A New Look at the Diabase of the Southwest Laurentia Large Igneous Province (SWLLIP): Speeding Laurentia and Stagnant Slabs

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Here's "A new look at the diabase of the Southwest Laurentia Large Igneous Province: Speeding Laurentia and stagnant slabs."

The view below the title is of the Ibex Hills, CA, where the dark green diabase intrudes the basement rocks and the middle and upper units of the Crystal Spring Formation.

The Take-Away:

The chemical composition of the SWLLIP diabase exhibits a subduction component which becomes more prominent from the northwest to the southeast.

We propose this was produced by deep water cycling via stagnated slabs in the mantle transition zone (MTZ).

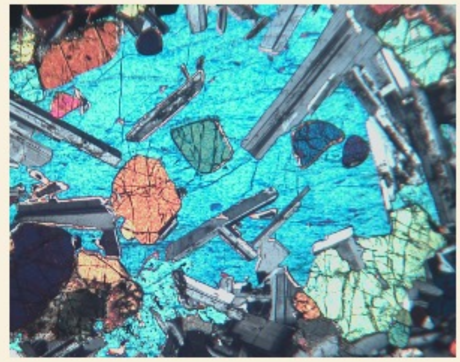
This process is enhanced by rapid plate motion such as that of Laurentia at about 1.1 Ga ago.

This is in a nutshell what we hope to convince you of in this talk.

To keep this model simple, we purposely omitted felsic rocks that may be part of this magmatic event, focusing on the diabase of the province exclusively in hope that this can contribute to a clearer picture of what was happening in Laurentia at this time.

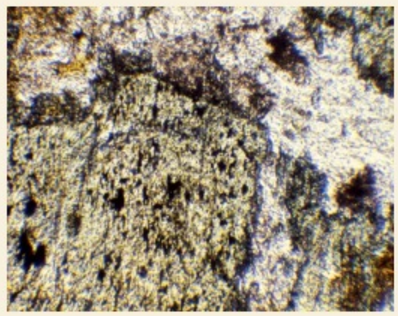
What is diabase?

As used in North America: an intrusive equivalent of basalt with an ophitic texture.



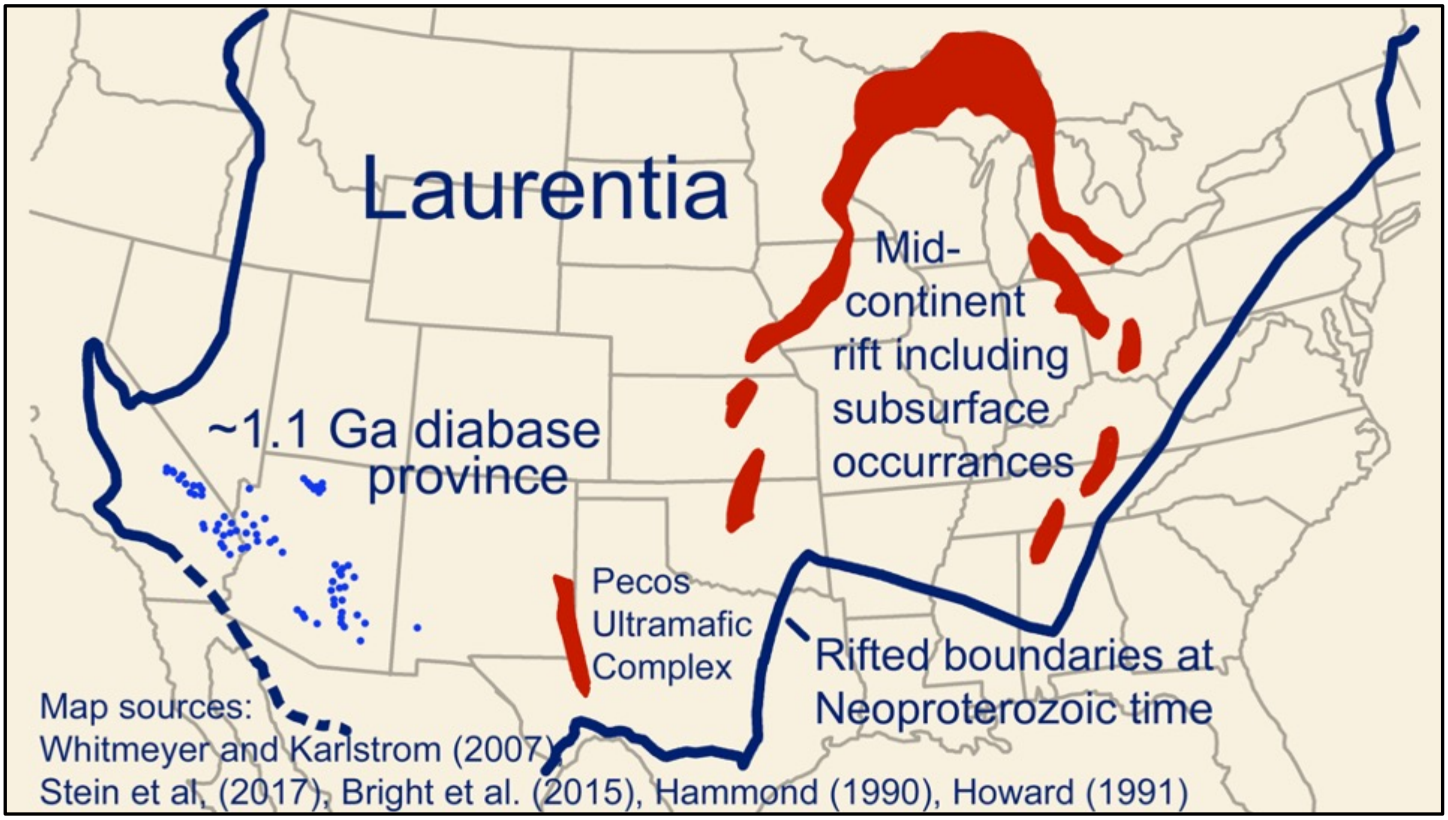
Major primary minerals are plagioclase, olivine, augite, and iron-titanium oxides.

These are often replaced by secondary phases such as amphibole, epidote, chlorite, sericite, and leucoxene.



Diabase is an intrusive equivalent of basalt with an ophitic texture. Although the southwest Laurentia diabase was intruded regionally as shallow sills instead of reaching the surface as flows, its size and general features qualify it as a continental flood basalt province.

The upper right image is fresh diabase with augite, plagioclase and olivine from Sierra Ancha, AZ. The lower two are examples of the prevalent secondary alteration. The amphibole replacing augite is from the Avawatz Mountains, CA, and the apatite-rich example with chlorite partially replacing mafic minerals is from the Santa Catalina Mtns, AZ.

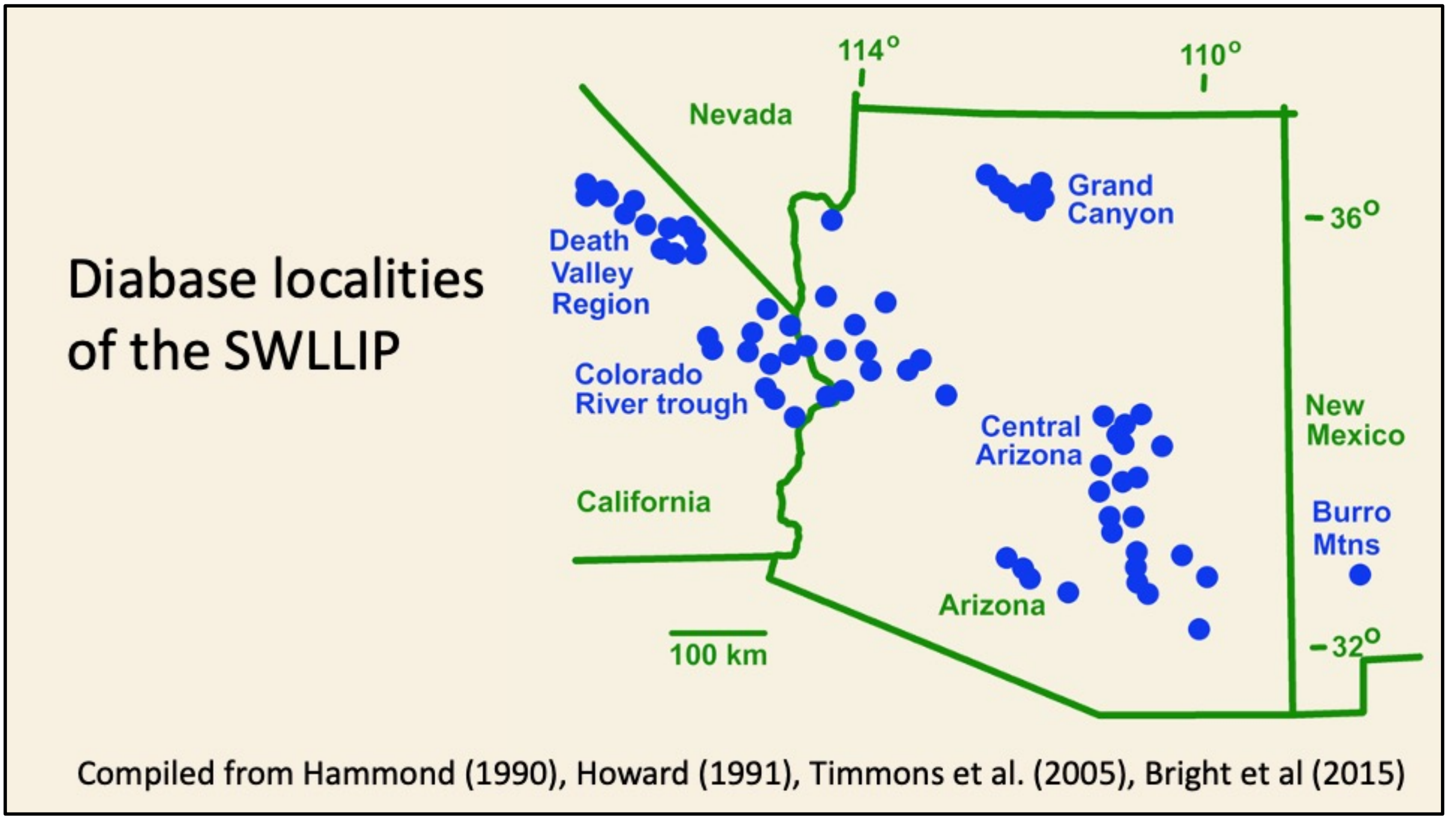


Putting this in the context of Laurentia, the area within the dark blue boundaries is the southern part of what remains of the Midproterozoic supercontinent,

In the broad timeframe of about 1.1 Ga. the Earth was warmer and the mantle ~55^{0} C hotter according to Van Kranendonk and Kirkland, (2013).

Laurentia was a hotbed of mafic magmatism. The most prominent expression of this is the Midcontinent rift, here shown in red including surface exposures and subsurface locations.

Occurrences of SWLLIP diabase are represented by blue dots.

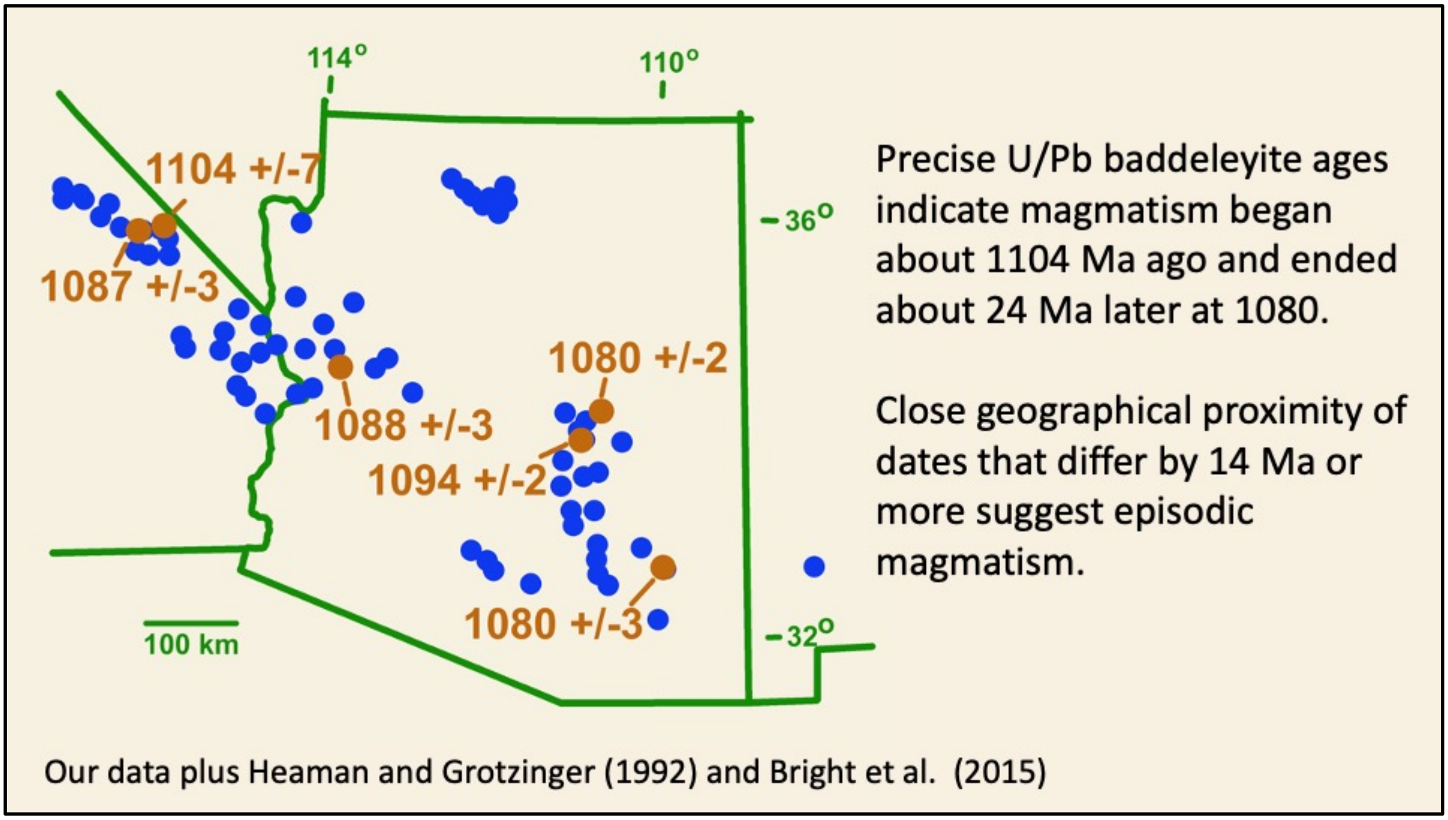


These diabase localities, all described in the literature, include sills, feeder dikes, and subhorizontal sheets in crystalline basement rocks. Possibly correlative basalts and mafic intrusions associated with felsic rocks have been omitted.

Sills in the Death Valley region are hosted by the Crystal Spring Formation of the Pahrump Group. Those in Grand Canyon are hosted by the Unkar Group, and central Arizona sills intruded the Apache Group. Upper lever sills at some locations intruded into sediment too soft to confine the magma in a dike reaching the surface, which explains the lack of lava flows in the region.

These stratigraphic groups have been interpreted as shallow marine deposits which were possibly once connected in a regional seaway. They show no evidence of uplift or significant extension associated with the diabase magmatic episode.

Localities in the Colorado River trough, southern Arizona and New Mexico are dikes and originally subhorizontal sheets in metamorphic or granitic basement rocks. Howard (1991) argues that some of these were intruded at depths as great as 13 km.



The 1104 Ma age shown on this map is the work of my colleagues, and details about it were reported in our poster in the 2019 GSA annual meeting. The other dates were chosen by Bright et al. (2015) as being the most precise among an assortment of dates of various quality.

These ages establish that mafic magmatic activity spanned a period of about 24 million years.

Note the two pairs of closely spaced ages which differ by about 14 Ma and suggest repeated episodes of magmatism.

Facts about stagnant slabs summarized from Goes et al. (2017, *Geosphere*)

1. Good tomographic data exists for 22 Cenozoic subduction zones.
2. Ten of these subduction zones exhibit stagnant slabs ranging from 800 to 1600 km in length.
3. Subduction accompanied by trench retreat (trench location moving toward the ocean basin) is the most basic form of subduction.
4. The amount of trench retreat is generally correlated with the length of the stagnant slab.

Now for some background concerning our model:
Stagnant slabs are an essential part of the deep-water cycling model. The 2017 Geosphere paper by Goes et al. has a great review of stagnant slabs. Some facts to consider are

1. Good tomographic data exists for 22 Cenozoic subduction zones.
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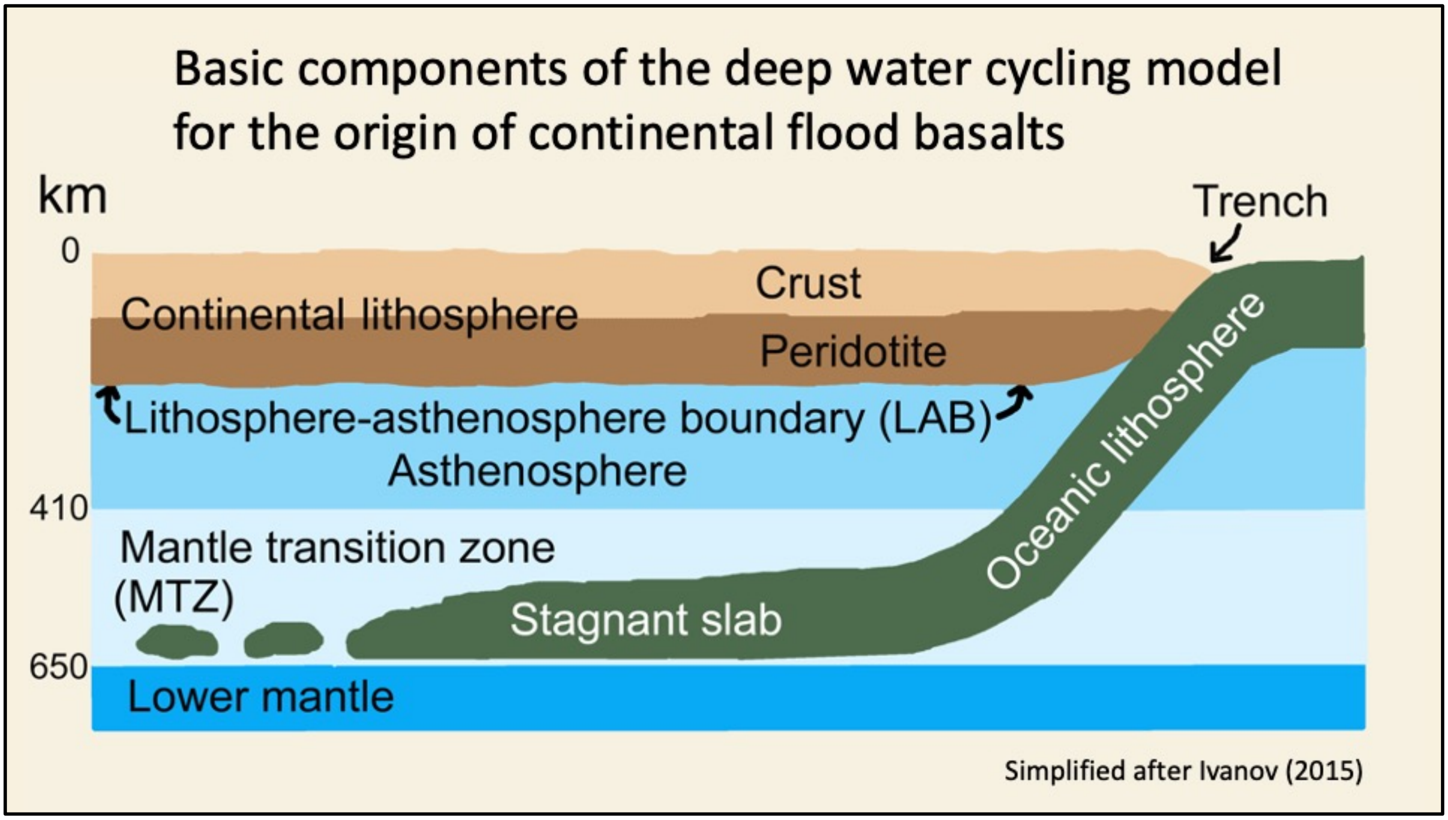
Trench retreat is a feataure of this scenario.

If plate tectonics at 1.1 billion years ago were similar to today's, we would expect stagnant slabs to have been common.



In this model the stagnant slab is buoyantly neutral in the Mantle Transition Zone where the mantle minerals transition into new phases, such as olivine transforming to wadsleyite. The peridotite represents the lithospheric mantle. The LAB is the boundary below which melts will accumulate and form a ponded melt reserve.

Steps in the deep-water cycle process:

1. Rapid subduction of cold oceanic lithosphere allows it to descend through the asthenosphere without dehydrating.
2. Slab moves horizontally in the MTZ due to neutral buoyancy.
3. The slab warms in the MTZ giving off hydrous fluids which rise buoyantly.
4. Hydrous fluids added to the asthenosphere cause it to melt **without an increase in temperature.**
5. Strong lithospheric lid traps melts along the LAB, allowing large volumes of melt to pond there.
6. Melt pond travels with the plate and acts as a lubricant to enhance plate motion.
7. Convergence-related stresses trigger extensional lithospheric faults which allow the pond to drain rapidly upward.

Here are the steps in deep water cycling:

1. Rapid subduction of cold dense oceanic lithosphere allows it to descend through the asthenosphere without dehydrating.
2. the slab then moves horizontally in the MTZ due to neutral buoyancy.
3. The slab warms in the MTZ giving off hydrous fluids which rise buoyantly.
4. Hydrous fluids added to the asthenosphere cause it to melt **without an increase in temperature.**
5. The strong lithospheric lid traps melts along the LAB, allowing large volumes of melt to pond there.
6. Melt pond travels with the plate and acts as a lubricant to enhance plate motion.

7. Convergence-related stresses produces extensional lithospheric faults which allow the pond to drain rapidly upward.

This model has been applied to continental flood basalt provinces such as the Siberian LIP (Ivanov, 2015, and Wang et al., 2015);
the Chifeng CFB of East Asia (Wang et al., 2015);
the Karoo-Ferrar LIP (Ivanov et al. 2017), and
the Greater Kerguelen LIP (Olierook et al., 2019).

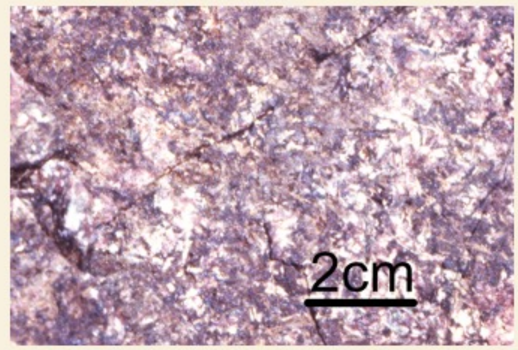
So what's the evidence for the SWLLIP diabase deep water cycle?

This model been applied to continental flood basalt provinces such the Siberian LIP; the Chifeng CFB of East Asia; the Karoo-Ferrar LIP, and the Greater Kerguelen LIP .

This process produces moderately "wet" basaltic magmas.

For comparison:
Ocean island basalts have 0.3 to1.0 wt% water (Xia et al., 2016).
Mafic arc magmas average ~4 wt % water, range is 2-6 wt% (Plank, 2013).

The average water content for 56 samples from across the SWLLIP region determined by LOI is 2.2 wt%, strongly suggesting a subduction component.



Pegmatitic texture from Kingston Range diabase

This was a wet magma.

Ocean island basalts, classically attributed to plume sources, have low water contents, 0.3 to 1.0 wt%.

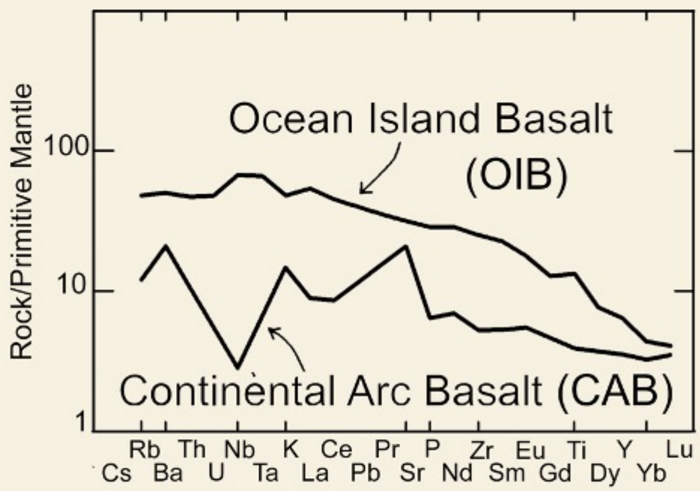
Mafic arc magmas are hydrated by fluids coming of the subducting slab and are water rich, generally 2-6 wt% and averaging about 4 wt%.

The original water content of the diabase magma is difficult to establish. There are many complicating factors, but LOI (loss on ignition) is a first approximation. The average LOI for 56 samples from across the SWLLIP is 2.2 wt%. The presence of pegmatitic pods within sills, contact metamorphic aureoles, and widespread secondary alteration in both sills in sedimentary rocks and in dikes in the crystalline basement also indicate that the magma was wet.

Spider (multi-element) diagrams reveal a subduction component:

Puffer (2001) pioneered using multielement diagrams to compare continental flood basalts with OIB and CAB, noting that some were OIB-like and others were CAB-like, but all had some features that distinguished them from these two standards.

Normalization values and standard OIB after Sun & McDonough (1989), continental arc basalt 272825 after Hickey et al. (1986)



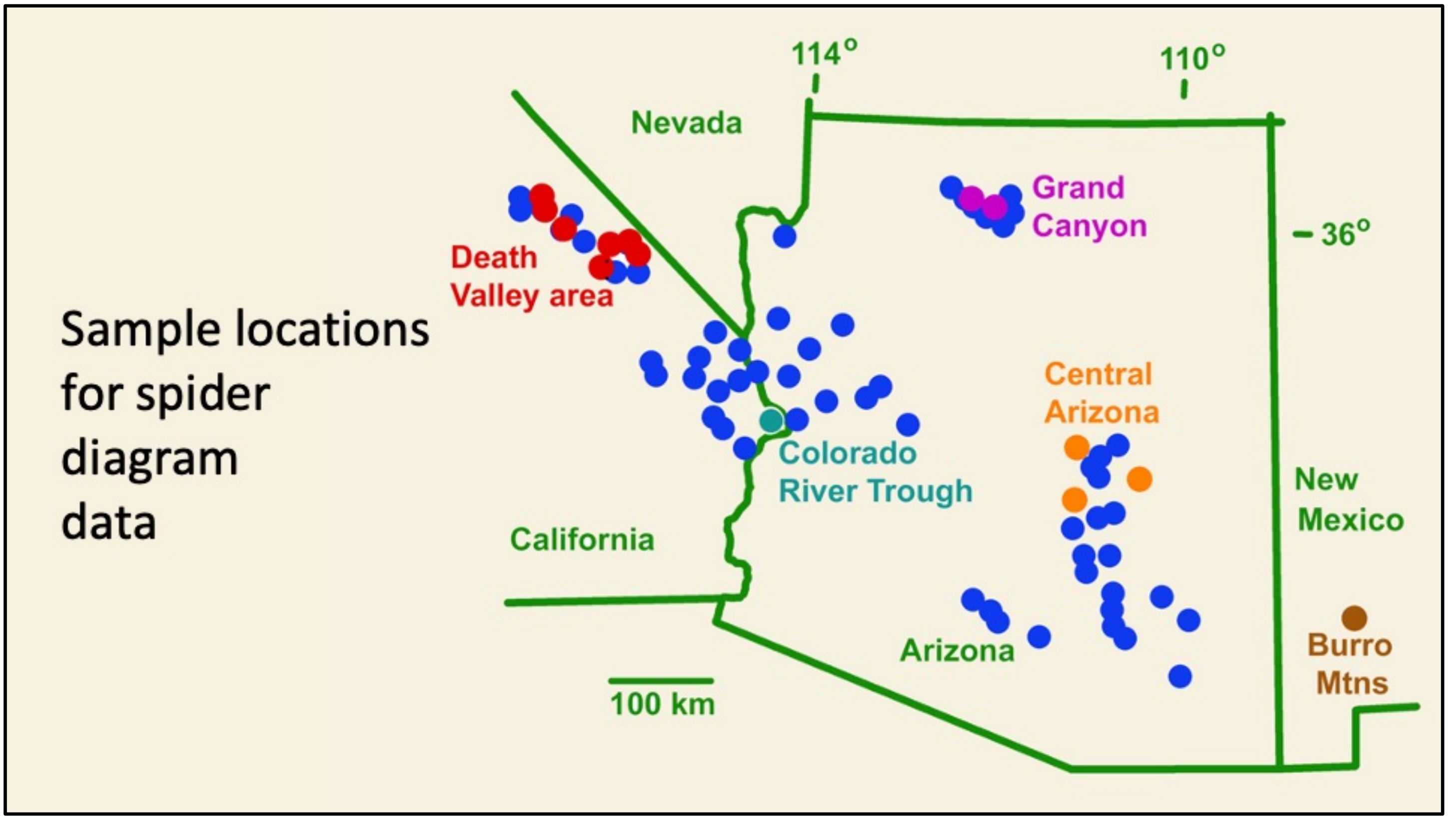
We are going to examine just of a few of these elements in relation to these standards

Positive spikes for Rb, Ba, K, and Sr are typical for hydrated mantle melts because they preferentially partition into the water leaving warming subducted slabs.

Nb is incompatible with water and prefers to remain in the dewatering slab, so it is characteristically depleted in arc basalts. Notice the deep negative Nb anomaly for the CAB in the figure.

Notice that OIB, which have very low water contents, do not show the extreme fractionation of CAB, but have a modest enrichment in Ti.

The data will show that both OIB-like and arc-like rocks are found this province, as they are in provinces such as the Siberia LIP and the Chifeng CFB where the case for deep water cycling is compelling.

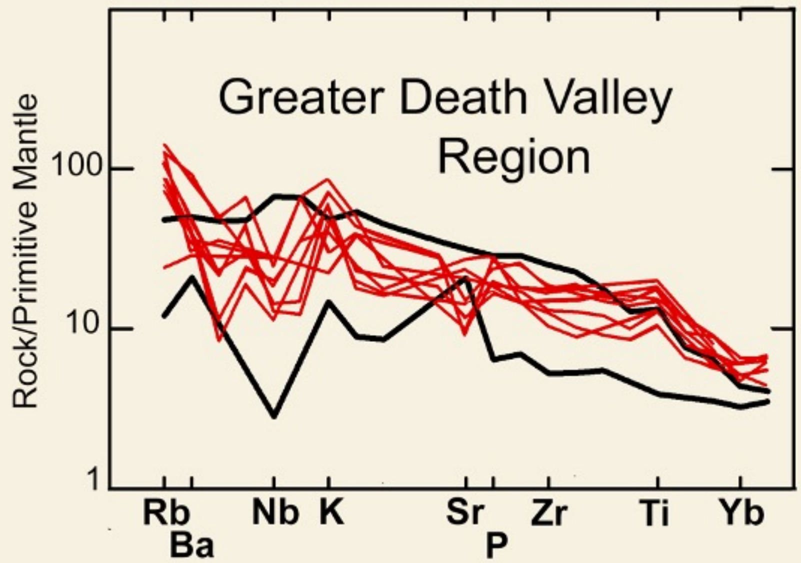


Let’s examine spider diagrams from different regions of the province. Specific sample locations are color coded. Death Valley, Colorado River trough, Central Arizona, and Burro Mountains areas form a NW to SE trend. Grand Canyon data helps complete a regional picture.

Most OIB-like region.

Pattern is generally more OIB-like with Ti enrichment.

High Rb and K with relatively low Nb indicate an arc-like subduction component in the melt.



Includes data from C. Wrucke (written communication).

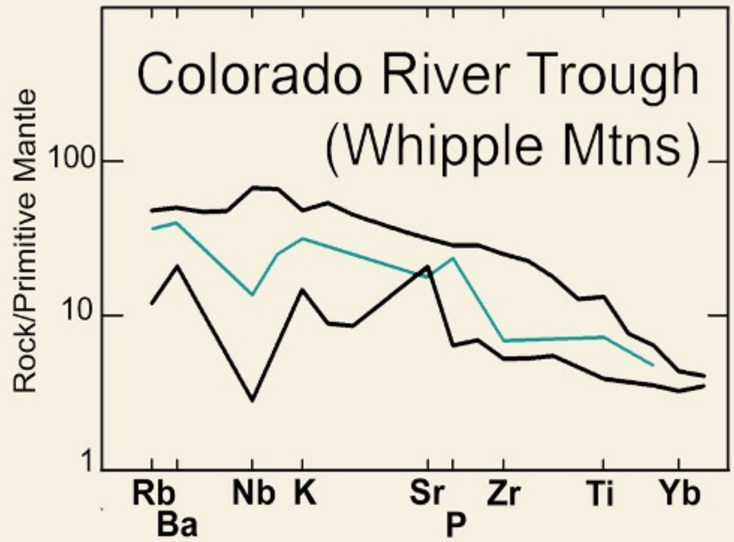
The greater Death Valley region has the most OIB-like diabase.

These samples are from a NW trend about 200 km long. They are strongly enriched in the fluid-mobile elements Rb, Ba, and K. A negative Nb anomaly is present. This combination indicates some subduction component. but the concentrations of these elements is considerably higher than in arc basalts. The high field strength elements, from Zr and to the right edge of the diagram are OIB-like, most obviously in the enrichment of Ti.

Intermediate composition:

Nb is moderately depleted and K and Rb are not strongly enriched.

P and Ti are both enriched compared to CAB.



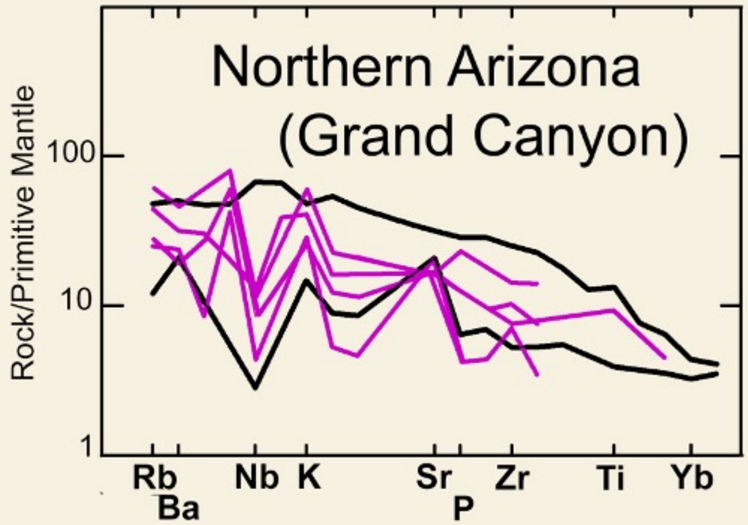
This pattern from the Whipple Mountains fits rather neatly between the two reference standards, a good intermediate example. The “V” above Nb is again indicative of a a subduction component, and the elevated Ti concentration is more OIB-like.

[The peak at P comes and goes throughout the diabase province, likely a function of the strong fractionation of apatite observed within single sheets.]

Strong evidence of a fluid component:

Deep Nb anomaly and strong enrichment in water-mobile K, U, Ba, Rb as well as Sr, akin to the CAB standard except concentrations are mostly higher.

Ti value is more OIB-like.

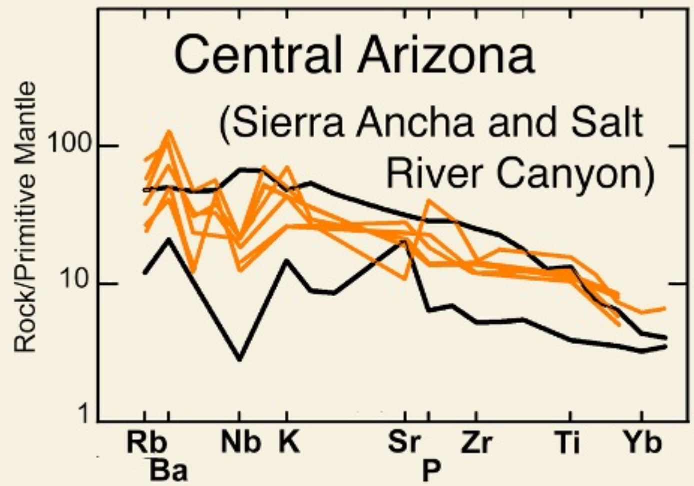


Includes data from Snelling et al. (2003)

There is strong evidence of a fluid component. inn the Grand Canyon samples
The 4 incomplete patterns are from a cross section of a single sill at Bass Rapid and vary because of differentiation within the sill, however, the relative fractionation between the water-mobile elements and water-avoiding Nb are preserved. The complete pattern is from a near Phantom Ranch and has OIB-like Ti.

Moderately OIB-like:

Similar to Death Valley area but with generally lower concentrations of elements across the diagram. Clear subduction component but otherwise more OIB-like.



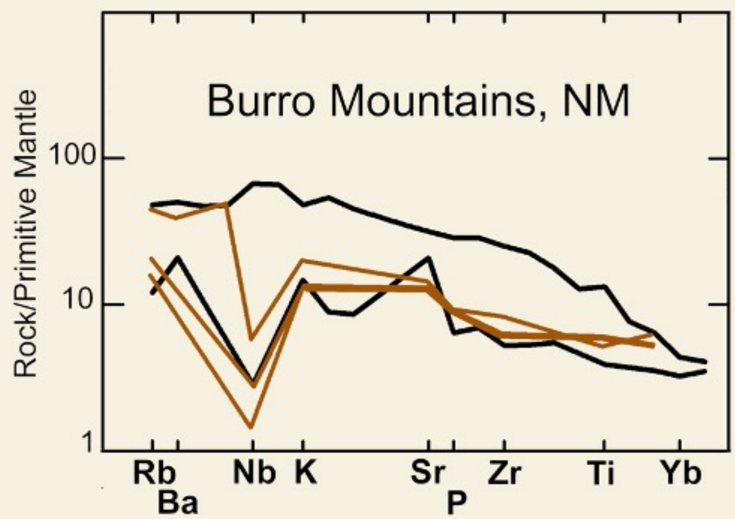
Includes samples from Bright et al. (2014)

This diagram is similar to that for the OIB-like Death Valley area diabase, but it has generally lower concentrations of elements across he diagram, especially for Ti, making Central AZ diabase less OIB-like than Death Valley diabase. As for other areas the depletion of Nb compared to fluid-mobile K and Ba indicate a subduction component.

Most CAB-like:

These samples clearly have an arc-like characteristic.

The Burro Mountains are at the SE edge of the province and are interpreted as having been nearest to the subduction zone.



Data from Bright et al. (2015)

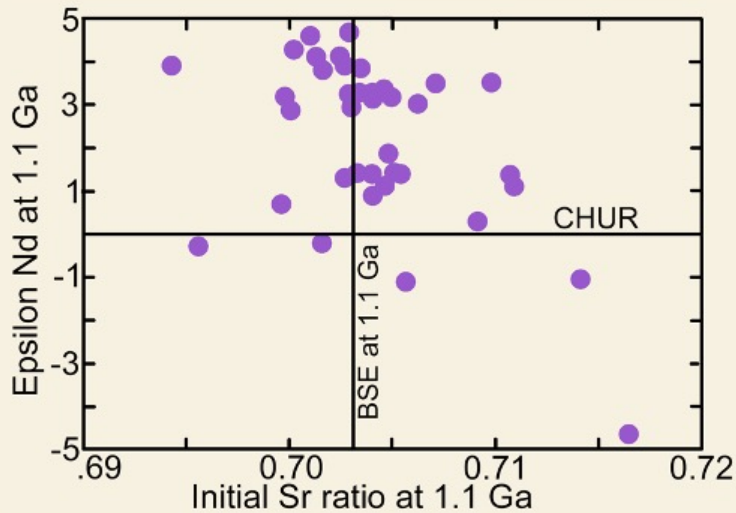
The patterns of these three samples from the Burro Mountains are obviously arc-like, in strong contrast to the OIB-like patterns for the Death Valley region.

Recall that the Death Valley region is at the NW end and the Burro Mountains are at the SE end of our diabase province. The other locations are intermediate in composition to the two end members. This trend is attributed to the Burro Mountains being closest to the subduction zone and the Death Valley region being farthest from it. A similar relationship was reported for the Siberian LIP by Wang et al. (2015)

Isotopic evidence:

Many sources could cause this variation in the initial Sr ratios, some are related to water cycling.

The eNd range is huge and probably not compatible with crustal contamination, suggesting a heterogeneous mantle source with distinct isotopic characteristics.

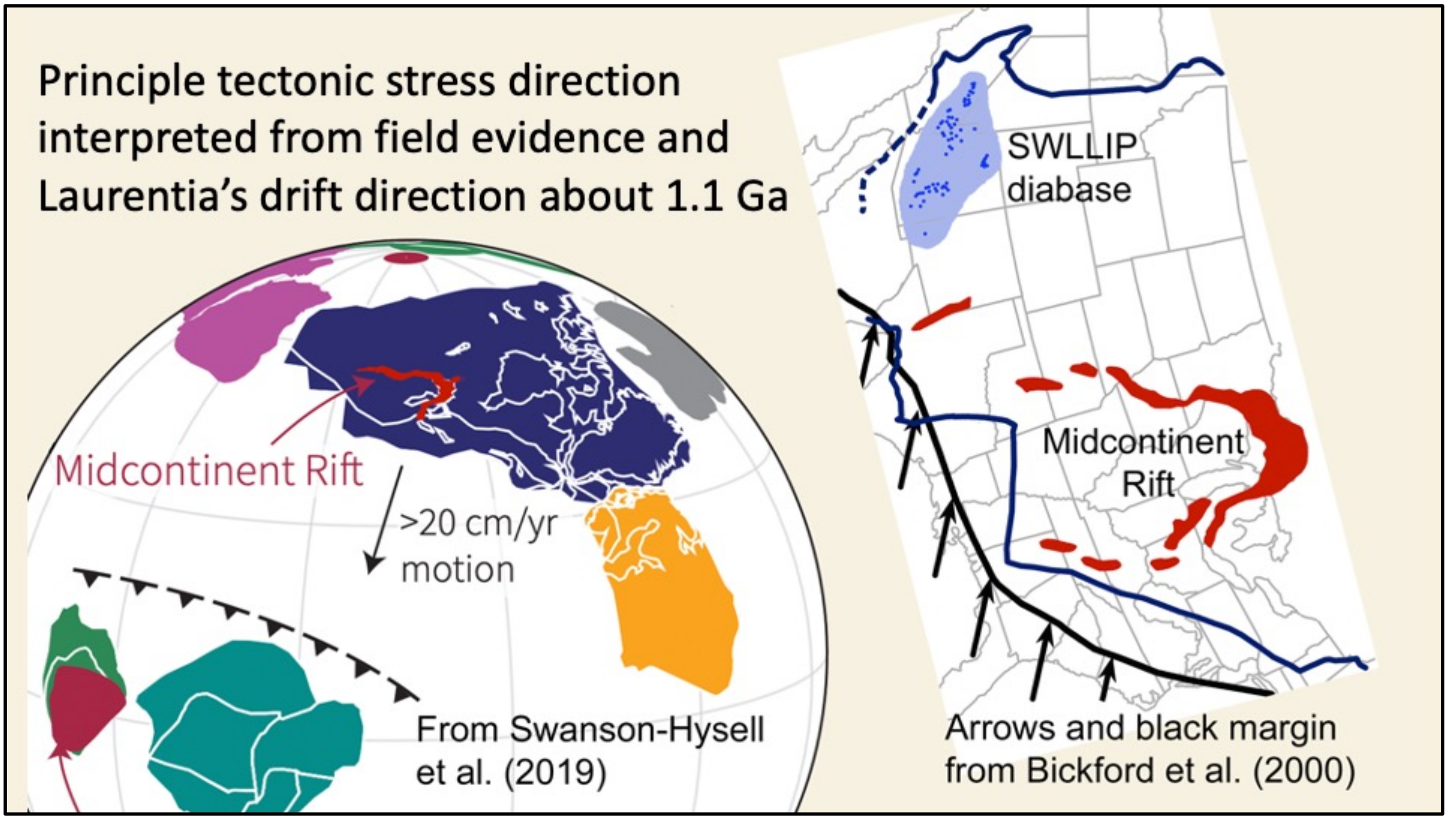


Includes data from Hammond and Wooden (1990), Snelling et al. (2003), and Bright et al. (2015)

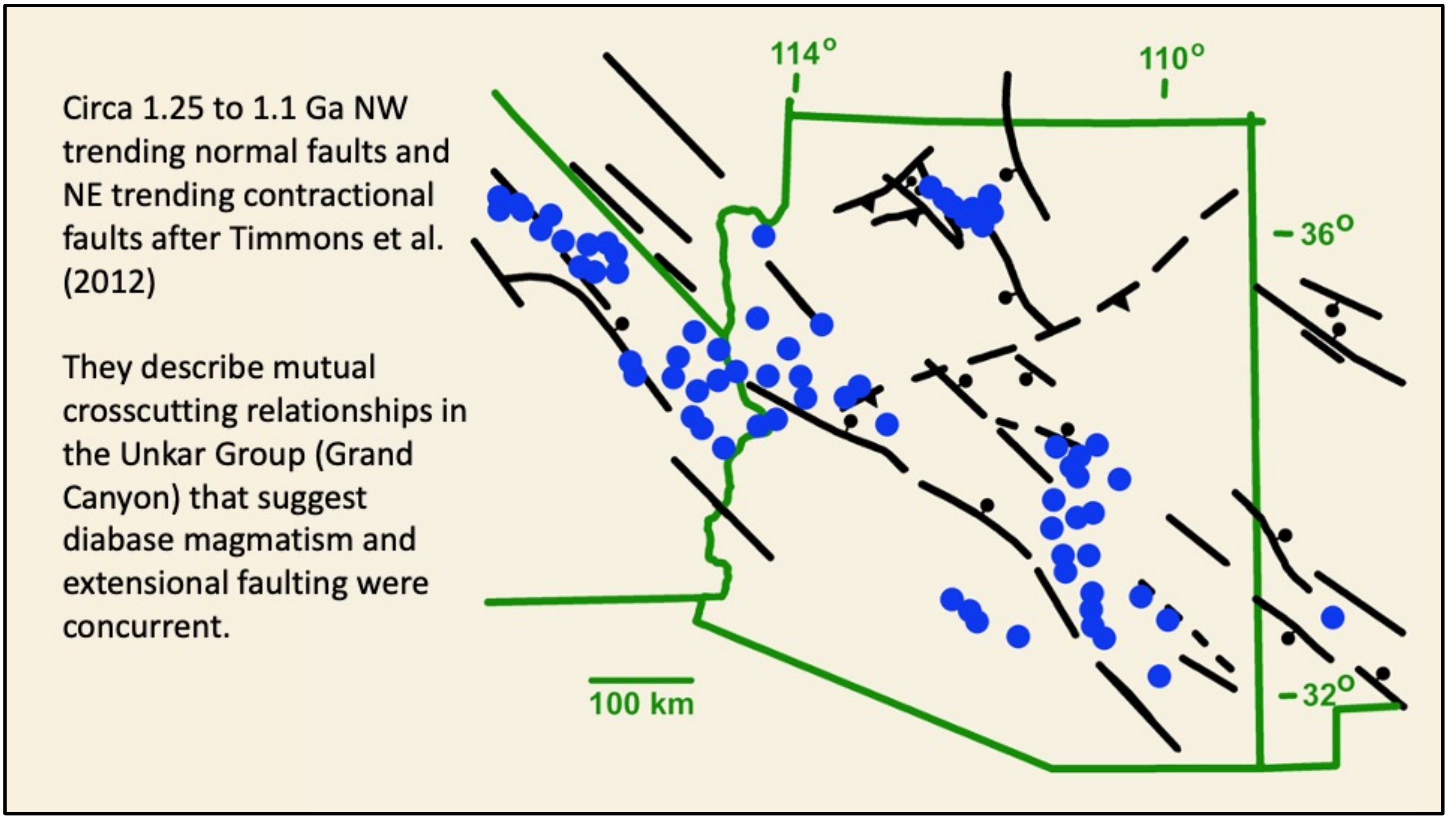
The range of initial Sr ratios and epsilon Nd values is compatible with this model. The scatter of the initial Sr ratios could have several causes, including causes associated with the deep-water cycling process.

The epsilon Nd range is huge. It is probably not compatible with crustal contamination because the Nd values have a large range compared to the diabase major element compositions that are quite alike. The range may represent heterogeneities in the mantle source, another feature of this model.

Next let's set the stage for the model.

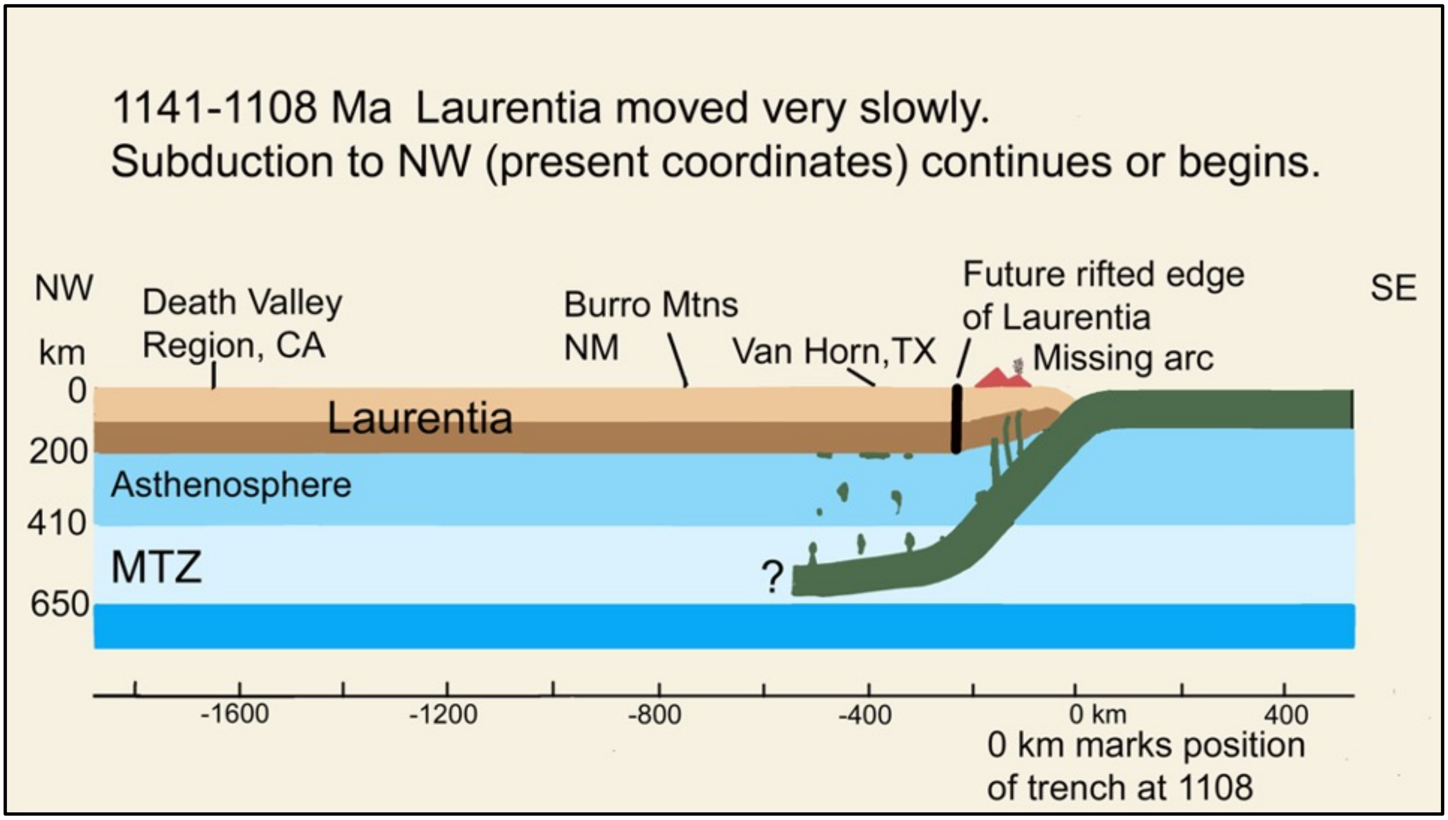


Bickford et al. (2000) proposed convergence along the SE margin of Laurentia. Using the MCR as a marker to orient these two maps, the principle tectonic stress direction of Bickford et al. is approximately parallel to the drift direction indicated by Swanson-Hysell et al., although the sense of motion is opposite. In contrast with Swanson-Hysell et al., and in agreement with what is observed on Earth today, we envision a subduction zone under the leading edge of Laurentia as it journeys to lower latitudes.



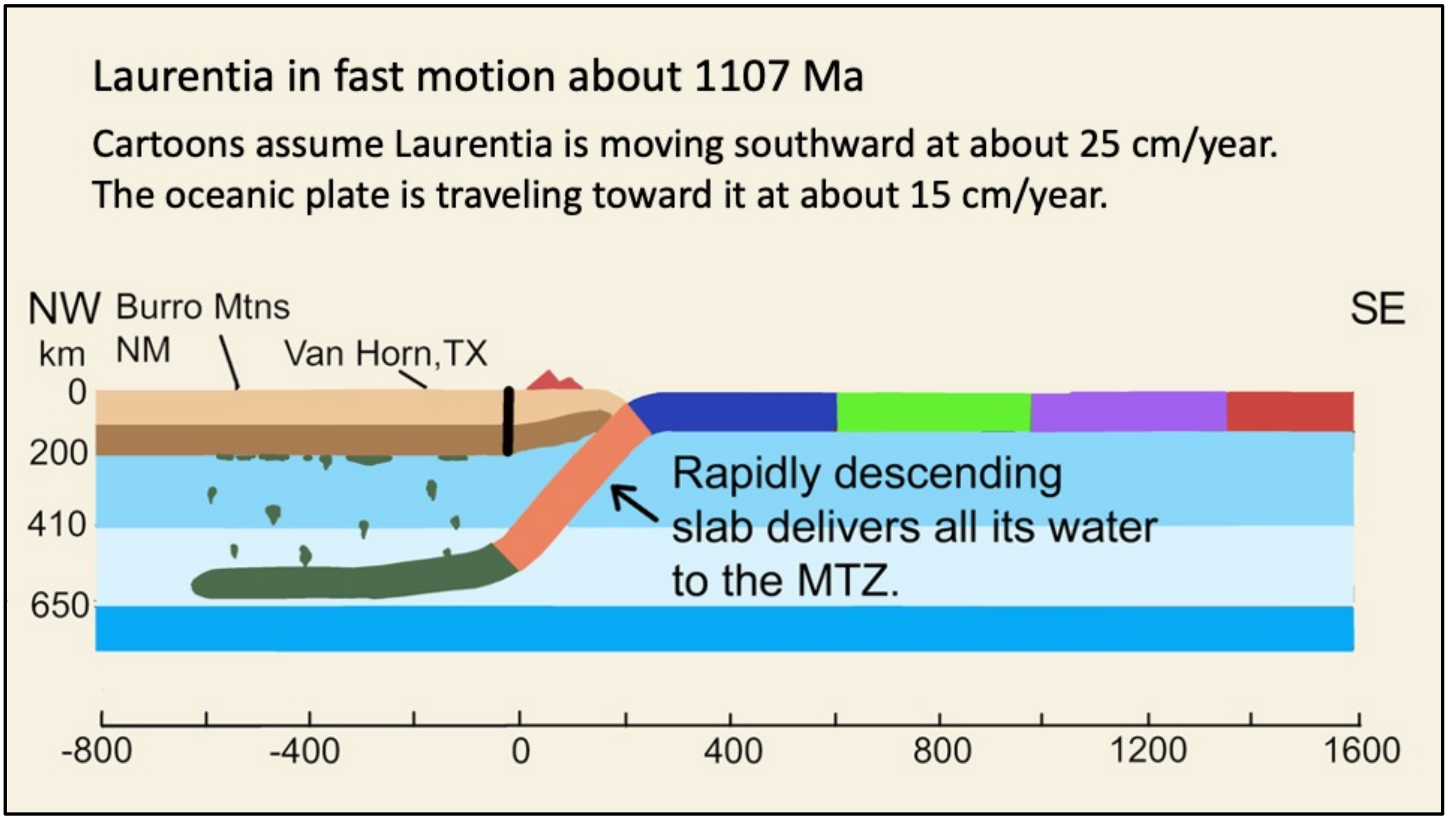
Supporting evidence from the SWLLIP and adjacent areas includes widespread NW trending normal faults and fewer NE tending contractional faults that are compatible with far field stress from a subduction zone on the SE margin (today's orientation of Laurentia). Although the age of the faulting is not well constrained, mutual crosscutting relationships between Unkar Group strata and the diabase suggest that extensional faulting and magmatism were concurrent. In addition, Howard (1991) and other authors have documented NW trending diabase dikes through out the region.

Now please consider a series of cartoons to put our story in chronological order.



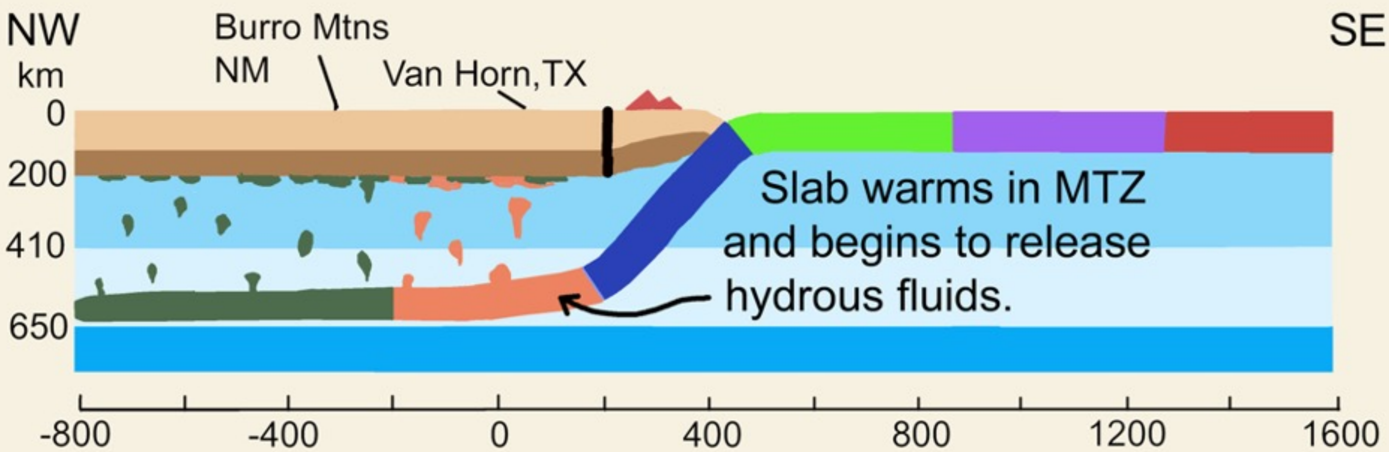
We are setting out to form a melt pond at the LAB boundary that can be ready to erupt when triggered. It is possible that some melt is already stored up from earlier subduction episodes, but the rapid motion of Laurentia can make it a “perfect storm” for this process, so this saga will start from scratch.

Note that the 0 km on the scale marks the position of the trench at 1108. This is a reference point that indicates how far the trench retreated (moved into the ocean basin) as subduction progressed.



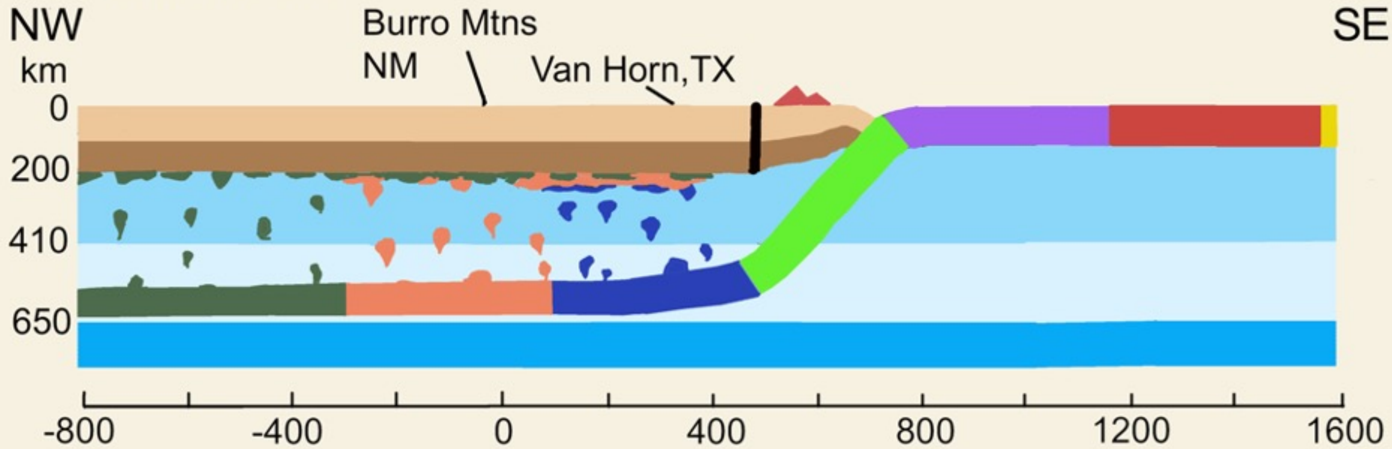
Diapirs of hydrous melts are rising from the warming slab and causing melting in the asthenosphere. The melts are trapped at the base of the lithosphere, and the melt pond begins to grow.

At about 1106 Ma the rapidly subducted portion of the slab hydrates the asthenosphere more rapidly, and the melt pond at the LAB grows.



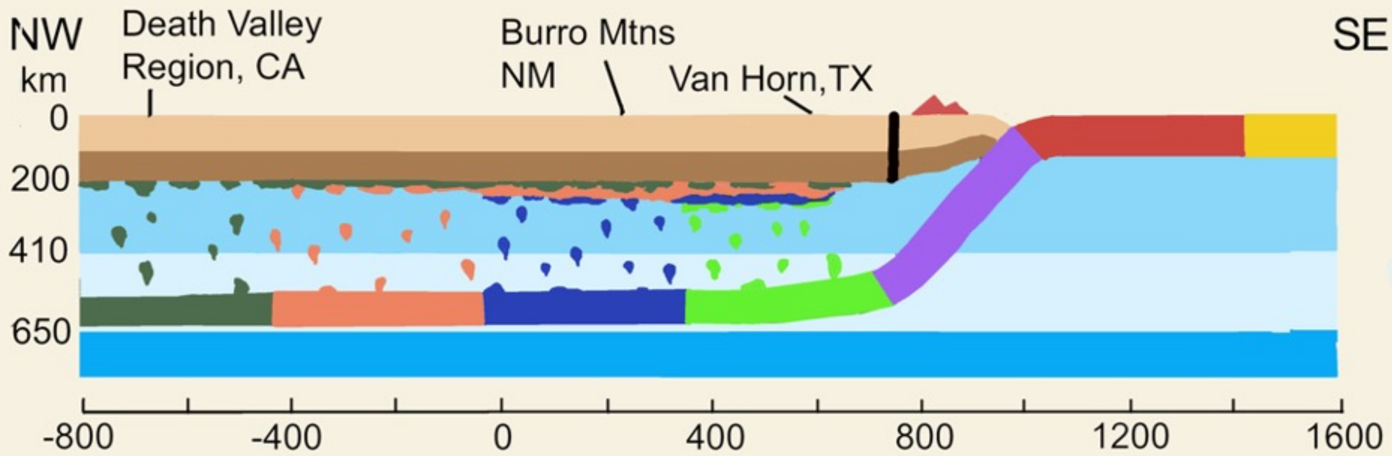
By this time some of the rapidly subducted slab is warming in the mantle transition zone. With more hydrous fluid to give off, the melt pond trapped at the lithosphere-asthenosphere boundary will grow faster.

1105 Ma. The different colors accumulating in the melt pond represent sources with different isotopic signatures, illustrating how varying initial isotopic ratios in the diabase can be sourced in the mantle.

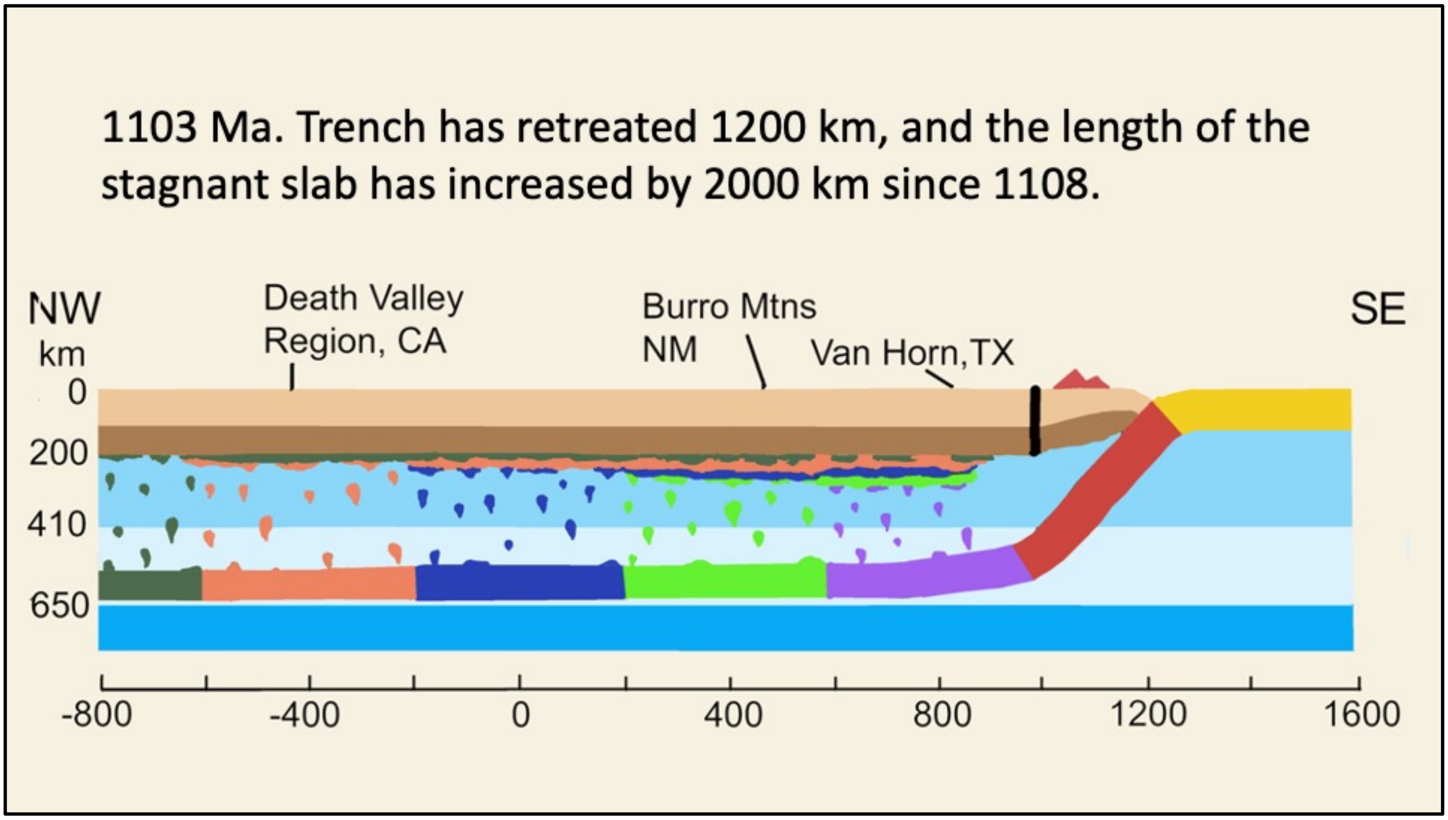


The different colors accumulating in the melt pond represent sources with different isotopic signatures, illustrating how varying initial isotopic ratios, as shown in the epsilon Nd and initial Sr diagram, can be sourced in the mantle.

1104 Ma. The way this model was constructed, leaves the melt pond a bit thin in the Death Valley region, but reasonable adjustments can be made.

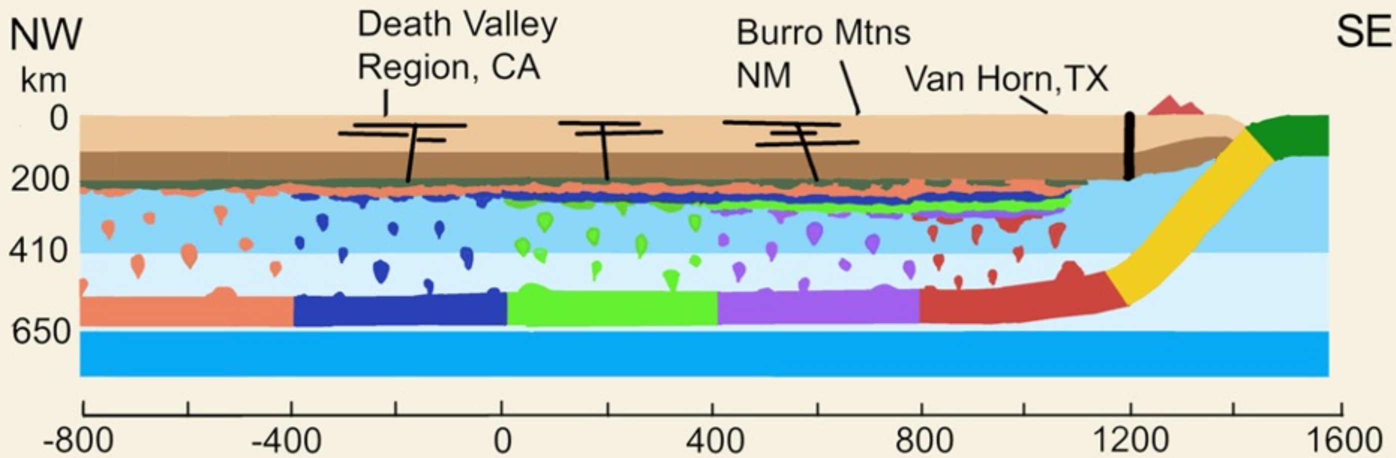


Here we have arrived at 1104 Ma, 1104 is the oldest of our ages, and it happens to be for the Death Valley area. The melt pond there still looks undersupplied. This would not be so if the model used a faster drift speed for Laurentia, if subduction were faster, if the model assumed there was already some melt in the pond at the start, or any combination of these. Alternatively, given that the uncertainty on the age is +/- 7 Ma, assuming that the actual age for initial magmatism was 1102, allows enough time to produce a well-supplied melt pond.

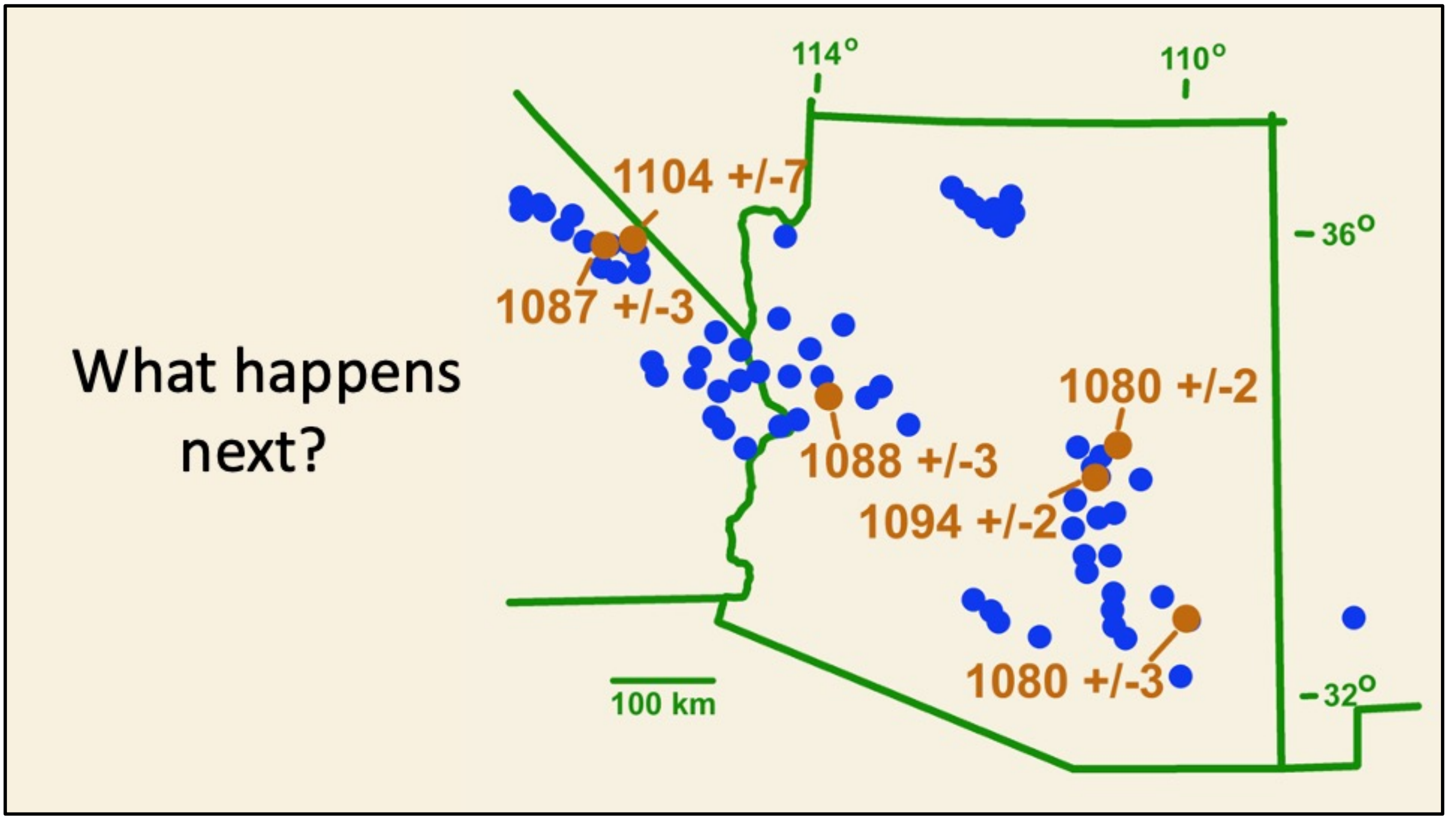


At 1103 he trench has retreated 1200 km since 1108 Ma, which is about half the distance Laurentia is thought to have traveled at high speed between 1108 and 1096.

1102 Ma. Convergence-related stress in the NW direction triggers extensional faulting through the lithosphere, enabling the melt pond to drain upward.



Now with plenty of melt in the pond at 1102 (within the error of our 1104 date) floods of basaltic magma rapidly rise toward the surface along NW trending extensional faulting in the lithosphere. The specific smoking gun that triggered the faulting is unknown.



Let's pause here and consider where we are in this scenario. We're about halfway along Laurentia's dash to the south. What happens between now and 1096 when, as described by Swanson-Hysell et al. (2019), the continent slows and changes direction?

Does the time gap between 1104 Ma and 1094 for diabase ages in this map signify well-separated magmatic pulses or is it an artifact of scanty data?

If the melt pond drained at 1104 and rapid subduction continued, there would be ample opportunity to replenish it before a pulse at 1094 in SWLLIP.

The change in plate motion and intrusion of the huge body of Duluth Gabbro and associated basaltic volcanism in the Mid-continent rift at 1096 seem undeniably related to more magmatism in the SWLLIP at 1094. Continued changes in stress regime as the continent adjusts to its new position could produce the events at 1087 and 1088. The error values for these dates allow them to be very close to 1094.

Beyond that the story becomes more speculative. Was there enough stagnant slab material under stalled Laurentia to continue dehydrating and replenish the melt pond for another pulse at 1080 and what triggered it?

Hopefully adding a deep-water cycle model to the continent-wide discussion of Laurentian mafic magmatism about 1.1 billion years ago will spark new ideas and continued interest in the problem.

Thank you for your attention.

Remember The Take-Away!

The chemical composition of the SWLLIP diabase exhibits a subduction component which becomes more prominent from the northwest to the southeast.

We propose this was produced by deep water cycling via stagnated slabs in the mantle transition zone (MTZ).

This process is enhanced by rapid plate motion such as that of Laurentia at about 1.1 Ga ago.

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