Report from the 17th International Conference on Thermochronology

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Abstract

The 17th International Conference on Thermochronology (Thermo2021) was held in Santa Fe, New Mexico, on September 12-17, 2021. This bi-annual conference series evolved via the coalescence of the International Workshops on Fission Track Thermochronology, held since 1978, and the European Workshops on Thermochronology. It has become the premier forum for thermochronology practitioners and users to discuss fundamental and methodological topics and opportunities related to their science and its future. Each conference is independently organized, and a Standing Committee consisting of past organizers and other community members helps to ensure their continuation into the future. Thermo2021 was greatly affected by the COVID-19 pandemic. Normally the meeting would have been expected to draw ~250 attendees, but travel restrictions limited in-person attendance to 86, plus 21 remote presenters. Nearly all in-person participants were from the US, and only four were international. Talks and posters were distributed among five themes: (U-Th)/He; fission track; other thermochronometers; frontiers in data handling, statistics, interpretation methods, and modeling; and integration and interpretation. Although COVID-19 presented many challenges, it also allowed the Organizing Committee to adapt creatively and transform adversity into opportunity. In particular, the smaller number of attendees permitted more talks by students and early-career scientists, both within the theme sessions and in the Charles & Nancy Naeser Early Career Session. Discussion time was prioritized: at a Tuesday evening "swap meet" for ideas, in 30-40-minute time slots within each theme session, and in Friday afternoon breakouts for the first four themes and another dedicated to early career and DEI issues. These were used to identify emergent ideas and concerns across a broad range of topics, from the theory and practice of the various thermochronometric techniques, to their interpretation through thermal history modeling and other methods, to anticipated trends in data dissemination and management, to the needs of the next generation of thermochronologists, particularly in the US. Each Friday breakout designated a scribe who recorded the discussion and distributed their notes. Each group then designated one or more writers to transform the notes into text for this White Paper. Notes or early write-up versions were provided to the international thermochronology community, and feedback solicited. In addition, cross-cutting themes that occurred across multiple breakout groups were identified and compiled. This White Paper is the outcome of these efforts. We hope that it will serve as a record for the meeting, and an overview of where

the predominantly US-based component of the thermochronology community considers the current state of knowledge to be and where future efforts should be directed, for developing both the science and its human infrastructure.

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INTRODUCTION

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SUMMARY OF EMERGENT THEMES

By improving our understanding of the physical and chemical processes underpinning our thermochronometers, we can push the frontiers of the science that can be done with thermochronology.

- Our understanding of thermochronometric systems have come a long way (e.g., radiation damage effects on helium diffusion, fission track annealing kinetics, etc.), and this has enabled us to tackle a much wider set of geological problems using thermochronology (e.g., deep time thermal histories and the origin of the Great Unconformity, frictional heating on fault surfaces, and others).
- Although great strides have been made, we also repeatedly heard at the meeting about how there are aspects of our thermochronometers that we don't fully understand (e.g., complex degassing behavior observed in CRH experiments) or don't yet have an adequate means to address with conventional analyses (e.g., complex parent nuclide zonation patterns and the effect of these patterns on (U-Th)/He ages).
- In particular, there are compelling parallels emerging between observations within the (U-Th)/He community, long-known observations of multiple diffusion domain-like behavior of argon in K-feldspars, recently developed noble gas thermochronometers (e.g., ^{3}He in quartz), and even solid-state thermochronometers (e.g., OSL), that point to the importance of defects or imperfections in crystal structures to controlling the behavior of our thermochronometers.
- Efforts to understand the role of defects/imperfections in thermochronometer behavior at a mechanistic level, and how defects themselves transform as a function of temperature and time, could significantly improve our abilities to interpret thermochronometric datasets (particularly over-dispersed ones), and could once again enable us to push the frontiers of the types of geoscience questions we are able to tackle with thermochronology. Moreover, such efforts could catalyze cross-disciplinary collaborations that are currently weak (e.g., materials science, nuclear energy, cosmochemistry).
- We collectively recognized that sample characterization prior to dating can provide critical information for interpretation. Doing so has already provided some of the critical insights cited above, and more is needed to use emerging observations and additional characterization to advance the application of thermochronology to geoscience questions. What type of characterization and then how to best integrate characterization into current measurement and modeling workflows are open questions.

Community-wide standardization is needed to both improve our science and make thermochronology a more equitable and sustainable field.

- There are many examples in our field of places where it is difficult to compare results or synthesize data and/or models because of how our data/models are reported. This limits our ability to innovate with respect to our methods (e.g., growing our thermal history modeling capabilities), and therefore our ability to advance what we can do with these methods (e.g., synoptic analyses using large datasets).
- In some cases, we have appropriate tools already available for data/model reporting (e.g., reporting protocols, image-based FT analyses), and we need to push for community-wide adoption of these approaches. In other cases, we need to develop new avenues for reporting and/or data sharing (e.g., data treatment protocols, access to kinetics data, modularization of modeling softwares). In the latter cases, we shouldn't reinvent the wheel, but use models that already exist in other geoscience subfields (e.g., Community Surface Dynamics Modeling System (CSDMS) as a model for thermal history modeling software).
- Early career individuals who are in the process of setting up new labs are frequently finding the lack of access to standards to be a barrier (e.g., mineral standards and gas standards, spike

solutions, doped glasses). Having community-wide standard 'libraries' (e.g., something akin to what the EARTHTIME initiative did) would help eliminate these barriers for early career researchers, and also lead to better reproducibility and methodological transparency across labs. This could help resolve some (but definitely not all) of the issues our community faces with respect to overdispersed data.

- Efforts toward standardization will also lower the barrier to entry for new/novice users of thermochronometric data, and likely lead to more careful application of these data to a range of geologic questions by a range of users.

Our community must rise to the challenge of making the technical aspects of our work and our data widely accessible. This must be part of a broader imperative to increase diversity within the thermochronology community.

- This meeting was unique in that, due to COVID-19, it by and large reflected what the U.S. (but not the international) thermochronology community looks like. This led to a much higher level of representation for early career scientists, which was across the board viewed as a positive aspect. However, Black, Indigenous, and People of Color are highly underrepresented in the thermochronology community, and that was reflected in who attended this meeting.
- Many of the issues discussed above about standardization are intertwined with issues about making the technical aspects of our work and our data more transparent and widely available. We think the lack of equal or easy access to our techniques and data is a contributing factor to making our field lack diversity, but there are certainly others that we need to work as a community to identify and address.
- The "nuts and bolts" of thermochronology can be both quite complex, and also quite expensive, both of which contribute to its inaccessibility.
    - With regard to the former, our community should use existing formats to make the technical aspects widely accessible (e.g., publishing technical notes, putting together videos/tutorials). However, we should also identify a means for compiling these resources and making their availability widely known.
    - With respect to the latter, the AGeS program has been a wonderful launching point and exemplar for making geo- and thermo-chronology data more widely accessible at the graduate level. As a community, we should push to see AGeS or similar initiatives to not only continue but expand to include a wider range of participants (e.g., undergraduates, high school?, different types of institutions) and a wider range of activities (e.g., mentoring, financial resources for characterization work).

(U-TH)/HE THERMOCHRONOLOGY

The field of (U-Th)/He thermochronology has expanded rapidly over the past decade and is now a well-established and accepted thermochronologic technique. The expansion of (U-Th)/He thermochronology has led to the development of a range of techniques and models, generating much debate and discussion around "best practices" for producing accurate results using the chronometer. If (U-Th)/He thermochronology is going to continue to grow as a method, then there needs to be a unification and standardization of many aspects of the methodologies used in (U-Th)/He dating. In particular there needs to be a concerted effort to develop accurate and standardized kinetics models and laboratory practices.

Many researchers have identified variable and incomplete radiation damage accumulation, radiation damage annealing, and models of He diffusion kinetics to be a major source of uncertainty in the thermal histories produced using the (U-Th)/He technique. The development of accurate models of kinetics requires a community effort to physically characterize samples prior to dating, and centralized reporting of all characterization data. Moreover, whatever characterization the community comes to consider as necessary should be affordable and accessible to anyone generating (U-Th)/He data. The issue of developing accurate kinetics also requires the identification of kinetics standards on which different kinetic processes (annealing, He diffusion) can be tested and measured. A centralized geologic site would allow for multiple labs to use the same mineral samples to benchmark not only their kinetics models, but all methods used in generating (U-Th)/He data and thermal histories.

PHYSICAL STANDARDS

Thorium spikes for (U-Th)/He: There is a need for a standardized and widely available Th spike for IC-PMS analysis during the (U-Th)/He dating. Many laboratories in need of a Th spike have the added difficulty of restrictive school, state, and country specific radioactive material handling licensing that prevents them from synthesizing a Th spike of their own at their home institution. For many laboratories that operate in regions with restrictive radioactive material policies, the Th spike would fall within an acceptable level of radioactivity, but the raw materials need to make the spike exceed the allowable radioactivity. To ensure all institutions in need of a Th standard have equal access, some of the larger laboratories could serve as central synthesizers and distributors of the Th spike.

Mineral standards for oxides (U-Th)/He: The (U-Th)/He oxides community needs to identify and distribute mineral standards to which their dates can be calibrated. Oxide (U-Th)/He dates can be complicated because of grain sizes and mineral morphologies; these effects should be taken into consideration when choosing oxide standards.

Kinetics mineral standards for all (U-Th)/He: Kinetics standards need to be identified and distributed to all laboratories working on improving various kinetics models used in (U-Th)/He thermochronology. For zircon and apatite (U-Th)/He, the standards would need to have a range of radiation damage levels, a range of annealing (natural annealing over geologic times and temperatures is preferable), and a range of radiation damage zonation styles. For oxide (U-Th)/He, the standards would need to have a standardized chemistry (mineralogy), a range of grain sizes.

LABORATORY EFFORTS

Characterizing Samples to Advance Models of Diffusion and Annealing Kinetics: The largest source of uncertainty that remains within the (U-Th)/He methodology is the incomplete understanding of what mineral-specific characteristics dictate individual-crystal He diffusion and mineral annealing kinetics (Zeitler et al., this meeting). The need for better constrained kinetics is most apparent in zircon (U-Th)/He dating, where it is speculated that zonation can cause consequential local variation in both diffusion and annealing kinetics. At the Thermo2021 meeting, the community agreed that the most effective approach to address the issue of zonation and kinetics in zircon is to, when feasible, characterize samples using a range of techniques prior to dating, and importantly, to report those characterization data. Some of the characterization techniques that have shown promise for illuminating the relationship between zonation and kinetics are laser ablation inductively coupled plasma mass spectrometry (Hodges et al., this meeting), Raman spectroscopy mapping (Thurston, this meeting), continuous ramped heating (Guo et al., this meeting; Idleman & Zeitler, this meeting), and scanning electron microscopy.

Benchmarking: Efforts have been made to benchmark whether different thermal history models can reproduce the same results. However, there has been little effort to benchmark the entire (U-Th)/He dating process from sample collection through modeling (e.g., Ketcham et al., 2018). To benchmark the entire (U-Th)/He dating process, laboratories would need to identify and study a single centralized geologic site with limited innate dispersion to help isolate variations in results that are due to differences in technique. The completion of a series of benchmark studies at the centralized geologic site would allow for the community to see how much variation is generated from lab to lab and how well different laboratory techniques are converging on a single reproducible solution. The use of centralized geologic sites would also allow for mineral "standards" to be collected and tested for kinetics generated by virtue of using grains that all share the same thermal history. This would simplify the procurement of different kinetic standards mentioned above. If the centralized geologic site were to be studied by not only multiple laboratories, but using multiple chronometers, the (U-Th)/He system could be calibrated to other chronometers (fission track, vitrinite, Ar/Ar) allowing for a better understanding of how all chronometers can converge to generate a more robust thermal history.

CENTRALIZED DATABASE

The accuracy of the thermal histories derived from (U-Th)/He data is limited by our current kinetics models, so there is an urgent need to improve these models that we hope will be met in the near future. One of the best ways to ensure that these developments occur in a reasonable time-line is to report any and all crystal characteristics that may impact the kinetics at play in (U-Th)/He thermochronology. There is a backlog of characterization data that has gone unreported by many laboratories, and hopefully an even larger amount of characterization data that will be generated and reported in an effort to improve our understanding of (U-Th)/He kinetics. This volume of data requires a centralized and organized means of reporting and storage so that it can be easily sourced for the development and testing of improved kinetics models. The best way to report and store this data is in a centralized, online database.

The need and utility of a centralized database is evident, but there are several barriers to its execution that need to be explored further. First, the database would require a certain amount of long-term funding to pay for the site domain and maintenance. Second, given the amount of data that are generated by the thermochronology community, a centralized database would likely require a dedicated person to oversee the reporting and organization of the data. Stewardship of the database should not be a strictly volunteer position, as the amount of time required to keep it organized and operational would be nontrivial. In order to meet these monetary needs, some sort of community sourcing would need to be established to promote equal access and responsibility to the database.

FISSION-TRACK THERMOCHRONOLOGY

Fission-track analysis has proven to be a durable and accurate thermochronometric technique. Despite being more labor-intensive and providing relatively large uncertainties compared to noble-gas methods, the visual characterization, uniquely high information content of confined track lengths, and well-developed fundamentals make it an irreplaceable tool that both stands alone and complements other thermochronometers.

Our experience, based on requests for analyses, is that demand for fission-track analysis within the USA is high, and will remain so for the foreseeable future. There is a clear under-supply of fission-track laboratory capacity to accommodate this demand. Further, because it does not depend on mass spectrometry and its associated support staff, fission-track analysis remains uniquely accessible to faculty across a wide range of institutions, providing hands-on, low-cost thermochronometric research to students at all levels. To meet current and future demand, we propose three tiers of recommendations to ensure the availability of high-quality, innovative, and accessible fission-track thermochronology within the USA.

IMMEDIATE REQUIREMENTS

Financial and material support for new fission-track facilities is required within the USA to meet the geoscience community's demand for fission-track thermochronology:

Accessible dosimeter glasses and mineral standards. U-doped glasses (Bellemans et al., 1995) are critical for maintaining the well-established External Detector Method (EDM). The existing supply of standardized glasses is dwindling, although some remnants remain in some international labs (B. Kohn, personal communication). Standardized production of new glasses is necessary to ensure continued use of the EDM and maintain inter-laboratory consistency. Additionally, we need to increase access to existing mineral standards and continue developing new standards for emerging mineral systems (e.g. monazite).

Image-based analysis hardware and software. The future of fission-track analysis is evolving toward the use of high-quality image capture technology (Gleadow et al., 2009), allowing laboratories to improve accessibility, transparency, and reproducibility. Image capture and analysis also enables new measurements and analysis protocols that promise to improve efficiency, quantity, and quality of fission-track datasets (e.g., Tamer & Ketcham, this meeting). Upgrading existing facilities as well as supporting new facilities in the acquisition/development of image-based systems will ensure fission-track thermochronology will grow as a reliable and easily accessible method in coming decades.

Support for human infrastructure. Fission-track thermochronology is underpinned by well-trained analysts who produce reliable and high-quality data. In contrast to other geo- and thermochronometric techniques, fission-track thermochronology requires comparatively limited instrumentation, and instead leans disproportionately upon its human infrastructure, whose developed expertise is not straightforward to communicate or offload. Therefore, to maintain and grow this infrastructure, financial support is required for analysts who produce fission-track data, participate in the continued development of community standards (e.g. regarding data acquisition, reporting, curation, interpretation), and provide a stable repository of expertise.

A platform for inter-laboratory centralized communication and collaboration. With such a platform, different laboratories within the USA should be enabled to informally share method development, standards, and laboratory calibration tests.

REQUIREMENTS FOR THE GROWTH OF FISSION-TRACK THERMOCHRONOLOGY:

Fission-track thermochronology has been the cornerstone of thermochronometric analysis since its inception in the 1960s. To ensure that fission-track thermochronology continues to evolve and grow for the next 60 years, we propose measures for continued development of the fission-track method and complementary analytical techniques.

Image capture and processing software. As outlined above, the future of fission-track analysis lies in image analysis and expanding its availability and use will be central to realizing this future. As more systems are purchased or developed (e.g., Nachtergaele & De Grave, this meeting), additional considerations will arise, such as repositories sufficient to house, curate, and share the image data, and inter-operability of different image acquisition and analysis systems. Such a system will lay the foundation for machine-learning algorithms that will propel fission-track towards increasing standardization and automation.

Additional mineral systems. Fission-track analysis is dominated by the application of the apatite fission-track system, with relative neglect of other mineral systems such as monazite (e.g., Jepson et al., this meeting; Jones et al., this meeting), titanite, epidote, and zircon which could greatly expand the capacity and applicability of fission-track thermochronology to higher and lower temperature ranges. Therefore, we suggest the revival and advanced method development for alternative fission-track systems, as well as development of new mineral systems such as rutile to open up new research possibilities for the geoscientific community.

Complementary chronometric data. The preservation of the analyzed grains in fission-track thermochronology allows the remaining material to be reused so that it can easily and affordably be coupled with additional thermochronometric dating techniques such as U/Pb and (U-Th-Sm)/He, allowing for single grain double- and triple-dating. Further facilitating the use of complimentary chronological tools will greatly expand the capacity and applicability of fission-track thermochronology.

Complementary geochemical data. Add-on analyses (e.g., electron-beam, LA-ICP-MS, Raman) are required to better detect compositional variation within and among grains, providing information on both provenance and annealing kinetics, making fission-track data more robust and informative (e.g., Ansberque et al., this meeting). The under-utilization of such analyses reflects various barriers including time, cost, and instrument availability, which need to be lowered.

Continued development of theory and characterization of kinetics. Although current annealing models have been successful in enabling productive data interpretation, they remain empirical and incomplete. Recent work on etching structure (Ketcham & Tamer, this meeting), low-temperature annealing, and compositional effects on annealing point to various opportunities to develop a deeper understanding of the fission-track system that will result in more robust interpretation for established minerals and accelerate development of new ones.

THE FUTURE OF FISSION-TRACK THERMOCHRONOLOGY WITHIN THE USA

Ultimately, we propose that the future of fission-track analysis within the USA will be concentrated around image-based systems, able to handle a variety of minerals and analysis protocols. Hosted on an accessible database or national consortium, image-based fission-track will support accurate, precise, robust, transparent, and reproducible analysis. Such a system will also serve as a platform for materials to help in the training of new users, lowering the hurdle for entry into this thermochronometric technique. An image-based database will allow fission-track users to produce their own data, with grain imaging the only barrier for entry, making fission-track analysis accessible to even the smallest users and budgets. Finally, such a database of images will provide the basis for applying machine-learning algorithms to fission-track analysis, paving the way for automated fission-track measurement. To ensure that this model is successful, the fission track community will require the human infrastructure (researchers, technicians, PIs) to support the training and mentorship of a larger group of analysts and the development and maintenance of community tools such as image databases and machine-learning algorithms.

OTHER THERMOCHRONOMETERS

While there was strong representation of the fission track and (U-Th)/He systems at the Thermo2021 meeting, there were only a few individuals in attendance who specialize in the development and application of other thermochronometers, including the $^{40}Ar/^{39}Ar$, U-Pb, luminescence, ESR, and cosmogenic noble gas systems. This in part reflects who was able to attend Thermo2021 during the COVID-19 pandemic; for example, developments in luminescence thermochronology are largely being driven by research groups outside the United States who were not in attendance. But it also reflects a clear trend in the thermochronology community over the last ~20 years toward low-temperature systems with applications to questions in landscape evolution and upper crustal tectonics. **We view it as imperative to re-engage with these 'other' thermochronometry communities, considering the central themes that emerged at the Thermo2021 meeting.**

One theme is the recognition of the understudied role of defects in modulating noble gas diffusion in minerals. Observations were shared that some apatite, zircon, and quartz grains exhibit complex helium degassing behavior during either continuous ramped heating measurements or stepwise degassing experiments (Idleman & Zeitler, this meeting; Tremblay et al., this meeting). This complex diffusion behavior resembles complex argon diffusion behavior observed in K-feldspars, often inferred to reflect noble gas diffusion in multiple diffusion domains (MDD) (e.g., Lovera et al., 1989) although other interpretations have also been put forward (e.g., Spikings & Popov, 2021). These observations about helium diffusion, when paired with theoretical calculations that predict much faster helium diffusivities in defect-free structures of the minerals commonly used for thermochronology (Gautheron et al., this meeting), suggest that 'imperfections' in mineral structures *beyond* radiation damage are playing an essential role in modulating helium diffusion in those minerals. Efforts to understand the effect of defects on noble gas diffusion in one mineral (e.g., helium in apatite) could lead to an improved understanding of complex noble gas diffusion behavior in another mineral (e.g., argon in K-feldspar), and vice versa. Moreover, there are potentially useful synergies with the luminescence/ESR communities, as the defects that act as luminescence signal traps and processes influencing traps and luminescence behavior (e.g., past exposure to heat and ionizing radiation, sample crystallinity and the presence of crystal plastic deformation) may also influence noble gas diffusion behavior. To this end, we encourage a stronger presence of the $^{40}Ar/^{39}Ar$ and luminescence/ESR communities, both at future Thermo meetings and more generally in efforts to understand the complex noble gas diffusion behavior that has now been observed in numerous phases.

A second theme is the potential for *in situ* methods to help resolve dispersion observed in (U-Th)/He datasets by accounting for parent and daughter nuclide heterogeneities at the sub-grain scale (Hodges et al., this meeting). It was recognized that other communities such as the *in situ* U-Pb geochronology community are much further along in understanding these spatial heterogeneity issues (e.g., Holder et al., this meeting), while the noble gas thermochronology community has been slower to develop and adopt *in situ* methods. This in part reflects the greater analytical expense and time investment of *in situ* methods compared to more 'conventional' approaches, particularly for noble gas-based thermochronometers, but the community was in general agreement that having greater access to and more data from *in situ* methods would be highly valuable. We therefore encourage greater interaction between these communities to exploit analytical and scientific advancements that could benefit both high- and low-temperature geo- and thermochronology.

A third theme is the strong encouragement of thermochronology studies that integrate across techniques and across disciplines, both within the geosciences (for example, with field geologists and petrologists) and in other STEM fields like materials science. The integration of both high-and low-temperature thermochronometers is being increasingly recognized as important for addressing questions in deep-time (e.g., Ronemus et al., this meeting) and in diverse thermal history settings (e.g., Goughnour et al., this meeting). Applications involving multiple thermochronometers, as well as studies that integrate thermochronology with other disciplines, will provide new insights into the sometimes complex thermochronometer behavior that the first two themes highlighted. Moreover, the pursuit of thermochronology studies that are interdisciplinary will create opportunities for broadening participation within our field, a key step toward improving the diversity of the thermochronology community. For example, Thermo2021 attendees widely agreed that more detailed sample characterization is necessary to address complex noble gas diffusion behavior (theme one) and sub-grain scale parent nuclide distributions (theme

2). It was also recognized that making routine, detailed sample characterization part of our methods will increase costs, perhaps to the detriment of researchers at places like primarily undergraduate institutions (PUIs). A solution, that also has potential to broaden participation in thermochronology, lies in a collaborative, interdisciplinary approach, wherein individuals with thermochronology analytical labs partner with individuals at institutions like PUIs who can do the characterization work.

In summary, stronger representation interactions with 'other' thermochronometers, as well as from other disciplines, is essential for future Thermo conferences and more generally in our community. Doing so will strengthen the science that we do and has the potential to broaden participation in thermochronology.

The field of thermochronology has been expanding rapidly and will continue to grow as new and innovative methods join the suite of well-tested existing methods. This is an exciting prospect and brings into focus the need for more consistent and transparent practices when it comes to handling data, reporting statistics, communicating methods, describing modeling, and clarifying interpretations.

To accommodate the rapid influx of data and new thermochronology methods, the community will benefit from the (i) standardization of reporting in manuscripts, (ii) ability to integrate different modeling software, (iii) publication of datasets or methods, and (iv) continuation of communication (Figure 1). Many of the community needs would be addressed by moving toward ICON-FAIR data and modeling practices (Goldman et al., 2021; Wilkinson et al., 2016), and we expand on each of these four areas below.

This white paper is a first step in documenting an initial list of "needs" created at the 17th International Conference on Thermochronology (Thermo2021), in Santa Fe, NM, USA. It is important to note that the needs outlined here and the suggestions for moving forward detailed below were contributions from those who participated in the Thermo2021 breakout session and those who responded to the feedback survey in the two months following the conference, most of whom are US-based students and early career researchers.

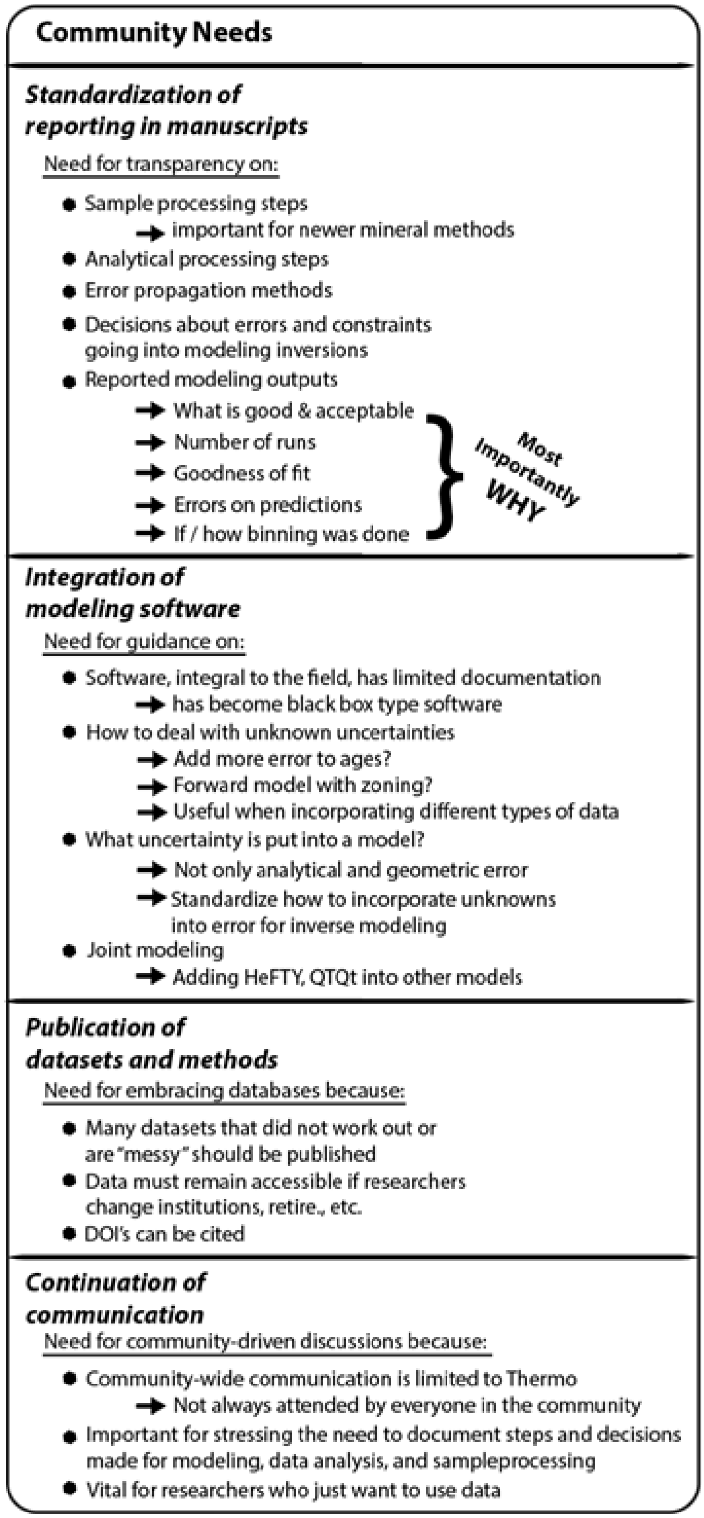

Figure 1: *Compilation of community needs and reasoning discussed during Thermo2021 breakout session: Frontiers in statistics, interpretation methods, and modeling.*

CURRENT STATE AND SUMMARY OF COMMUNITY NEEDS

STANDARDIZATION OF REPORTING IN MANUSCRIPTS

At present, thermochronologic data and methods are reported at the discretion of individual researchers and in numerous formats. The current patchwork of community standards is the product of an organic process, in which researchers write occasional method papers proposing standard approaches to particular aspects of reporting. Recent impactful contributions include, for example, frameworks for fully documenting modelling practices when using thermal history modelling software (Flowers et al., 2015; Gallagher, 2016). Additionally, there is a forthcoming special volume of the *Geological Society of America Bulletin* focused on "The Reporting and Interpretation of Geochronologic Data" which will outline reporting standards for several widely-used thermochronometers (Flowers et al., this meeting). At Thermo2021, contributions to this body of work included proposed best practices for assessing the results of thermal history models (Murray & Niemi, this meeting; Stevens Goddard et al., this meeting; Stoner, this meeting); new approaches for learning how to model thermochronologic data with HeFTy and QTQt (Abbey et al., this meeting); new tools for estimating and reporting uncertainties in (U-Th)/He ages (Martin et al., this meeting; Zeigler et al., this meeting), and overviews of the community databases and management tools Sparrow (Quinn et al., this meeting), LithoSurfer (Kohlmann et al., this meeting), and Geochron.org (McLean et al., this meeting).

However, new conversations within the thermochronology community reveal the need for a more structured process for discussing, writing, disseminating, and updating our community standards for reporting data and modeling methods in publications. It is imperative that this process produce citable publications for the researchers who lead and contribute to it, engage the community broadly, and anticipate and accommodate how standards and best practices will be a moving target as our discipline evolves and novel chronometers and interpretation methods become routine.

INTEGRATION OF MODELLING SOFTWARE

Currently, modelling software used by the community is a mixture of software produced by a handful of individuals that is widely used by many (e.g., HeFTy, QTQt, Pecube) and code written by individuals for their personal use that is not always well documented or widely available. The commonly used software packages are a huge service to the community. However, because they are maintained by individual researchers, the onus falls on them to update the software and it can be difficult for users to acquire the latest versions and documentation. Additionally, training on how to use these programs is done informally within thermochronology lab groups and formally via short courses at the biannual International Conferences on Thermochronology, and therefore access to these critical tools is limited for researchers in the broader geoscience community. Comprehensive tutorials including how to make some of the more difficult decisions with inverse modeling (data uncertainty, geologic constraints, etc.) are not widely available (Abbey et al., this meeting). Not all of the modeling software is open source, making it difficult to integrate with other models or modify for novel applications.

More open documentation is needed regarding the modeling software used by the community. Modelling software, as well as documentation both on how to use the models and how to assess the outputs, could be centralized so that version tracking and integration with other models is achievable. In the long term, the community could benefit from a community modeling hub similar to those that have been developed in other communities, for example CSDMS in the earth surface processes community.

PUBLICATION OF DATASETS AND METHODS

At least from the perspective of the US researchers who attended Thermo2021, there is not currently a database that has the full community support for publishing datasets, including messy datasets that are not published in a manuscript but could, if made available to the community, be the foundation for future methodological advances. Several databases exist that could support repositories that meet the community needs including adhering to ICON-FAIR data principles, notably Geochron.org (McLean et al., this meeting) and the Australian scientific community's AusGeochem/LithoSurfer (Kohlmann et al., this meeting) (Table 1). We could also learn from how other communities that generate and interpret complex geochemical data, such as the cosmogenic radionuclide community, which successfully tackled creating a community database (e.g., Balco, 2020). Such a location would also be the repository for unpublished datasets that perhaps did not lead to manuscript publication but should nevertheless be shared. This will also increase the accessibility of data, which can become lost or complicated when researchers change institutions or retire.

CONTINUITY OF COMMUNICATION

Much of the communication within the thermochronology community happens during the International Conferences on Thermochronology, which convene every other year. However, not all researchers are able to regularly attend these meetings, and it is currently difficult to otherwise facilitate community-wide discussions related to best practices in handling data, reporting statistics, communicating methods, describing modeling, and clarifying interpretations.

BENEFITS OF STANDARDIZATION AND PROTOCOLS

Clear and up-to-date community standards for how, where, and when thermochronologic data and metadata are reported and stored will make our entire field more accessible. Such standards remove barriers to successful interpretation and publication of thermochronologic data for our growing user base, facilitate the compilation and interpretation of large datasets for both method development and geologic studies, and give the broader community access to thermochronologic data, regardless of laboratory or field access, thereby offering an invitation to innovate and maximizing the impact of our data.

SUGGESTIONS FOR MOVING FORWARD

In this contribution, we suggest approaches that can address the thermochronology community's needs for better standards for reporting data and metadata, communicating methods, and describing, assessing, and interpreting modeling approaches and results (Table 1). We see these suggestions as a starting point, a springboard to promote open, ongoing communication and inspire individuals to spearhead efforts that meet these needs. These contributions will require substantial time and should not be relegated to early career professionals, but instead should be a community effort that results in steady progress on community-identified needs. We also recognize that these tasks will require substantial, ongoing effort and there should be a system of compensation and/or recognition for individuals who contribute to this work. Finally, we emphasize the community aspect of this endeavor, which will benefit not only from the experience of senior researchers but also the perspectives of those who are new to the field. By adopting a community-driven approach with continuous and transparent communication, our efforts—if successful—may serve as a model for other scientific communities.

Table 1: Suggested action plan to make headway on the needs of the community

Establish a listserv ~ *Supports: community communication needs*	**Reasoning / Justification**
	→ Way to communicate happenings in the community
	→ A place for pushing out new software or new versions of existing software
	→ Can be used to announce a publication or job opening/description
	Important Concerns and Community Decisions
	→ No desire for more emails
	→ Will posts be regular? monthly? annually?
	→ need to establish a way to submit posts to the listserv: need a host/monitor
Create reporting templates ~ *Supports: standardization of reporting & community communication needs*	**Reasoning / Justification**
	→ Way to clarify what everyone should be reporting: e.g., unified standard for metadata; format for all steps of workflow
	→ A time to create standards for accessibility, e.g., of published datasets (not just uploading pdfs)
	Important Concerns and Community Decisions
	→ Who decides what is kept or rejected as community standards
	→ We'd need a group to create these templates, request feedback, finalize versions as field evolves, and maintain version control
Inaugurate a centralized location for modeling software *(e.g., website)* ~ *Supports: modelling software integration & community communication needs*	**Reasoning / Justification**
	→ Can house documentation for differences between versions, and recommendations for when and how to use different models
	→ Host links to tutorials and teaching material for each software
	→A place for a "living" document to keep recommendations updated
	→ Can keep downloadable templates to easily edit for reporting
	Important Concerns and Community Decisions
	→ What community feedback on what should be present
	→ Must be created so screen readers can be used
More use of technical notes as publications ~ *Supports: dataset and methods publications, standardization, & community communication needs*	**Reasoning / Justification**
	→ Need publications for software, new and updated
	→ Brings up insights that are buried in the discussion of the paper: i.e., can be drawn out and expanded upon
	→ Highlights important information regarding mineral separation, lab measurements, "hidden curriculum", word of mouth, lab training, etc.
	→ Can be used as educational materials for lab or classes
	Important Concerns and Community Decisions
	→ Contributors deserve to get credit for these types of publications
Decide on a single database for publishing datasets (US researchers) & inter-database communication ~ *Supports: dataset and methods publications & community communication needs*	**Reasoning / Justification**
	→ Creates a platform for publishing "null results" or "messy data" so the community at large can work together to use and interpret it
	→ A way to give credit where credit is due if others can use the data. Note. publishing code through Zenodo provides a DOI
	→ If different databases work together to create interoperability: searching one effectively searches all
	→ Compiling not so useful datasets can provide a means to understanding the cause for the "mess"
	→ Allows for data to live on after someone has retired or a project has ended
	Important Concerns and Community Decisions
	→ There are many to choose from: e.g., Harvard Dataverse, Geochron, LithoSurfer, AusGeochem
	→ Sustainability: how is it maintained / who pays for it & Resiliency: what happens if sustainability model fails
Begin an annual internal review ~ *Supports: standardization of reporting & community communication needs*	**Reasoning / Justification**
	→ Each sub-field should solicit yearly feedback from the community, then send out standards back to the community
	→ A venue to create standards for accessibility, e.g., screen-reading accessibility, color blind, etc.
	→ Doing a little bit each year makes it more manageable
	→ Standard of metadata is always changing (higher standards, new standards for new methods)
	→ Community based, i.e., a central group finalizes and reports sends the standard updates, but the whole community will be surveyed to decide what standards should be updated
	Important Concerns and Community Decisions
	→ How will the members of the central group change (annually?), will they be compensated or recognized for their work in some way?

EARLY CAREER AND DEI SUBGROUP

Thermo2021 delivered an impressive showcase of research and ideas by early career scientists, including graduate students, postdoctoral fellows, research associates, and assistant professors. The smaller-than-typical meeting provided a unique opportunity for more early-career scientists to give oral presentations, contribute meaningfully to discussions, and form peer networks. We hope these opportunities continue to be prominent in the future to best support an engaging, inclusive, and diverse thermochronology community and advance our science. However, scientists from marginalized and underserved communities based on socioeconomic status, first generation student/education status, race, ethnicity, gender identity, sexual orientation, age, ability, and intersecting marginalized identities, continue to be underrepresented in thermochronology. As a community we can work to recruit and support our underserved members through **access** to information and high-quality data, **outreach** efforts, and strong **mentorship** networks. The theme of increasing access to and broadening participation within the thermochronology community is prominent throughout the Thermo2021 White Paper. This final section serves to highlight and summarize these ideas.

ACCESS

Access to data, resources, and information is key to ensuring an individually and institutionally diverse, well-informed thermochronology researcher and user base. The community, particularly early career and novice users, will benefit from efforts to standardize reporting protocols, access to easily available and navigable methodological resources, transparency in modeling approaches, and access to data reported in databases. New thermochronology labs will benefit from standards and assistance in acquiring materials and creating data collection protocols. It is important to recognize the challenges that laboratories face, from financial and staffing logistics to COVID-19 delays, which have an out-sized, career-impacting effect on new laboratories and early-career researchers.

It is additionally critical to recognize and address financial barriers to thermochronologic data collection. We point to a current example of a valuable resource for alleviating financial barriers, supporting cross-institution collaboration, and broadening access to thermochronology: the NSF-funded AGeS (Awards for Geochronology Student Research) program, which supports U.S. graduate student projects and associated geo- and thermochronology analytical costs up to $10,000. In addition to such programs, we encourage established and new thermochronology labs to consider specific pricing for undergraduate student researchers and cross-institution type (i.e., PUI, government agency, R1, etc.) collaborations, and to include financial support for smaller scale, collaborative projects, and projects that support underrepresented minorities within external grant proposals.

We also emphasize the value of participating in the biannual Thermo meetings and recognize the substantial financial barriers that prevent broader conference attendance. Future Thermo meeting planners may consider tiered pricing for students and maintaining a free virtual component, such as pre-meeting online sessions (à la Virtual Thermo2020) or recording and making available plenary and awardee talks to enhance access. Ultimately, broadening access to thermochronology through Thermo meeting attendance is critical for equity, innovation, and expanding the reach of our field.

OUTREACH AND MENTORSHIP

Outreach, recruitment, and retainment efforts will support a diverse thermochronology community. At the Thermo meeting and other international meetings, this could include pre-meeting short courses focused on thermochronology method basics and thermal modeling, career panels and workshops, a specific time or space to advertise graduate school, post-doctoral, faculty, and industry career opportunities, pre-meeting community boards for new members of the community to find potential roommates and organize near-peer mentorship, travel grants, a student-only or early career networking opportunity, early-career oral sessions, and lightning (1-minute) poster talks during related oral sessions. The thermochronology community can build off of established recruitment and mentorship structures, such as the Geological Society of America

On To the Future program, which pairs students from underrepresented minority groups with mentors to establish connections before, during, and after the annual conference. We may consider leveraging our connections to and positions within established professional associations such as EGU and AGU to host networking events and information sessions, workshops, or short courses for interested novice users at annual conferences.

Strong mentorship networks lead to improved recruitment, success, retention, and sense of belonging for early-career scientists and people who identify as a member of one or more marginalized group (e.g. National Academies of Sciences, 2019). PIs and mentors within the thermochronology community need to combat unconscious and affinity biases when recruiting students and researchers. They should also create concrete mentorship plans with their mentees, and consider and execute plans to involve undergraduate and graduate students in authentic, valuable science experiences. The Thermo meeting can serve as a forum to discuss and brainstorm successful mentorship and recruitment strategies. We encourage the development of tiered mentorship systems to provide greater opportunity for near-peer and peer mentorship and allow early career scientists to take on mentorship and leadership roles. Thermo serves as an excellent environment to craft these mentorship networks through informal meetings (i.e., icebreaker events, daily small at-conference lunches, meeting fieldtrip) and intentionally designed meetings (i.e., topic-specific small group discussions, cross-institution and career stage meetings). The community can also take advantage of resources such as Slack (see thermochron.slack.com) and Zoom to grow online, accessible networks following Thermo meetings.

Collectively, we need to be innovative, collaborative, and intentional, and to dedicate time and resources to the goal of broadening successful participation in thermochronology.

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