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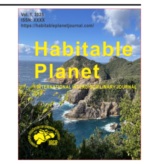

Guidelines for testing hypotheses: A case study of episodic crustal production versus supercontinent-linked selective preservation

Stephen J. Puetz*

475 Atkinson Dr, Suite 704, Honolulu, HI 96814, USA

ABSTRACT

From a big picture perspective, the major components of scientific research include metaphysics, scientific paradigms, scientific hypotheses, scientific data, and tolerance toward various ideas. Based on these components, six guidelines are established for conducting geological research: awareness of underlying assumptions, development of falsifiable hypotheses, testing hypotheses, tolerance of competing hypotheses, replicating results, and obtaining representative sampling. Using these guidelines, a case study follows, which reviews empirical tests of the episodic crustal production hypothesis and the supercontinent-linked selective preservation hypothesis. The results support the episodic crustal production hypothesis while falsifying two key postulates of the selective preservation hypothesis.

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Research Highlights

- Guidelines for geological research formulated from major components
- Case study on episodic crustal production and supercontinent-linked selective preservation
- The results support the episodic crustal production hypothesis
- The results falsify two key postulates of the selective preservation hypothesis

*Email: puetz.steve@gmail.com

1 Introduction

While striving to improve our understanding of geological processes from the steady stream of published data and information, an important question arises: How does one optimally process these virtually limitless volumes of information? There is no easy answer. However, a step back from the confines of the various geological disciplines, and a step toward the broader scope of understanding rules for conducting scientific research provides a solid base for processing new information. While this big picture approach might initially seem reasonable, in practice, inconsistencies in the rules prevent widespread application. Thus, system wide rules across all branches of science remain elusive. To better understand the big picture, a review follows with the multiple components identified by prominent 20th Century philosophers (Hollinger, 1973). Major components of scientific research include metaphysics, scientific paradigms, scientific hypotheses, scientific data, and tolerance (Puetz, 2022). The divergent focuses of the prominent philosophers led some to treat metaphysics as either useless speculation or sets of contradicting worldviews (Ladyman, 2012). However, focus should not be confused with contradiction.

Metaphysics deals with the nature of the universe, which involves making decisions about basic, unprovable beliefs about its operation, called fundamental assumptions (Collingwood, 2020; Borchardt, 2004, 2007). For example, is the universe finite or infinite in time? Or is the universe finite or infinite in space? Collingwood noted that an individual often reacts with a "ticklish" response when fundamental assumptions are questioned. Think of this as the emotional part of science that few want to admit to, and many want to avoid mentioning at all costs. Collingwood (2020) believed that some natural scientists despise metaphysics because they dislike having their fundamental assumptions questioned. Borchardt (2004) defines fundamental assumptions in terms of opposing, unprovable worldviews such as materialism versus immaterialism, causality versus acausality, conservation versus creation and destruction, irreversibility versus reversibility, and infinity versus finity. These can be broadly defined as deterministic assumptions versus indeterministic assumptions.

Based on fundamental assumptions and empirical evidence, each investigator must choose which scientific paradigm to align with (Kuhn, 1963, 1970). Kuhn noticed that founders of new paradigms generally have little success in changing the minds of scientists aligned to an established paradigm that is failing. As a rule, young scientists and those new to the field (still making up their minds and still establishing personal fundamental assumptions) determine whether a new paradigm provides an enhanced framework for conducting scientific investigations (Kuhn, 1963, 1970). A dominant paradigm tends to be a stable worldview spanning decades or even centuries. However, history shows that cracks generally develop when a dominant paradigm fails to explain new observations (Kuhn, 1963, 1970). When that happens, a new, innovative paradigm can overthrow the failing paradigm quite rapidly. As an example, in the early 20th Century, the prevailing geological paradigm posited that the continents were permanently fixed over all time, in their present locations. German meteorologist and geophysicist Wegener (1912) challenged that hypothesis by formulating the first complete statement of the continental drift hypothesis. By 1930, Wegener's theory had been rejected by most geologists. He was widely criticized, his evidence mocked, and his character maligned, and Wegener's theory sank into obscurity for the next few decades (Conniff, 2012). However, continental drift ideas eventually developed into theories of seafloor spreading (Hess, 1962), plate tectonics (Wilson, 1966), and episodic openings-closings of ocean basins (Wilson cycle). Thus, starting in 1962, the paradigm of permanently fixed continents began to collapse and by the early 1970s was replaced with the present plate tectonics paradigm.

Within a given paradigm, various competing hypotheses generally develop. Assessing the validity of each hypothesis can be challenging. However, Popper (1959, 1963) established rules for conducting empirical research by focusing on falsifiable hypotheses, which Popper treated as scientific hypotheses. That is, if a hypothesis is scientific, then it can be disproven if it is false. Thus, to be scientific, a hypothesis can be either true or false. If the hypothesis is false, then the research community will be in a good position to disprove it. Popper considered all other hypotheses as non-scientific, referring to them (somewhat cynically) as safe theories. That is, a non-scientific theory is too poorly defined to be disproven, if it is false.

Various types of measurements and observations constitute the scientific data that are critical for developing and testing scientific hypotheses. Just like a contested hypothesis, scientific data can be equally contentious. Depending on the hypothesis one favors, the data can be considered either flawed or new and enlightening. An example demonstrates the need for tolerance of new ideas and new observations. After Shechtman et al. (1984) struggled to publish his eventual Nobel-winning observation of a five-fold quasicrystal structure in an electron microscope, the most intense battles came during post-publication scrutiny. Established quantum chemistry prohibited the quasicrystal structure that Shechtman observed (Van Noorden, 2011). A principal founder of quantum chemistry, Pauling (1985), steadfastly doubted the veracity of the observations described by Shechtman et al. (1984). An intense confrontation developed. Based on the convictions of their underlying assumptions, each approached the problem differently and asked different questions. Pauling (1985) believed quantum chemistry was correct as stated, and asked: What is wrong with Shechtman's observation? Conversely, Shechtman et al. (1984) believed his observation was correct, and asked a different question: What is wrong with Pauling's theory? While neither can be faulted for acting on their beliefs, this example illustrates why assumptions are critical in scientific research. Assumptions often influence the types of questions an investigator asks and then tries to answer. While defending his findings, Shechtman encountered resistance from his employer, and he was asked to leave his job (NobelPrize.org, 2011). However, Shechtman persisted, eventually won the 2011 Nobel Prize in chemistry, and contributed to a paradigm shift in chemistry, physics, and materials science (Van Noorden, 2011; Hargittai, 2011). Conversely, Pauling continued his dogmatic stance toward his own theories throughout his life and automatically assumed Shechtman's observations were flawed. Instead of considering the possibility that his own theory was not entirely correct, Pauling needlessly instigated an intense attack against Shechtman's character and observations.

Perhaps the need for tolerance towards new and opposing worldviews is the most important part of fair and balanced scientific research. The long history of undue criticism and character assaults against innovative scientists led Lakatos (1978) to suggest tolerant scepticism toward new but potentially undeveloped hypotheses. Russell (1948) also considered tolerance as the ideal for conducting research because it has two sources: (a) the realization that one might be mistaken, and (b) the belief that free discussion will promote the view that one favors. This latter opinion must be held by anyone whose ideas are formed on rational grounds. Conversely, dogmatists fear that free discussion would show their beliefs to be groundless, and that is why a dogmatic theorist favors censorship (Russell, 1948). The scientific community has yet to adopt a uniform set of rules for conducting research. For instance, Earth scientists tend to prefer interpreting observations by emphasizing causality, whereas physicists generally prefer interpreting data by defining processes in terms of equations (sometimes referred to as mathematical physics). This assessment is partially made from my personal experiences – where reviewers encouraged manuscript revisions to speculate about causes for the empirical observations of cycles found in detrital zircon age distributions. This emphasis on causality over empiricism is similar to the state of 17th Century physics. At that time, Isaac Newton's empirical formulation of gravity drew significant criticism (Ducheyne, 2011). The detractors claimed that Newton's gravitation equation was meaningless without identifying the cause for the "spooky" gravitational action at a distance. Yet, the equations are still widely used today even while physicists continue to debate the cause of gravity (Ducheyne, 2011; Verlinde, 2011; Chen, 2020). Because of mathematical formulations, physicists have accepted the concept of empirical falsifiability, whereas geologists in most part have not. Geologist Mark Harrison is among those at the forefront criticizing Earth scientists for diverging from the physical sciences on this front. Harrison (2020) states that the fragmentary nature of the rock record and the extraordinary timescales involved lend themselves to theoretical frameworks that embody multiple geophysical assumptions. New results introduced into such a geological framework either support the existing hypothesis or require an *ad hoc* adjustment to prevent falsification. Although the *ad hoc* explanation gives the appearance of valid science to some geologists, the tendency to not challenge the underlying assumptions of the preferred narrative is disconcerting (Harrison, 2020).

2 Methods

Given this historical background on fundamental assumptions, scientific paradigms, the structure of scientific hypotheses, questions about the validity of data, and tolerance toward new ideas and observations, this presentation turns to guidelines for conducting geological research. These suggested guidelines were gradually developed based on both historical philosophical recommendations and personal challenges faced while testing a variety of geological hypotheses.

2.1 Awareness of underlying assumptions

Awareness of the assumptions being made in association with a hypothesis can greatly influence the design of tests attempting to falsify it. Thus, it is critical to understand the assumptions as much as possible. In practice, this is exceedingly difficult because the underlying assumptions generally go well beyond the immediate branch of science under investigation – forming a type of infinite regress of assumptions. For instance, a reliable study of the U-Pb age distribution of detrital zircon depends on correct assumptions being made when tuning a mass spectrometer to make U-Pb measurements. In turn, the spectrometer-related assumptions depend on other assumptions being made by specialists in isotope chemistry. Further in turn, the isotope chemistry assumptions depend on the validity of assumptions held by particle physicists. Regardless of the branch of science, these seemingly endless chains of inter-dependent assumptions generally make solving scientific problems immensely complex. In most instances, investigators will defer these decisions to experts in the associated disciplines. Doing so is often the most convenient and practical approach. However, it can lead to unawareness of key assumptions and flawed testing in at least two ways: (a) unawareness of a key assumption anywhere along the chain limits the possibilities for designing a rigorous test of a hypothesis, and (b) when accepting an incorrect assumption, test results are more likely to be biased. Despite these obstacles, spending time to understand as many underlying assumptions as possible can enhance the design of tests aimed to rigorously test the hypothesis of interest.

2.2 Developing falsifiable hypotheses

When formulating a hypothesis, it should be defined with as much detail as possible, so a clear path forward is available to disprove it, if the hypothesis is false. That is, work diligently to make the hypothesis falsifiable. Along these lines, be sceptical of the "safe theory" that Popper (1963) so despised — a hypothesis too poorly defined to be disproven if it is false. There is often little difference between a safe hypothesis and a valid but undeveloped hypothesis, and they can be considered as equivalent. Both types of hypotheses will almost certainly be subjected to considerable questions and criticisms. In this case, the developer is obligated to provide additional details about the hypothesis so that it can fully develop into a falsifiable format. Failure to respond to valid criticisms leaves the hypothesis in a safe format — meaning that it will remain unscientific.

2.3 Testing hypotheses

Regardless of the popularity or general acceptance of a hypothesis, every hypothesis must be rigorously tested to determine if the hypothesis is valid. A special effort should be made to try to disprove the hypotheses we believe are correct. It is permissible, and recommended, to also pursue the natural tendency of attempting to disprove the hypotheses we oppose. However, when doing so, it is equally important to make attempts to disprove the hypotheses we prefer.

2.4 Tolerance

Always remain tolerant toward undeveloped and well-defined scientific hypotheses that are currently out of favor (Russell, 1948; Lakatos, 1978). Tolerance is important because a minority hypothesis could provide a more correct explanation of existing observations. Unyielding views obstruct scientific discovery. Conversely, open discussions about contradictory hypotheses, questionable data, and other relevant topics serve as the backbone of scientific progress.

2.5 Replicate results

Opponents of competing hypotheses often argue that a certain set of data are flawed in various ways. To minimize this risk, it is optimal to conduct new studies with independent data to determine if the results are replicable (Puetz et al., 2024a). For example, results from sampling that fails to reflect the true composition of the studied population is especially prone to being non-replicable. Repeated tests that successful replication results elevate the credibility of the sampling methods and the data.

2.6 Representative sampling

Closely aligned with data quality, a key investigative consideration is whether the sampled data is truly representative of the population being studied. When designing a sampling strategy, key questions include: (a) Is the population distributed homogeneously or heterogeneously? A homogenous population has the same properties everywhere, which makes the selection of sampling points irrelevant. Conversely, a heterogenous population has divergent properties, which requires even sampling throughout all regions of the population. (b) Were the samples collected randomly, or based on pre-determined, non-random selections? Non-random samples generally require special pre-analysis treatments that are not required for random samples. (c) If the study is global, are all regions of the globe sampled? The same holds for continental and regional studies. (d) Are all areas of the population sampled proportionally? If not, and if the population is distributed heterogeneously, then the samples must be weighted using either inverse spatial or inverse spatial-temporal methods (Stehman and Selkowitz, 2010; Keller and Schoene, 2012; Puetz et al., 2024a, 2024b). (e) All studies and all populations differ in some respects. Thus, additional sampling considerations might be relevant, beyond the four mentioned here. For example, detrital zircon grains for U/Pb analysis are almost always collected as cluster samples (a group of samples from the same rock), rather than a single grain from each rock. Samples collected as a cluster generally require special pre-analysis treatments (Lo and Watson, 1998, Stehman and Selkowitz, 2010; Puetz et al., 2017).

3 Case study

A review of a previous study, which tested the selective preservation hypothesis (Puetz and Condie, 2021), provides an example of how the rules from Section 2 can be applied. Currently, two competing hypotheses are given to explain the wide variation in zircon age peaks and valleys over time: (a) Some interpret zircon age peaks as actual episodes in crustal production (Stein and Hofmann, 1994; Condie, 1998; Arndt and Davaille, 2013; Parman, 2015; Walzer and Hendel, 2017), whereas others propose that collisional phases of the supercontinent cycle cause variation in crustal preservation potential which in turn produces the episodes recorded in detrital zircon histograms (Hawkesworth et al., 2009, 2010, 2019; Dhuime et al., 2011). To help resolve this dispute, a key question is: How does one go about disproving each hypothesis, if false?

When conducting analyses to try answering such questions, the potential exists for introducing biases related to zircon preservation, transport, analytical methods, and/or other unidentified processes. Zircon transportation is unlikely to be a major factor in biasing U-Pb detrital zircon age distributions because (a) transportation factors are irrelevant for igneous zircon ages, and (b) multiple independent global U-Pb age distributions from igneous and detrital zircons are nearly identical for the interval 3300–20 Ma (Puetz et al., 2025). The potential for analytical bias in U-Pb zircon ages was recently evaluated in terms of accuracy and precision. Specifically, U-Pb ages are reasonably accurate, ±5 myr, whereas the same ages show considerable imprecision, ranging from ±10 to ±40 myr (Puetz and Spencer, 2023; Puetz et al., 2024a). When ages are accurate but imprecise, then large sample sizes are required to properly identify age peaks (∼300,000 samples in our detrital zircon studies). With these accuracy limitations in mind, and assuming that global sampling is sufficient, cycles from zircon age distributions should be easily detected for periodicities exceeding 30-myr, whereas cycles in the 10-to-30-myr range are still possible to detect but with considerably greater uncertainty. And finally, continental crust (and associated zircon) is continually being destroyed. However, the potential for zircon preservation bias only becomes relevant if, at a given age, global destruction is non-random. This and other topics related to zircon preservation are further discussed later in this section.

As typically happens in all sciences, the initial versions of episodic crustal production hypothesis were poorly defined, and thus undeveloped. However, a recent version (Puetz and Condie, 2021) provides more details by postulating the following: (a) the observed detrital-zircon age distribution is proportional to crustal production; (b) crustal destruction occurs randomly from the collective processes of surface weathering and erosion, delamination of lower continental crust and mantle lithosphere, and subduction; (c) at any given point in time, the percentage of continental crust of a given age that is destroyed is roughly proportional to the percentage of crust of that age that is preserved globally; and (d) rather than a single periodicity, the variation in zircon/crustal ages occur as a combination of four harmonic cycles: ∼810, 270, 90, and 67.5-myr (Puetz et al., 2025). This version of the episodic production hypothesis contains several refined details that should provide a sceptic with multiple means of disproving the hypothesis, if any detail is false. Our own tests support this hypothesis, but the key support must ultimately come from tests beyond our own research teams.

Now, consider a falsifiable version of the selective preservation hypothesis. Like the early versions of the episodic crustal production hypothesis, the sparsity of details in the original version of the selective preservation hypothesis (Hawkesworth et al., 2009) prevented falsification attempts. One potential argument against testing the selective preservation hypothesis is that all evidence was destroyed via unusually high destruction rates at certain points in supercontinent cycle. If one accepts this argument, then the selective preservation hypothesis is indeed a "safe hypothesis" — one that is non-scientific, cannot be tested, and is based solely on belief. However, in actuality, this argument has two components that indirectly make the selective preservation hypothesis falsifiable: (a) the episodic destruction is linked to the supercontinent cycle, which has a poorly defined periodicity generally believed to last from 400-myr to 800-myr (Nance et al., 2014; Mitchell et al., 2021); and (b) major valleys in the detrital zircon age distribution correspond to supercontinent phases when new continental crust was destroyed at unusually high rates while continental crust of all other ages were preserved with minimal destruction. If one accepts these as the basic tenets of selective preservation, then several means exist for testing it. Going forward, consider the second tenet as the "single-age destruction" postulate.

A study of pre-orogenic and post-orogenic detrital zircon age distributions for ten Phanerozoic orogens (Fig. 1) tests the single age destruction hypothesis (Puetz and Condie, 2021). The age distributions for these ten orogens are nearly the same for the pre-orogenic and post-orogenic intervals (Fig. 2), which means the same populations of rocks are being eroded and transported pre- and post-orogen. More importantly, elevation maps show that these large orogenic belts are not being destroyed in a significant way, regardless of the divergent tectonic settings for each. The mountain chains remain, even though small portions of the chains continually erode. Because instances of single-age destruction are not found in Phanerozoic orogenic belts, it is doubtful single-age destruction occurred during the Precambrian.

Results from the time-lapse zirconography method (Parman, 2015) tentatively support the episodic crustal production hypothesis and falsify the selective preservation hypothesis. Using a 500-myr intervals to bin samples based on depositional ages, Parman found that peaks and valleys in zircon ages were transferred through time. This indicates that crustal preservation potential is proportional to original production volumes – which, again, contradicts the selective preservation hypothesis. However, it might be argued that the 500-myr bin size used in Parman's study approximately equals the duration of the supercontinent cycle, and thus, fails to reflect possible variation in global tectonic settings over time.

To address this concern, Puetz and Condie (2021) used a larger global detrital zircon database with more extensive global sampling coverage (Puetz and Condie, 2019) to reduce the bin size to 300-myr for depositional ages greater

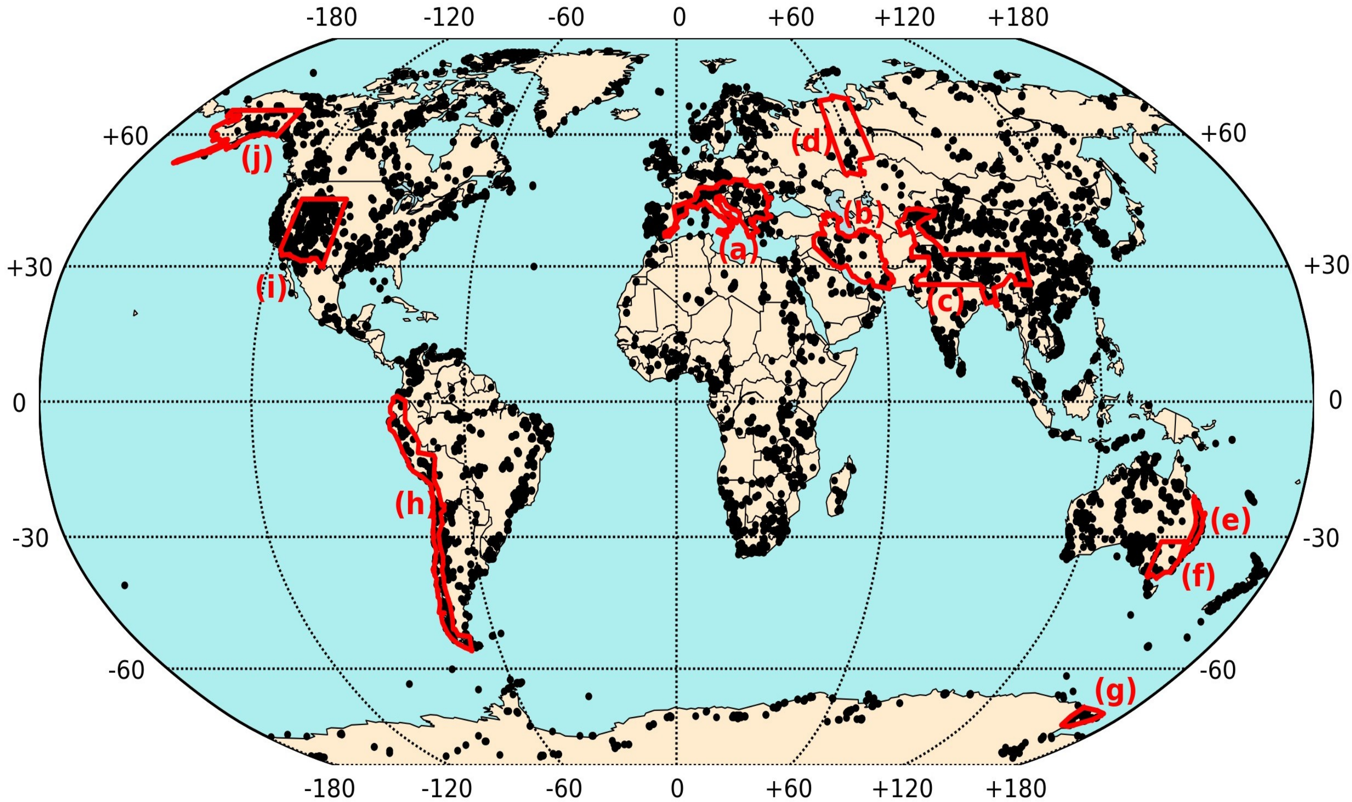

Fig. 1. Sample locations of ten Phanerozoic orogens (red outlines). Black dots show locations of all detrital zircon samples from the global database of Puetz and Condie (2019). Orogens are: (a) western Alpine-Himalayan, (b) central Alpine-Himalayan, (c) eastern Alpine-Himalayan, (d) Uralian, (e) New England, (f) Lachlan, (g) Ross, (h) Andean, (i) North American Cordillera in the south-central United States, and (j) North American Cordillera in southern Alaskan.

than 500 Ma, and to further reduce the bin sizes to 35-myr to 200-myr during the Phanerozoic. The bin sizes vary because all age distributions were constructed to be global, and too few samples are available with Precambrian depositional intervals. Thus, to meet the globality requirement, 300-myr is the smallest practical limit for the bin size during the Precambrian. The resulting age distributions (Fig. 3) confirm the results from Parman (2015). The much finer depositional age resolution (Puetz and Condie, 2021) minimizes the risk that large age-windows mask preservation potential due to changing global tectonic settings. The finer resolution of the detrital zircon age distributions confirms Parman's finding that crustal age peaks and valleys are transferred through time.

Perhaps the most critical blow to selective preservation is the fact that the hypothesis postulates that variation in preserved zircon ages is a consequence of the supercontinent cycle. Yet another test (Puetz et al., 2025) found that zircon age distributions have at least four harmonically related periodicities of 810, 270 ($^1/_3$ of 810), 90 ($^1/_9$ of 810), and 67.5-myr ($^1/_{12}$ of 810) spanning the interval from 3300 Ma to present. While the 810-myr cycle might be linked to the supercontinent cycle, the three higher frequency cycles are not. With the detrital zircon records revealing periodicities much shorter than the supercontinent cycle, this falsifies the hypothesis that variation in preserved continental crust is caused by preservation potential linked to phases of the supercontinent cycle.

In defence of the original undeveloped version of the selective preservation hypothesis (Hawkesworth et al., 2009), at that time the only available zircon age distributions were low resolution, generally 50-myr bin size or larger. Because of this, the higher frequency cycles were neither detected nor investigated until recently. However, as often happens in all sciences, new data gradually became available that permitted analyses that were previously not possible. The latest data from six independent zircon time-series (three detrital and three igneous) show the harmonic cycles of ~810, 270, 90, and 67.5-myr are highly replicable, and thus, very likely to be real (Puetz et al., 2025). Using the guidelines presented here, new studies should help advance geosciences forward — moving toward the eventual understanding of the multiple periodicities observed in the global zircon archives.

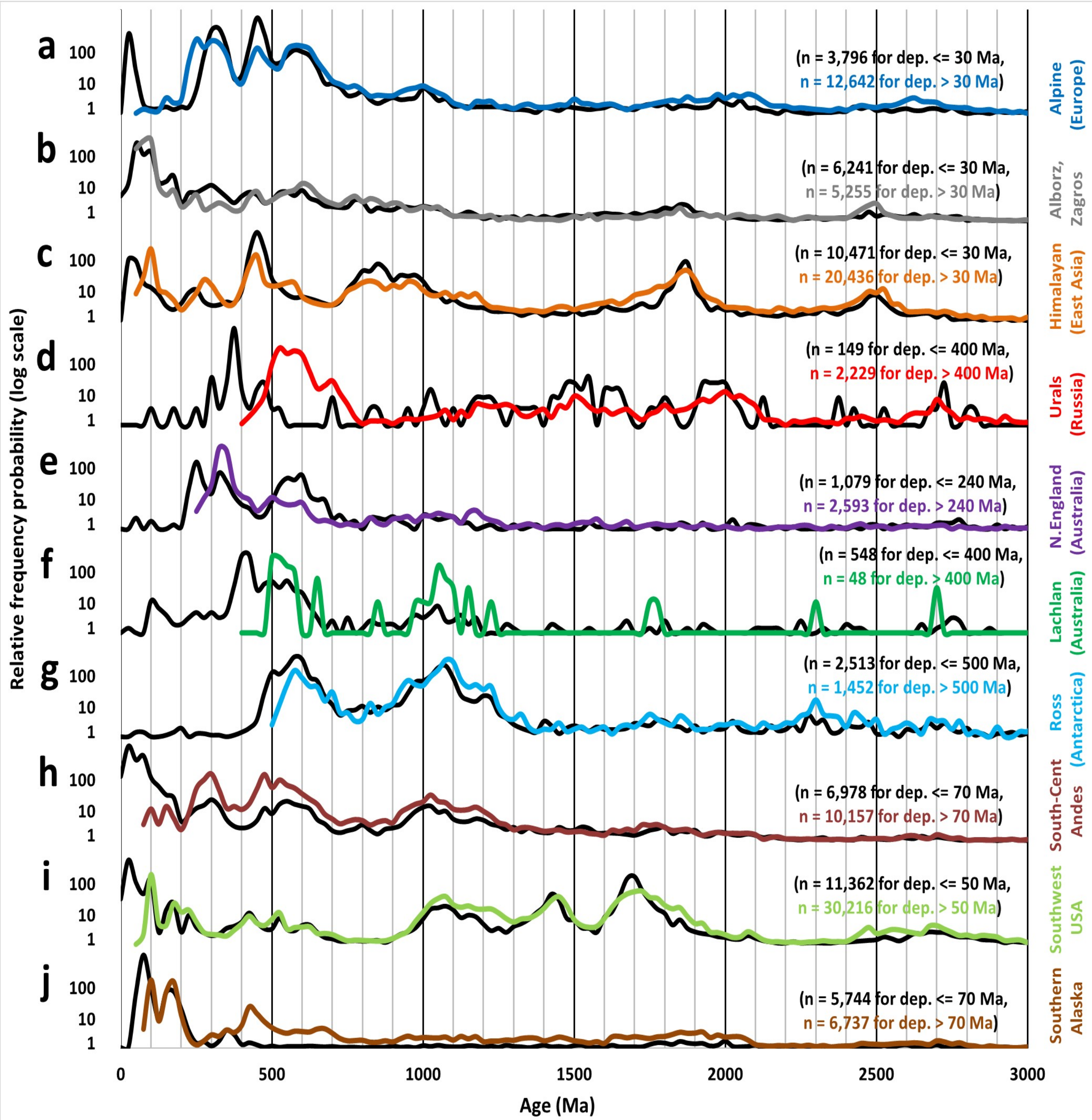

Fig. 2. U/Pb detrital zircon age distributions from ten Phanerozoic orogens. Orogenic ages are from samples outlined in red in Fig. 1. Detrital zircon data are from the database of Puetz and Condie (2019). In the panels, black curves illustrate age distributions for samples with depositional ages $\leq$ mid-point of the orogeny, whereas coloured curves illustrate age distributions for depositional ages $>$ mid-point of the orogeny. The orogens and their approximate age-ranges follow: (a) Alpine orogen, 140–0 Ma, (b) Caucasus, Alborz, and Zagros orogens, 100–5 Ma, (c) Himalayan orogen, 50–0 Ma, (d) Uralian orogen, 325–250 Ma, (e) New England orogen, 260–225 Ma, (f) Lachlan orogen, 540–440 Ma, (g) Ross orogen, 550–480 Ma, (h) south-central Andean orogen, 200–0 Ma, (i) North American Cordillera orogens in southwest USA, 270–0 Ma, and (j) southern Alaska accretionary orogens, 200–0 Ma.

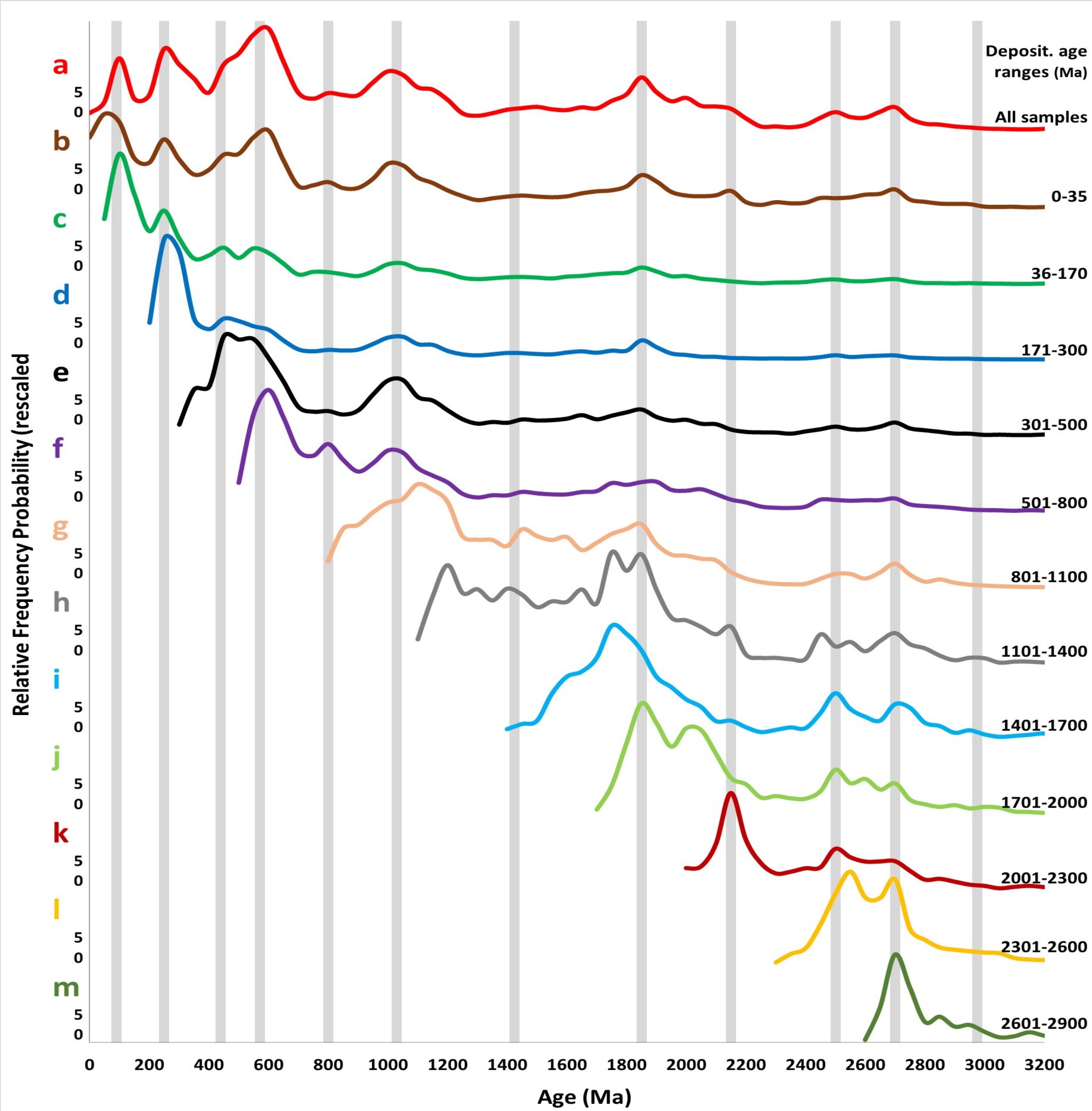

Fig. 3. Time-lapsed zirconography at intervals of 300-myr or less. U/Pb detrital zircon age distributions from the database of Puetz and Condie (2019), using 14 maximum depositional age-ranges, with sample sizes designated by *n*: (a, red) global age distribution for all detrital samples (*n* = 766,658); (b, brown) 0–35 Ma depositional ages (*n* = 155,099); (c, green) 36–170 Ma depositional ages (*n* = 152,483); (d, blue) 171–300 Ma depositional ages (*n* = 107,084); (e, black) 301–500 Ma depositional ages (*n* = 131,073); (f, purple) 501–800 Ma depositional ages (*n* = 91,835); (g, tan) 801–1100 Ma depositional ages (*n* = 38,554); (h, grey) 1101–1400 Ma depositional ages (*n* = 13,860); (i, light blue) 1401–1700 Ma depositional ages (*n* = 14,823); (j, light green) 1701–2000 Ma depositional ages (*n* = 26,894); (k, dark red) 2001–2300 Ma depositional ages (*n* = 8,812); (l, orange) 2301–2600 Ma depositional ages (*n* = 9,380); and (m, olive) 2601–2900 Ma depositional ages (*n* = 9,206) Gray vertical backgrounds identify ages with multiple common peaks.

4 Conclusions

Based on ideas from the prominent 20th Century philosophers, six guidelines are presented for conducting geological research: awareness of underlying assumptions, development of falsifiable hypotheses, empirical testing of hypotheses, tolerance of competing hypotheses, replicating results, and obtaining representative samples. As a case study, these guidelines provided a means for assessing the validity of the episodic crustal production hypothesis and the selective preservation hypothesis. The results show harmonic cycles of ∼810, 270, 90, and 67.5-myr, of which the latter three cannot be explained by the supercontinent cycle. This finding essentially falsifies the postulate that phases of the supercontinent cycle cause the observed periodicity in the preserved detrital zircon archives.

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Declaration of competing interest

The author declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit author statement

Stephen Puetz: Conceptualization; Investigation; Visualization; Writing—original draft and revision.

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