JOURNAL PAPER

Later Lead Uptake: A New Way Zircons May Get Their Lead

By Matt Nailor (with editorial contributions by Donny Budinsky)

Truth In Research (2025)

Introduction

When geologists measure the age of zircon crystals, they usually assume that all the lead inside was produced slowly, atom by atom, as uranium decayed over billions of years. But what if some of that lead wasn't made inside the zircon at all? What if it arrived later, carried in by hot fluids from neighboring minerals that had already produced radiogenic lead?

That's the idea behind a new model we can call the **Later Lead Uptake (LLU) and Primordial-Ratio Lead (PRL) model**.

Zircon could have inherited radiogenic lead that was **created from the start**, **delivered by fluids** and locked in. Basically zircons could have **inherited** radiogenic lead (Pb*) later after their formation, that was **already existing on earth from creation** and then **delivered by hot fluids** into tiny cracks and damaged rims that later healed and "locked in" the lead in place.

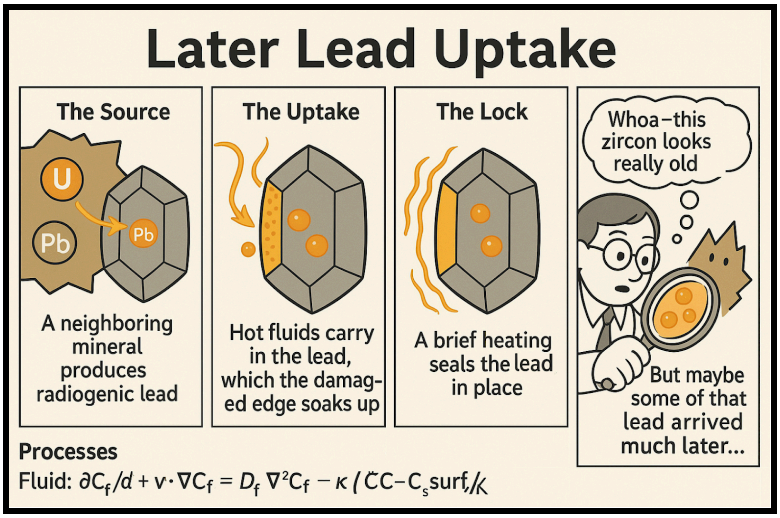

Image 1.

How it works (story):

1. God created the Earth, it was formed with water and the land was under this water.

2. The lead at this time was formed in the ratios we observe today, including radiogenic lead.

3. Zircon crystals form and absorb radioactive elements like Uranium and Thorium but do not take up lead.

4. Later, hot, slightly acidic water dissolves some of that already-radiogenic lead. As the salty hot water (think hydrothermal) flows through micro-fractures in zircon crystals they pick up Pb as Pb^{2+} chloride/fluoride/carbonate complexes. Since zircon acts like a sticky filter: The fluid seeps through microcracks; damaged zircon takes up the lead as ions or tiny Pb-bearing complexes. Pb complexes stick or exchange into these rims or along micro-veins.

5. Even a brief heating/cooling cycle heals the rim and traps the imported Pb.

Basically zircons obtained a microscopic crack that filled with hot, salty water. That fluid contained radiogenetic lead that was dissolved in it and delivered it to the zircon which then healed and trapped it inside.

Not all lead in Earth's crust was created by uranium decay. A portion of lead formed **at the beginning** already split into the same isotopes we call "radiogenic" today (^{206}Pb, ^{207}Pb, ^{208}Pb) **in roughly today's proportions**. Rocks and fluids then **sorted and mixed** that pre-set lead into minerals like zircon.

This means the following.

1. **Start with pre-mixed lead**
   When Earth's crust formed, the lead wasn't a blank slate. It already contained the "daughter" isotopes in near-modern ratios. Think of it like pre-dyed paint: different colors (lead isotopes) are already in the bucket.

2. **Separate into "reservoirs"**
   Early melting and crystallization separated the crust into pockets with **slightly different lead recipes** (some a bit more $^{206}Pb/^{207}Pb$, some a bit less). These pockets live on in old pre-flood basement rock layers.

3. **Mineral sorting during crystal growth**
   As minerals formed, they **took up lead differently**. Zircon generally hates lead in its crystal lattice, but tiny inclusions, defects, or nearby fluids can still **introduce lead** during or soon after growth.

4. **Local plumbing re-mixes the lead**
   Hydrothermal fluids and microfractures **move pre-existing lead around**, concentrating it in rims, cracks, or neighboring minerals—without needing uranium to decay inside the zircon.

5. **What "ages" then measure**
   If you assume all lead came from uranium decay, those **built-in isotope proportions** can be **reinterpreted as time**. Patterns like "concordant ages" can emerge from **mixing lines**, **preferential loss**, or **repeat fluid events**, rather than radioactive clocks.

Now these are bold claims, anyone can just say "well God created the elements like they are today", but is there any proof for this? Yes, there is. Multiple lines of evidence actually. Let's first take a look at the lead paradox. This discovery was found when they looked at the ratios of radiogenic isotopes (^206Pb, ^207Pb, ^208Pb) to the non-radiogenic isotope (^204Pb) and found that they don't line up with what we'd predict from simple uranium/lead (U/Pb) and thorium/lead (Th/Pb) decay over deep evolutionary time. According to evolution, this is what the scientists found.

Earth's history.

- **The mantle today looks too radiogenic (too much ^206Pb/^204Pb and ^207Pb/^204Pb)** compared to models.

- But at the same time, **the bulk silicate Earth (BSE)** should still reflect chondritic (primitive solar system) compositions.

This mismatch is the paradox.

Since lead in all its forms has been observed to form in the ratios they exist in today in laboratory experiments rather than as they would have existed billions of years ago. Then we do not have to look at the daughter elements as a result of decay, requiring long ages. Rather we can look at the observed evidence that directly solves this paradox and also gives us a clue regarding zircon crystals and how they might have obtained such lead.

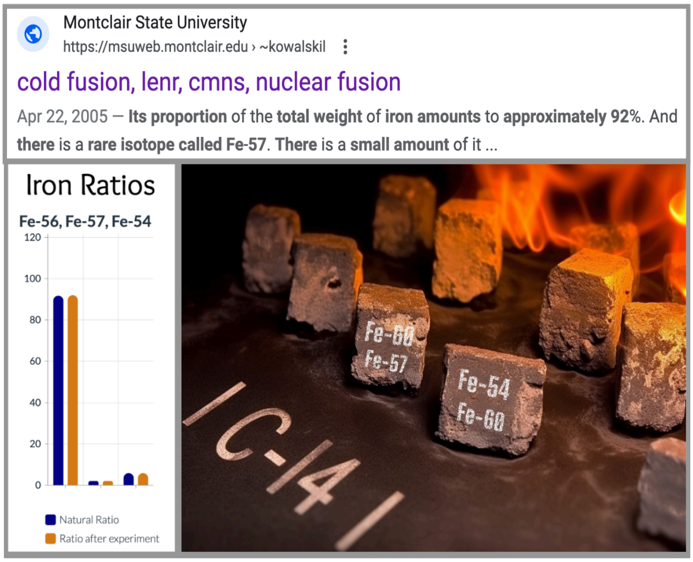

Image 2. (Kowalski, 2006)

Scientists often assume that the lead found inside tiny zircon crystals was created slowly by the radioactive decay of uranium over billions of years. But what if some of that lead didn't come from inside the zircon at all? What if it was *borrowed* from neighboring minerals and carried in by hot fluids?

To explore this idea, researchers can build a simple computer model of what happens inside a zircon crystal during one of these short-lived fluid events.

What the Model Simulates

1. **The flood:** The hot water picks up dissolved lead from the neighbor mineral.

2. **The delivery:** As it flows along any cracks, the fluid presses that lead against the zircon's rim.

3. **The uptake:** The damaged outer rim of the zircon acts like a sticky filter, soaking up lead far faster than its inner core could.

4. **The lock:** If the zircon heats up, even briefly (say, to ~250 °C) and then cools, the rim heals. Its pores close, and the captured lead is "locked in place."

What the Model Measures

- **How much lead gets trapped** in the zircon rim compared to the core.
- **How much stays put** after the rock cools down (the target is at least 80–90% retention).
- Whether the captured lead could make the zircon **look older than it really is** if measured in the lab.

What LLU/PRL predicts (distinct, testable clues)

1. **Lead without uranium (systematically)**
    - You'll find **Pb-rich / U-poor domains** (rims, cracks, inclusions) not as random contamination but as **consistent features** tied to rock fabrics and fluid pathways.
2. **Pb–Pb consistency across different minerals**
    - Co-genetic minerals with **very different U contents** (e.g., zircon, feldspar, sulfides) should sometimes share **similar Pb-Pb isotope ratios**, because they sampled the **same primordial reservoir**, not because they evolved radiogenically at the same rate.
3. **Mixing lines that mimic "discordia"**
    - On U–Pb plots, linear arrays (traditionally read as "Pb loss through time") can arise from **binary mixing** between two pre-set lead reservoirs (e.g., core vs. rim; inclusion vs. lattice; two fluid pulses).
4. **Geographic fingerprints**
    - Terranes with distinctive crustal histories (e.g., uranium-rich Australia) should show **repeatable Pb-Pb "house styles"** across many rocks, reflecting **reservoir inheritance**, not just mineral ages.
5. **Decoupling from other clocks**
    - Where other chronometers (e.g., Ar–Ar, fission tracks) say "young," zircons may still give **very old U–Pb ages**—because those ages mainly reflect **primordial ratios + later sorting**, not elapsed time.

Can We Test These Ideas?

If zircons only look ancient because they absorbed pre-existing lead or helium (instead of producing it slowly inside), then we need clear, falsifiable ways to tell the difference. Fortunately, there are several straightforward tests scientists can run.

---

1. Compare minerals with and without uranium

Take several minerals from the same rock — some that hardly contain any uranium and others that are uranium-rich.

- **PRL/LLU view:** They should sometimes show **similar lead-isotope ratios**, because they all sampled the same pre-existing lead reservoir.
- **Decay view:** Their lead should **directly track how much uranium each mineral contained** and how long it's been decaying.

---

2. Look inside a single zircon at the nanoscale

Using ultra-fine probes (like Atom Probe or NanoSIMS), you can map exactly where uranium and lead sit inside a crystal.

- **PRL/LLU view:** Lead should appear in **hotspots tied to cracks, inclusions, or fluid scars**, often without uranium alongside it.
- **Decay view:** Lead should **line up with uranium zoning**, growing smoothly inward as if it were made in place.

---

3. Try a gentle chemical "wash"

Leach zircons to remove any obvious non-lattice lead (the kind stuck in pores or cracks), then re-measure them.

- **PRL/LLU view:** The supposedly "ancient" age signature should **drop significantly** once this extra lead is gone.

- **Decay view:** The ages should **stay consistent** even after surface or secondary lead is removed.

---

4. Cross-check with other dating methods

Compare zircon U–Pb ages with other clocks in the same rock, such as argon–argon, helium, or fission tracks.

- **PRL/LLU view:** U–Pb ages will often look **much older** than the others, because they are reading isotope ratios, not elapsed time.
- **Decay view:** After accounting for closure temperatures, the different methods should **agree broadly**.

---

5. Map lead reservoirs across regions

Survey lead isotopes across an entire province.

- **PRL/LLU view:** Rocks will show **coherent "reservoir patterns"** — groups of zircons and other minerals clustering by shared lead sources, not just thermal history.
- **Decay view:** Age patterns should mostly reflect **how long each rock has been cooling and holding uranium**.

What Would Falsify the New Model?

The PRL/LLU approach would fail if zircons consistently show:

- Perfect uranium–lead agreement everywhere,
- No signs of fluid involvement,
- No isotopic resemblance to neighboring minerals,
- No difference between fractured vs. isolated grains, and
- Pb–Pb patterns that line up only with uranium decay histories, not with shared reservoirs.

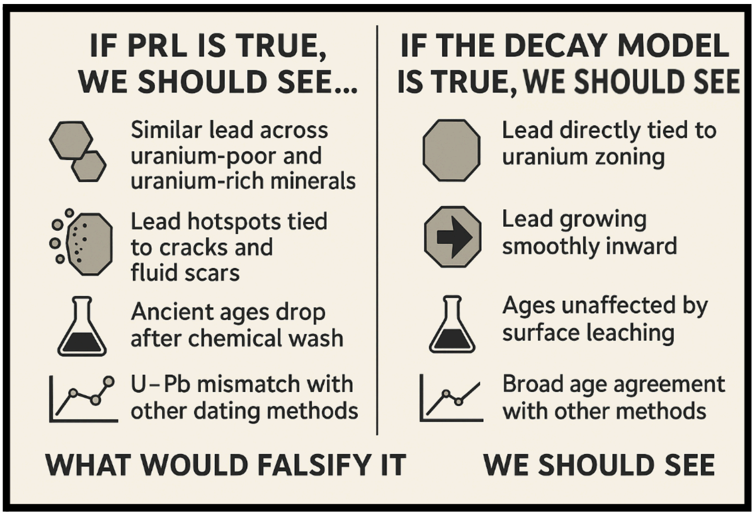

Image 3.

How LLU/PRL explains familiar data features

- **Very old zircon "ages" (e.g., Jack Hills):**
  Zircons grew in terrains that sampled a **primordial lead reservoir** already skewed toward "old-looking" ratios. Later fluids concentrated that lead in rims/inclusions, making ages look extreme if read as in-situ decay.

- **Concordant ages in some grains:**
  If a zircon is dominated by **one uniform primordial mixture** (little later disturbance), its spots plot neatly on concordia—not because uranium ticked for eons, but because **every spot samples the same initial recipe—Think of it like; the whole cake had the same ingredients from the beginning.**

- **Discordant arrays:**
  Often read as Pb loss through time, but under PRL/LLU they can be **mixing between two pre-set lead components** (core/rim; inclusion/lattice; early/late fluid), giving straight lines without invoking time. (Example: Piazolo, S., et al 2016: Microanalysis revealed **reverse discordance** in radiation-damaged domains – i.e. **excess radiogenic Pb relative to U** – due to Pb mobility and segregation. Also Peterman, E. M., et al 2016 *Nanogeochronology of discordant zircon measured by atom probe microscopy of Pb-enriched dislocation loops*. **Science Advances, 2**(9), e1601318. Utilizing atom probe tomography, this study finds that in a ~2.1 Ga metamorphosed zircon, some radiogenic lead became trapped in **nanoscale dislocation loops** (~10 nm) during annealing, while other Pb was lost. These dislocation loop "clusters" contain **enriched Pb and virtually no U**, preserving the original crystallization age signal. It confirms that **discordant U–Pb ages** can result from nanoscale Pb-rich, U-poor domains formed during metamorphism. See Nailor M. 2025 for more examples.

Zircons are often presented as “perfect time capsules,” but in reality they are more like **containers with a lid that can pop open and shut depending on conditions**.

Why zircons can reopen

- **Heating events** (volcanic activity, metamorphism, deep burial) can increase the mobility of atoms inside the crystal. Lead and helium, which were thought to be locked in, can actually move in or out.
- **Cooling afterwards** can re-seal the structure, freezing whatever mix of elements is left inside.
- This means zircons can cycle between being a **closed system** (good time capsule) and an **open system** (contents can change).

What that means for dating

1. **Lead uptake or loss:** If radiogenic lead can move in or out during these “open” phases, the measured ratios of uranium to lead no longer reflect simple in-house decay. They reflect a mix of **original composition + later events + whatever got trapped during the last “seal.”**
2. **Helium uptake or loss:** The same applies to helium. It can leak out during heating or be absorbed from fluids during fracturing. Later cooling traps whatever is left, creating the illusion of enormous time spans if we assume it all accumulated internally.
3. **False sense of security:** When zircon ages line up neatly on a concordia diagram, geologists usually interpret this as proof of billions of years of steady decay. But the same neat patterns can arise if the zircon simply **sampled a uniform reservoir of lead or helium and then got locked shut again**.

Zircons aren’t flawless clocks. They’re more like **thermos bottles that sometimes crack and get refilled, then reseal**. If they can open and close multiple times, how can we be certain that the ages we calculate—billions of years—really reflect Earth’s history, rather than a story of fluids, heat, and repeated resets?

What We'd Expect to See & What We Do See if LLU/PRL is True

- Zircon rims with **lots of lead but little uranium**—a mismatch that shouldn't happen if all the lead came from inside. Do we find this? We actually do and plenty: Grauert (1974), Xu (2012), Mathieu (2001), Kusiak (2015), Piazolo (2016), Peterman (2016), Valley (2014). Grauert, B., et al in 1974 was the first landmark study which used isotopic analysis and fission-track mapping to show that detrital zircons can **gain lead (and uranium)** from external sources, indicating lead-enriched zones not produced by the zircon's own U decay. This was confirmed by Xu et al in 2012 which documented **"reverse" age zoning** in zircons—older apparent ages at rims relative to cores—caused by radiation damage and fluid leaching of Pb. This was noticed at the Oklo natural reactor zone by Mathieu, R. et al in 2001 in **Chemical Geology, 171**(3–4), 147–171 Reports that zircons in the vicinity of natural fission reactors at Oklo show **Pb-rich altered rims and galena (PbS) inclusions**. The lead has radiogenic isotopic signatures, indicating it was mobilized by fluids into the zircon, creating **lead-rich zones with little or no uranium**.

- **Patchy patterns** of lead near cracks or healed rims. **Utsunomiya (2004)** – Discovered **Pb nanoparticles in Archean zircon** concentrated near radiation damage and microcracks, showing Pb migration and clustering at the nanoscale. **Kusiak (2013)** – Showed with ion imaging that **radiogenic Pb was mobilized** within zircons, appearing in **patchy domains tied to cracks and inclusions**. This demonstrated Pb could move after formation, complicating age readings. **Whitehouse (2014)** – Demonstrated that during **ultra-high temperature metamorphism**, Pb moved and pooled in rims and cracks, creating **patchy patterns** within zircons from southern India. **Kusiak (2015)** – Used electron microscopy to discover **metallic lead nanospheres** (tiny Pb particles) inside ancient zircons. These formed when Pb segregated into clusters during metamorphism, often unrelated to uranium. **Peterman (2016)** – Revealed **nanometer-scale dislocation loops** inside zircons that trapped Pb but excluded U, creating **tiny Pb-rich, U-poor zones** that skew U–Pb ages. **Piazolo (2016)** – Found that **deformation in zircon** causes trace elements like Pb to redistribute along **dislocations and healed cracks**, producing uneven Pb distributions unrelated to uranium. **Whitehouse (2017)** – Found **metallic Pb nanospheres** in metamorphosed zircons, again showing that Pb had migrated and concentrated in altered micro-domains rather than staying where uranium was. **Ge (2018)** – Reported an apparent **4.46 Ga zircon age** caused not by in-situ decay, but by **ancient Pb mobilization**. The Pb was concentrated in specific areas, including rims, creating the illusion of extreme antiquity. **Ge (2019)** – Found that some Jack Hills zircons contain **patchy enrichments of radiogenic Pb** that do not match uranium zoning, instead clustering along microstructures inside the crystal. This suggests Pb migrated and collected in damaged zones. **Kusiak (2019)** – Found **lead**

oxide nanospheres inside zircons that had been **deformed by seismic activity**, showing Pb migration into cracks and dislocation structures created during earthquakes. Across multiple studies, from Australia to India to Antarctica, scientists consistently find **patchy Pb enrichment near cracks, healed rims, and damaged zones in zircon**. These Pb-rich/U-poor spots break the assumption that all lead in zircon was produced in place by uranium decay — and they line up perfectly with your Later Lead Uptake model.

- Signs of **fluid involvement**—like chlorine, fluorine, or sulfur trapped alongside the lead. **Kusiak (2013)** used high-resolution imaging to show that lead often clusters in zircon alongside traces of fluid-related elements, while **Courtney-Davies (2021)** found tiny metallic lead particles in South Australian zircons that formed during ore-related fluid events. At Jack Hills in Western Australia, **Ge (2018)** reported a zircon that appeared to be 4.46 billion years old, but the age was likely an illusion created by ancient mobilization and concentration of lead rather than steady uranium decay. Other studies confirm this picture: **Kusiak (2015, 2019)** found both metallic and lead oxide nanospheres inside zircons, sometimes formed during seismic deformation, while **Whitehouse (2017)** showed that ultra-high temperature metamorphism can segregate lead into nanophases within the crystal. Advanced nanoscale techniques also reveal the role of crystal damage. **Peterman (2016)** discovered lead trapped in dislocation loops only a few nanometers wide, while **Piazolo (2016)** showed that deformation can shuffle lead into cracks and healed rims, producing patchy, uranium-free zones.

- Zircons in tectonically deformed zones should show **shock features** (planar deformation features, microfractures) together with “metamict-like” optical properties. Although zircons are often treated as robust and closed systems, a growing body of research shows that tectonic deformation and shock events can fundamentally alter their structure. Reddy (2006) demonstrated that zircon can undergo **crystal-plastic deformation**, producing microfractures and planar features that challenge the long-held assumption of chemical immutability. Building on this, Rimša (2007) found that **brittle fracturing followed by fracture healing** leaves zircons with patchy optical properties and disturbed U–Pb ages, giving them a metamict-like appearance even without long-term radiation damage. Subsequent work reinforced this connection between deformation and altered zircon textures. Piazolo (2012) documented **brittle–ductile microfabrics** in naturally deformed zircons, noting that their cathodoluminescence patterns became irregular and cloudy—closely resembling metamict textures usually attributed to billions of years of radiation damage. Similarly, Kovaleva (2015) identified **planar microstructures in zircons from paleo-seismic zones**, directly linking shock-related deformation features with structural and optical damage.

More recent nanoscale investigations add further weight. Kovaleva (2017) showed that **crystal-plastic deformation can redistribute trace elements and isotopes** within zircon, producing Pb-rich domains unrelated to uranium zoning, often concentrated along healed cracks or dislocations. Finally, Kovaleva (2020) synthesized these findings by reviewing zircon textures across magmatic, tectonic, and shock environments, concluding that **both tectonic stress and shock can produce polycrystalline, metamict-like aggregates** that mimic the optical effects of radiation damage.

Together, these studies show a consistent pattern: zircons in tectonically deformed or shocked zones **do not behave like closed, immutable clocks**. Instead, they develop **microfractures, planar deformation features, and patchy, metamict-like properties** that invite element migration and complicate radiometric dating.

How “metamict-like” textures could appear quickly

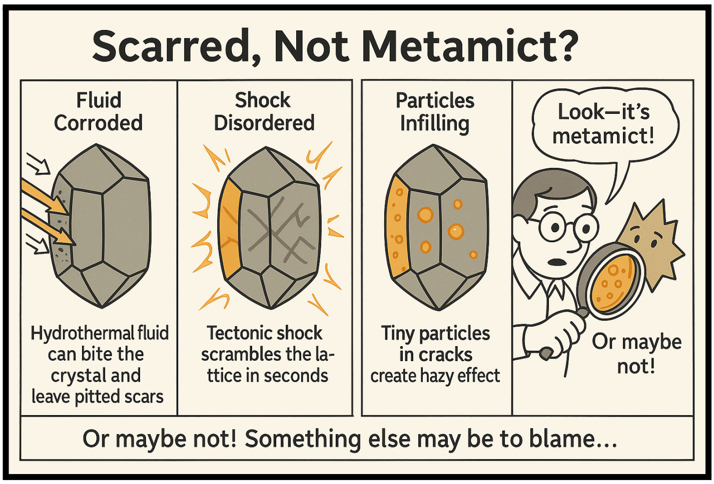

Image 4.

1. Fluid-assisted alteration masquerading as metamictization

- In conventional geology, metamict textures are blamed on **alpha-recoil damage** accumulated over eons.
- But: hydrothermal fluids (salty, hot, acidic) moving through zircon **etch and corrode the lattice**.
- This corrosion creates **patchy, cloudy, birefringent textures** almost indistinguishable from radiation damage under CL or Raman.

- In other words: what looks “metamict” might actually be **fluid-alteration scars**, happening rapidly during a few hot fluid events rather than over billions of years.

Prediction: Fluid-altered “metamict” domains will carry **non-lattice elements** (Cl, S, Pb) and inclusions; genuine radiation damage zones will correlate tightly with U/Th zoning.

---

2. Short bursts of accelerated recoil (not accelerated decay as a whole)

- Even without billions of years, **brief pulses of unusually intense nuclear activity** (e.g., catastrophic events during Flood/post-Flood scenarios, solar/geomagnetic anomalies) could deliver *a lot* of recoil damage in a very short time.
- That damage could mimic what normally takes eons, creating metamict-like zones “all at once.”
- This is different from the “accelerated decay” model—it’s more like **accelerated recoil energy release**, localized and event-driven.

Prediction: If so, metamict textures should be **patchy and abrupt**, not smoothly proportional to U/Th gradients. Zones of extreme damage might be sharply bounded.

---

3. Shock + heat from tectonic upheaval

- Catastrophic plate movements and rapid tectonic events (as in Flood geology models) involve **massive mechanical shock + transient heating**.
- Shock can **disorder crystal lattices** in seconds—think shocked quartz from impact craters.
- That kind of “impact metamictization” could mimic radiation damage without deep time.

Prediction: Zircons in tectonically deformed zones should show **shock features** (planar deformation features, microfractures) together with “metamict-like” optical properties.

4. Nano-particle infilling that mimics damage

- If fluids carry nano-particles (oxides, sulfides, Pb minerals) into microcracks, they can scatter light and create the same “cloudy look” as radiation-amorphized domains.
- These inclusions could explain why zircons look metamict under the microscope, without assuming enormous radiation doses.

Prediction: High-res TEM should reveal **nano-particles or etching textures**, not just a homogeneously amorphized lattice.

How the Later Lead Uptake model fits this

In the **young-earth timescale**, zircons that appear “damaged” from radioactive decay could actually be:

- **Fluid-scarred** (corroded by Pb-bearing hydrothermal fluids that also delivered secondhand Pb).
- **Shock-disordered** (from catastrophic tectonic upheavals).
- **Short-burst irradiated** (from intense but brief nuclear activity events, if one accepts that model).

So the Pb import + “lock” mechanism doesn’t *require* billions of years of internal alpha damage. The “metamict” look could just be **collateral textures** from fluid and tectonic activity, coinciding with Pb uptake.

Falsifiable tests for this reinterpretation

- **Chemical test:** Are “metamict” zones enriched in fluid tracers (Cl, S, Pb) → then fluid damage, not just alpha recoil.
- **Textural test:** Do zones show shock deformation features (lamellae, planar cracks)? If yes, tectonic overprint.

- **Isotopic test:** Do Pb isotopes in “damaged” zones **match neighbors’ Pb** instead of zircon’s U decay? → then they’re secondhand Pb deposits.
- **TEM test:** If nano-particles are present, then the “cloudy” look is alteration, not lattice amorphization.

In short: under a young-earth framework, zircons might **look metamict** not because of billions of years of internal decay, but because they were **scarred, shocked, or infiltrated quickly** by catastrophic processes that also imported and locked in secondhand radiogenic Pb.

What about Helium?

Did not the helium also have to get there from decay?

In this view, zircons are not isolated clocks but tiny sponges with doors. During short episodes of hot fluid flow, their damaged edges open up and absorb what the fluids carry—pre-existing radiogenic lead or helium. A quick heat-and-heal step closes the door, locking those imports inside. Later, if we assume every atom came from slow in-house decay, we can mistake a brief “import and freeze” moment for deep time. The evidence to look for is simple: extra material at the rims, strongest along fractures, paired with fluid fingerprints and signs that the rim sealed right after the influx.

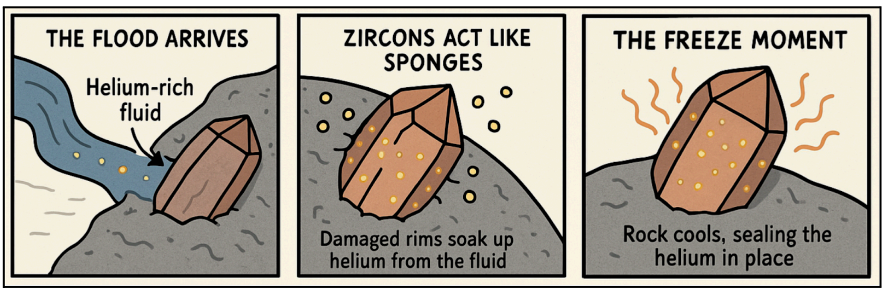

Image 5.

Are there other possible factors that could have caused lead to infiltrate zircon? Yes. Here are three other theories that could possibly explain why there is radiogenic lead inside zircon crystals that got there without actual radioactive decay.

1: “Quake-Driven Ion Swap” (Seismo-electromigration of Pb^{2+})

One-liner: Earthquakes in quartz-rich rocks generate tiny electric fields that can **push Pb ions** along wet grain boundaries **into** zircon, then later annealing **locks** them in.

How it works:

1. A quake stresses quartz → **piezoelectric fields** flicker on.
2. In thin films of fluid, those fields nudge **Pb^{2+} complexes** toward zircon surfaces.
3. **Damaged rims** (highly defective) take them up like a **charged sponge**.
4. A small, local heat pulse heals the rim → **diffusivity plummets** → Pb stuck.

Predictions:

- **Rim-biased Pb** aligned with **stress fabrics** or shear bands.
- Pb co-located with other electromigrating cations (e.g., **Ba, Sr, REEs**).
- **Fault-zone zircons** show more imported Pb than craton zircons with the same U.

Tests: Compare Pb maps with EBSD/CL stress textures; sample active shear zones vs. quiet terranes; look for co-enrichment of “fellow travelers” (Ba/Sr/REE).

2: “Chain-Recoil Catch” (Neighbor recoil implantation)

One-liner: Radiogenic Pb is **shot into zircon** by the **recoil kicks** from decay happening **next door**.

How it works:

1. In a neighboring U/Th-rich grain, the decay chain fires off multiple **alpha steps**; each step gives the daughter atom a **recoil shove**.

2. Near a grain boundary, those kicks can **launch daughters across nanogaps**.

3. Some of the **final Pb daughters** (or late-chain precursors that soon become Pb) **embedded** in the first few **tens of nanometers** of the zircon.

4. Over time, that side of the zircon looks **Pb-rich** even though it didn't make it itself.

Predictions:

- **Strongly one-sided Pb halos** on the zircon face **touching** the U/Th-rich neighbor.

- Ultra-thin enrichment zone (≤100 nm) visible only by **Atom Probe** or **TEM**.

- If you remove that face by FIB, the "extra-old" signal largely disappears.

Tests: Atom-probe tomography across the contact; NanoSIMS line scans from boundary inward; paired measurements of the neighbor showing corresponding **daughter deficits**.

3: "Dusting & Disguise" (Pb-nanoparticle precipitation in cracks)

One-liner: Zircon may host **tiny Pb-minerals** (e.g., PbS, PbO) **precipitated from sulfur/halogen-rich fluids** in microcracks; analyses can misread them as in-lattice radiogenic Pb.

How it works:

1. A sulfur-bearing fluid passes through microfractures.

2. It nucleates **nanoparticles** (galena-like PbS or Pb-oxides) inside tiny voids of zircon.

3. Spot analyses/ablation **sample those specks**, inflating the apparent radiogenic Pb.

4. Because they're not part of the zircon lattice, ages jump around by spot and **don't scale with U**.

Predictions:

- **Wild spot-to-spot ages**; Pb spikes correlate with **S or Cl** and with crack paths.
- Under high-res imaging you see **nanoparticle specks**; leaching removes them.
- Minimal correlation between Pb and zircon lattice elements (Zr, Si).

Tests: High-res TEM/EDS to see particles; pre-etch/leach experiments before analysis; sulfur mapping; compare large vs. tiny spot sizes (bigger spots average out spikes).

What would falsify these ideas?

- **Perfect U–Pb concordance and smooth Pb profiles tied tightly to U zoning (argues for pure in-situ production).**
- No Pb–fluid tracers (Cl/F/inclusions) and no rim/face asymmetry in Pb.
- Atom-probe shows **no** boundary-proximal Pb enrichment when neighbors are U/Th-rich.

References (APA 7th edition)

Grauert, B., Seitz, M. G., & Soptrajanova, G. (1974). Uranium and lead gain of detrital zircon studied by isotopic analyses and fission-track mapping. *Earth and Planetary Science Letters, 21*(4), 389–399. https://doi.org/10.1016/0012-821X(74)90149-7

Xu, X.-S., Zhang, M., Zhu, K.-Y., Chen, X.-M., & He, Z.-Y. (2012). Reverse age zonation of zircon formed by metamictisation and hydrothermal fluid leaching. *Lithos, 150*, 256–267. https://doi.org/10.1016/j.lithos.2012.01.004

Mathieu, R., Zetterström, L., Cuney, M., Gauthier-Lafaye, F., & Hidaka, H. (2001). Alteration of monazite and zircon and lead migration as geochemical tracers of fluid paleocirculations around the Oklo-Okelobondo and Bangombé natural nuclear reaction zones (Franceville Basin, Gabon). *Chemical Geology, 171*(3–4), 147–171. https://doi.org/10.1016/S0009-2541(00)00256-3

Kusiak, M. A., Dunkley, D. J., Wirth, R., Whitehouse, M. J., Wilde, S. A., & Marquardt, K. (2015). Metallic lead nanospheres discovered in ancient zircons. *Proceedings of the*

National Academy of Sciences, 112(16), 4958–4963. https://doi.org/10.1073/pnas.1423167112

Piazolo, S., La Fontaine, A., Trimby, P., Harley, S., Yang, L., Armstrong, R., & Cairney, J. M. (2016). Deformation-induced trace element redistribution in zircon revealed using atom probe tomography. *Nature Communications, 7*, 10490. https://doi.org/10.1038/ncomms10490

Peterman, E. M., Reddy, S. M., Saxey, D. W., Snoeyenbos, D. R., Rickard, W. D. A., Fougerouse, D., & Kylander-Clark, A. R. C. (2016). Nanogeochronology of discordant zircon measured by atom probe microscopy of Pb-enriched dislocation loops. *Science Advances, 2*(9), e1601318. https://doi.org/10.1126/sciadv.1601318

Valley, J. W., Cavosie, A. J., Ushikubo, T., Reinhard, D. A., Lawrence, D. F., Larson, D. J., Clifton, P. H., Kelly, T. F., Wilde, S. A., Moser, D. E., & Spicuzza, M. J. (2014). Hadean age for a post-magma-ocean zircon confirmed by atom-probe tomography. *Nature Geoscience, 7*(3), 219–223. https://doi.org/10.1038/ngeo2075

Ge, R., Wilde, S. A., Nemchin, A. A., Whitehouse, M. J., Bellucci, J. J., & Erickson, T. M. (2019). Mechanisms and consequences of intra-crystalline enrichment of ancient radiogenic Pb in detrital Hadean zircons from the Jack Hills, Western Australia. *Earth and Planetary Science Letters, 517*, 38–49. https://doi.org/10.1016/j.epsl.2019.04.005

Ge, R., Wilde, S. A., Nemchin, A. A., Whitehouse, M. J., Bellucci, J. J., Erickson, T. M., Frew, A., & Thern, E. R. (2018). A 4463 Ma apparent zircon age from the Jack Hills (Western Australia) resulting from ancient Pb mobilization. *Geology, 46*(4), 303–306. https://doi.org/10.1130/G39894.1

Kusiak, M. A., Dunkley, D. J., Wirth, R., Whitehouse, M. J., Wilde, S. A., & Marquardt, K. (2015). Metallic lead nanospheres discovered in ancient zircons. *Proceedings of the National Academy of Sciences, 112*(16), 4958–4963. https://doi.org/10.1073/pnas.1415264112

Kusiak, M. A., Kovaleva, E., Wirth, R., Klötzli, U., Dunkley, D. J., Yi, K., & Lee, S. (2019). Lead oxide nanospheres in seismically deformed zircon grains. *Geochimica et Cosmochimica Acta, 262*, 20–30. https://doi.org/10.1016/j.gca.2019.07.026

Kusiak, M. A., Whitehouse, M. J., Wilde, S. A., Nemchin, A. A., & Clark, C. (2013). Mobilization of radiogenic Pb in zircon revealed by ion imaging: Implications for early Earth geochronology. *Geology, 41*(3), 291–294. https://doi.org/10.1130/G33920.1

Peterman, E. M., Reddy, S. M., Saxey, D. W., Snoeyenbos, D. R., Rickard, W. D. A., Fougerouse, D., & Kylander-Clark, A. R. C. (2016). Nanogeochronology of discordant zircon measured by atom probe microscopy of Pb-enriched dislocation loops. *Science Advances, 2*(9), e1601318. https://doi.org/10.1126/sciadv.1601318

Piazolo, S., La Fontaine, A., Trimby, P., Harley, S. L., Yang, L., Armstrong, R., & Cairney, J. M. (2016). Deformation-induced trace element redistribution in zircon revealed using atom probe tomography. *Nature Communications, 7*, 10490. https://doi.org/10.1038/ncomms10490

Utsunomiya, S., Palenik, C. S., Valley, J. W., Cavosie, A. J., Wilde, S. A., & Ewing, R. C. (2004). Nanoscale occurrence of Pb in an Archean zircon. *Geochimica et Cosmochimica Acta, 68*(22), 4679–4686. https://doi.org/10.1016/j.gca.2004.04.018

Whitehouse, M. J., Ravindra Kumar, G. R., & Rimša, A. (2014). Behaviour of radiogenic Pb in zircon during ultrahigh-temperature metamorphism: An ion imaging and ion tomography case study from the Kerala Khondalite Belt, southern India. *Contributions to Mineralogy and Petrology, 168*(2), 1042. https://doi.org/10.1007/s00410-014-1042-2

Whitehouse, M. J., Kusiak, M. A., Wirth, R., & Ravindra Kumar, G. R. (2017). Metallic Pb nanospheres in ultra-high temperature metamorphosed zircon from southern India. *Mineralogy and Petrology, 111*(4), 467–474. https://doi.org/10.1007/s00710-017-0523-1

Courtney-Davies, L., Saxey, D. W., Fougerouse, D., Rickard, W. D. A., Fisher, L. A., & Reddy, S. M. (2021). Metallic-Pb nanospheres in zircon from the Challenger Au deposit, South Australia: Probing metamorphic and ore formation histories. *Mineralogical Magazine, 85*(6), 868–878. https://doi.org/10.1180/mgm.2021.73

Ge, R., Wilde, S. A., Nemchin, A. A., Whitehouse, M. J., Bellucci, J. J., Erickson, T. M., Frew, A., & Thern, E. R. (2018). A 4463 Ma apparent zircon age from the Jack Hills (Western Australia) resulting from ancient Pb mobilization. *Geology, 46*(4), 303–306. https://doi.org/10.1130/G39894.1

Kusiak, M. A., Whitehouse, M. J., Wilde, S. A., Nemchin, A. A., & Clark, C. (2013). Mobilization of radiogenic Pb in zircon revealed by ion imaging: Implications for early Earth geochronology. *Geology, 41*(3), 291–294. https://doi.org/10.1130/G33920.1

Kusiak, M. A., Dunkley, D. J., Wirth, R., Whitehouse, M. J., Wilde, S. A., & Marquardt, K. (2015). Metallic lead nanospheres discovered in ancient zircons. *Proceedings of the National Academy of Sciences, 112*(16), 4958–4963.

Kusiak, M. A., Kovaleva, E., Wirth, R., Klötzli, U., Dunkley, D. J., Yi, K., & Lee, S. (2019). Lead oxide nanospheres in seismically deformed zircon grains. *Geochimica et Cosmochimica Acta, 262*, 20–30. https://doi.org/10.1016/j.gca.2019.07.026

Peterman, E. M., Reddy, S. M., Saxey, D. W., Snoeyenbos, D. R., Rickard, W. D. A., Fougerouse, D., & Kylander-Clark, A. R. C. (2016). Nanogeochronology of discordant zircon measured by atom probe microscopy of Pb-enriched dislocation loops. *Science Advances, 2*(9), e1601318. https://doi.org/10.1126/sciadv.1601318

Piazolo, S., La Fontaine, A., Trimby, P., Harley, S. L., Yang, L., Armstrong, R., & Cairney, J. M. (2016). Deformation-induced trace element redistribution in zircon revealed using atom probe tomography. *Nature Communications, 7*, 10490. https://doi.org/10.1038/ncomms10490

Whitehouse, M. J., Kusiak, M. A., Wirth, R., & Ravindra Kumar, G. R. (2017). Metallic Pb nanospheres in ultra-high temperature metamorphosed zircon from southern India. *Mineralogy and Petrology, 111*(4), 467–474. https://doi.org/10.1007/s00710-017-0523-1

Nailor, M., & Budinsky, D. (2025). *The illusion of deep time: Systematic discordant radiometric ages and the myth of an ancient ocean floor*. https://doi.org/10.5281/zenodo.16956858

Kowalski, L. (2006, January 24). *On rates of nuclear reactions*. Department of Mathematical Sciences, Montclair State University. Retrieved April 22, 2005, from https://msuweb.montclair.edu/~kowalskil/cf/275gamow.html