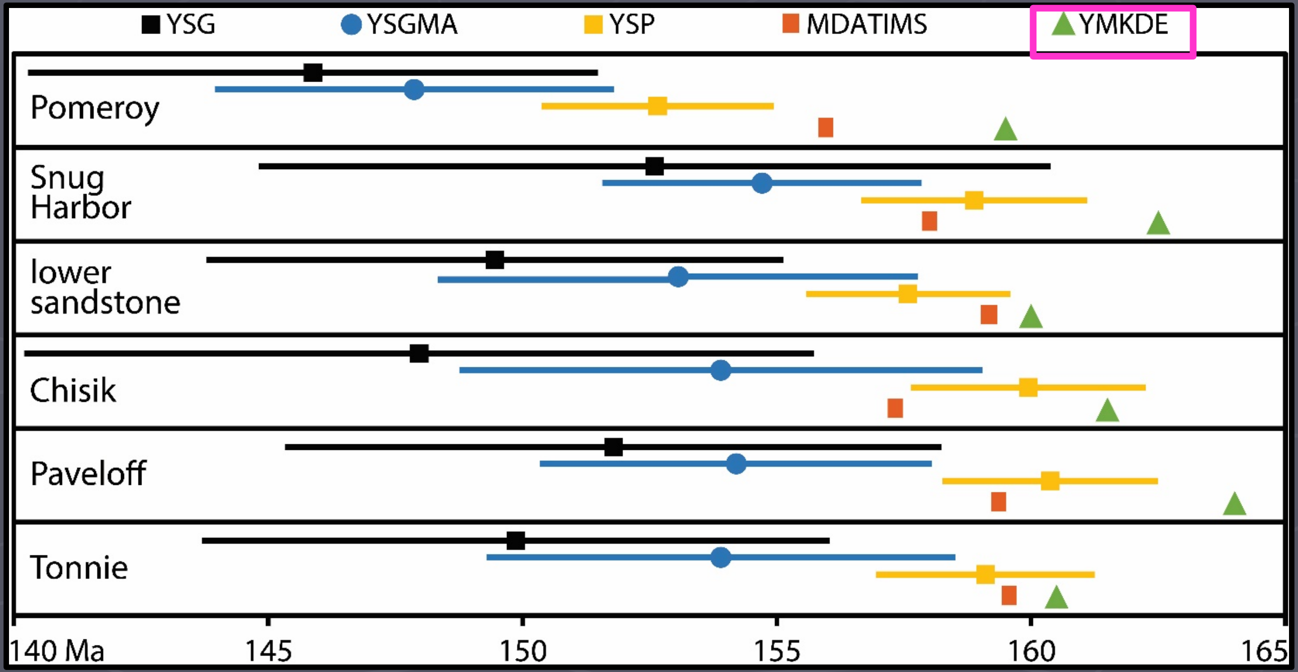
- Older than the CA-TIMS MDAs
- Full probability distribution includes truly older dates
  - PoF=0.00 for WMs of all dates per sample
- MDD relations hold regardless of PDP vs. KDE (including with various bandwidth parameters)
- Probability distribution MDDs lack uncertainty factor

MDDs: YSG < YSGMA < YSP < YMKDE

MDAs based on CA-TIMS dates

YSP best coincidence with CA-TIMS MDAs

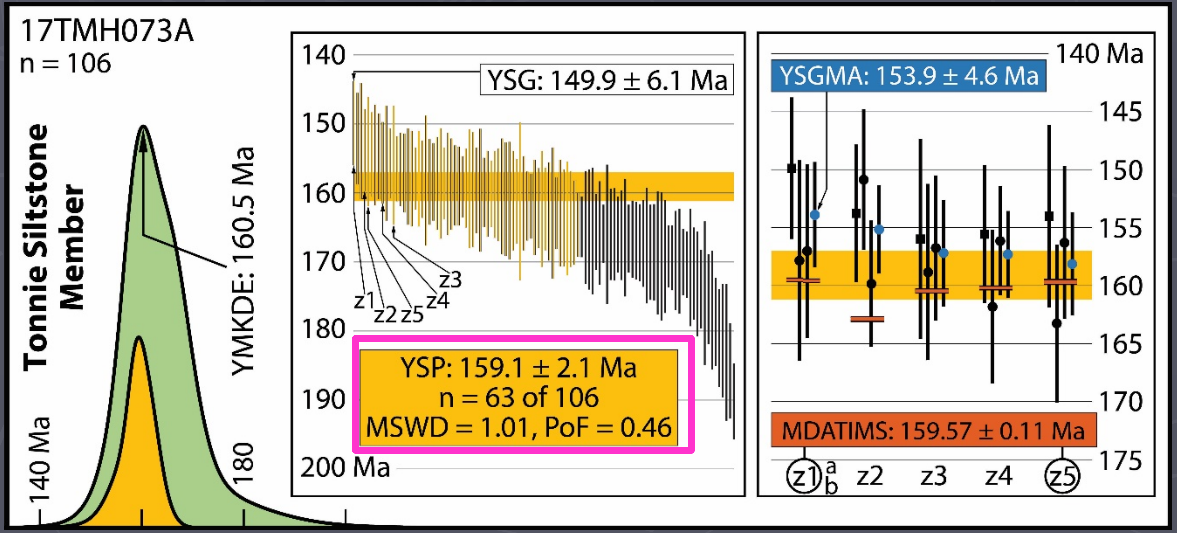




Maximum Depositional Dates (MDDs) and Ages (MDAs)

YSP:

- Selects youngest subset of dates with scatter that can be explained by uncertainties
- Extracts a normally distributed sub-sample from the tail of the youngest tail of the distribution
- These are our preferred MDDs due to explicit tie to statistical fluctuations during analysis, high *n*, and best overall coincidence with the CA-TIMS MDAs
- YSP sub-samples reflect coeval zircon crystallization as resolved by LA-ICPMS



MDDs: YSG < YSGMA < YSP < YMKDE

MDAs based on CA-TIMS dates

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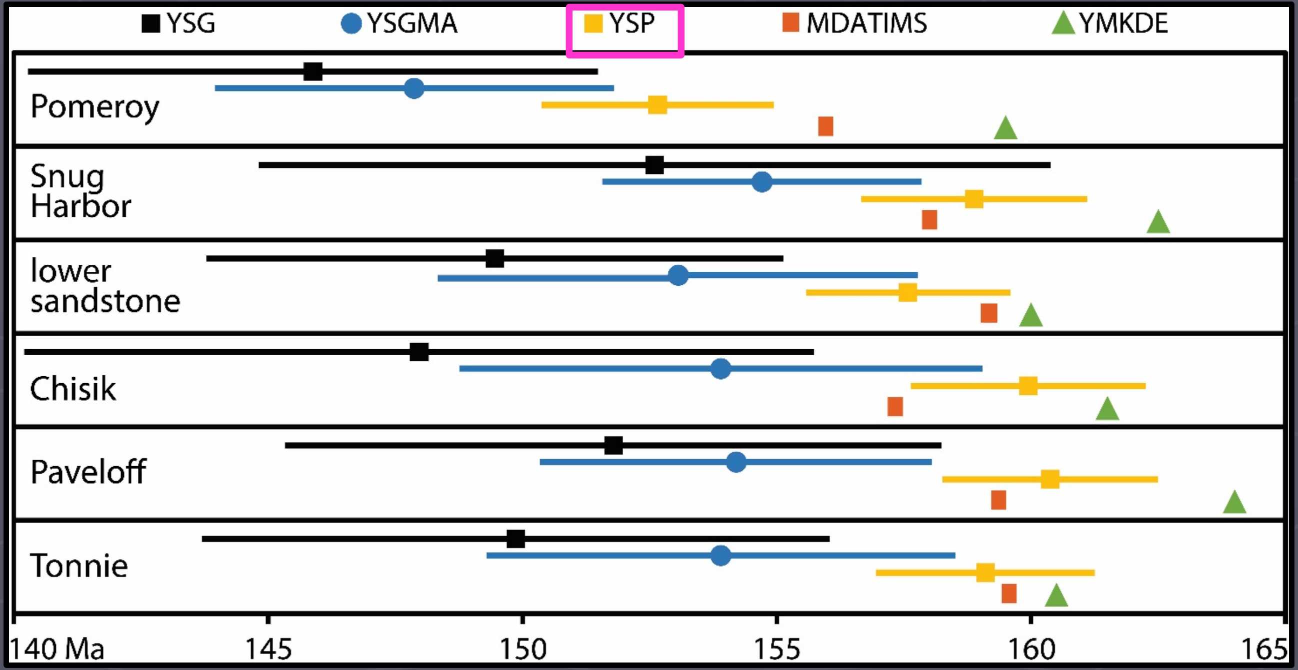


Maximum Depositional Dates (MDDs) and Ages (MDAs)

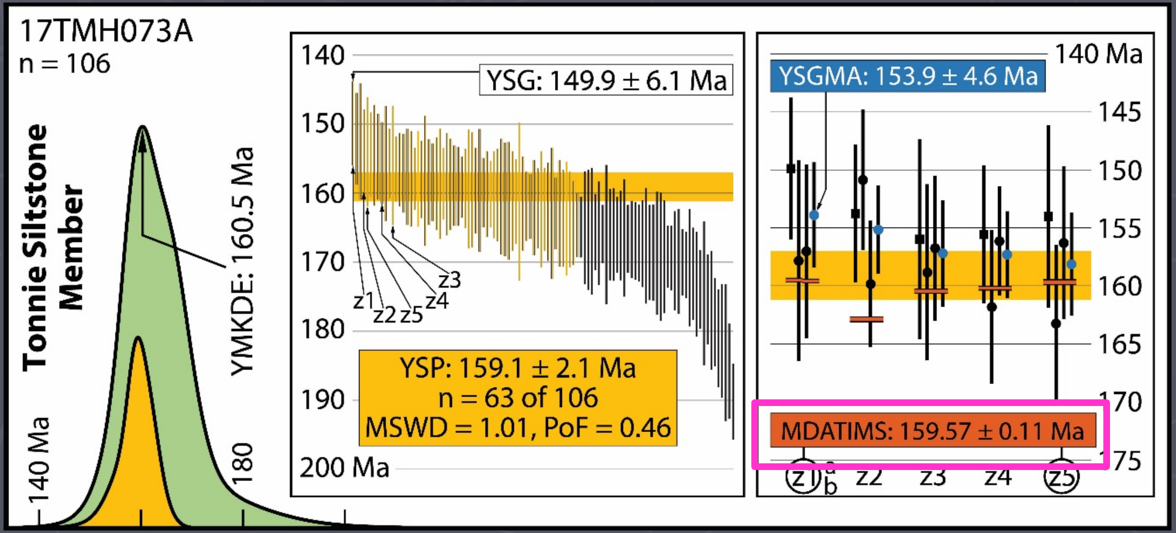
<u>CA-TIMS MDAs:</u>

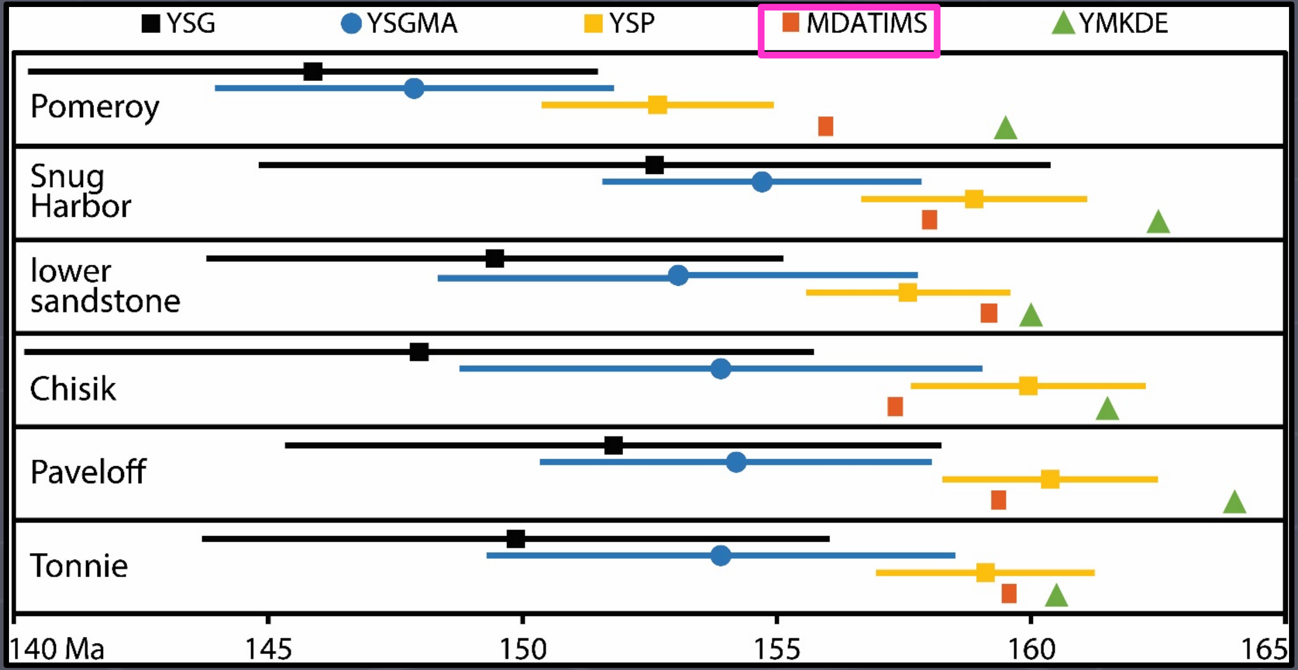
- Eliminates laser-induced matrix effects
- Mitigates and evaluates Pb-loss for Mz–Cz zircon
- Resolves complexities of interpreting lower precision, normally distributed LA-ICPMS dates
- Demonstrated reproducibility: Archived grain fragments from three critically young zircon yielded equivalent (i.e., overlap at 2σ) dates

MDDs: YSG < YSGMA < YSP < YMKDE

MDAs based on CA-TIMS dates

YSP best coincidence with CA-TIMS MDAs





LA-ICPMS and CA-TIMS DZ Study—Law of Detrital Zircon Conclusions and Recommendations

LA-ICPMS

- YSP preferred for densely sampled DZ populations
- Youngest single grain determinations are problematic; multiple analyses improve results
- Youngest KDEs will likely reflect truly older grains
- Matrix effects can compound distribution of dates and Pb-loss issues; all of these factors tend to yield Mz–Cz MDDs that are too young
  - Thermally anneal zircon prior to LA-ICPMS; carefully select secondary references

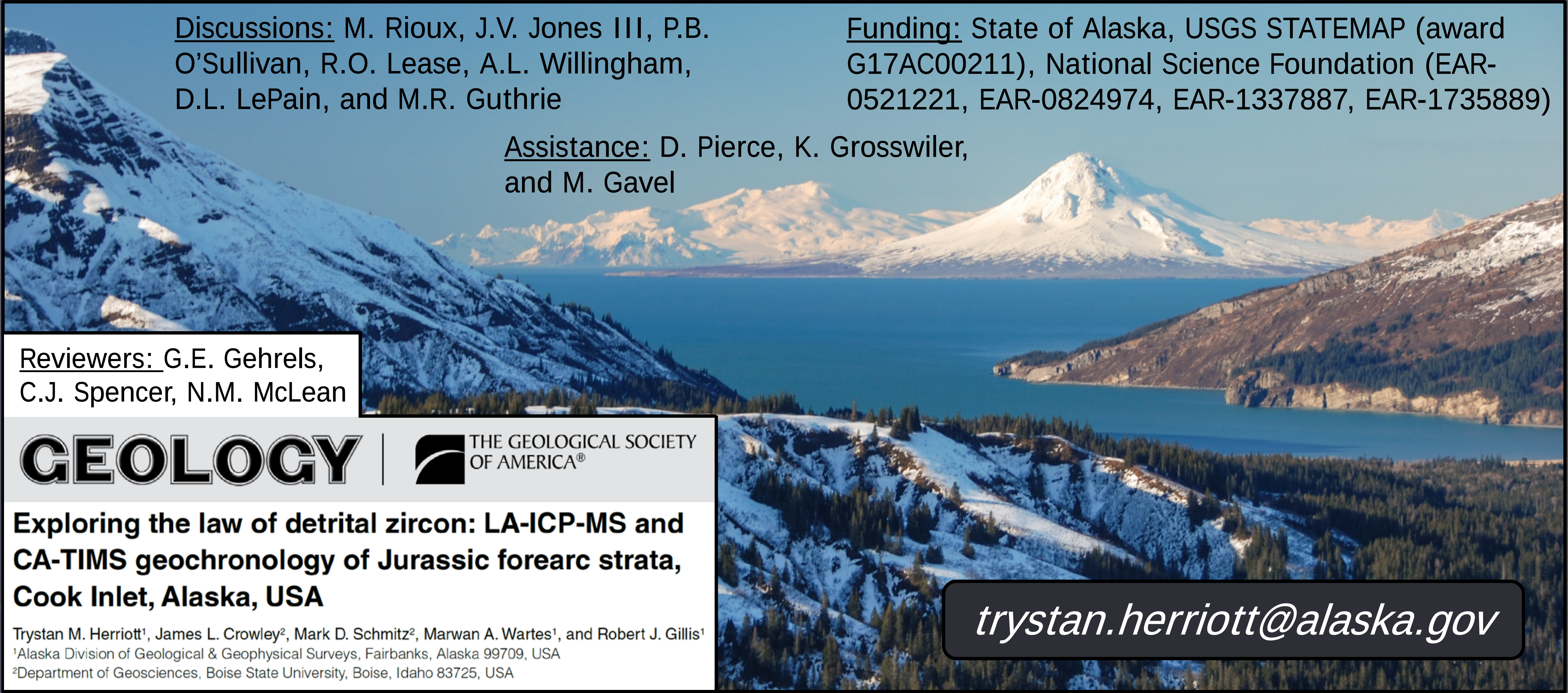
CA-TIMS

- Employ for critical applications
- The most robust MDAs are derived from WMs of equivalent CA-TIMS dates from multiple grains; analyze multiple fragments per grain to test intra-grain reproducibility and minimize geochronologic uncertainty

There will be cases where MDAs truly are younger than previous constraints suggest: Numerous CA-TIMS MDAs in this study are younger than Bathonian(?)–Callovian and Oxfordian faunal correlations indicate, underscoring the need for additional high-precision radioisotopic constraints to refine the Middle–Late Jurassic geologic time scale

Acknowledgments

Thank you. Questions?



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