Starting Tectonics and Making Continents

After reading this chapter, students should be able to:

- Describe the general idea related to the formation of continental crust and modern tectonics
- Differentiate different ideas about the differences in early tectonics models and how they are different than modern tectonics
- Explain why some rocks were formed in the Archean but are not still being formed today

The Beginning of Plate Tectonics and the Beginning of Continents – How One Caused the Other

Introduction

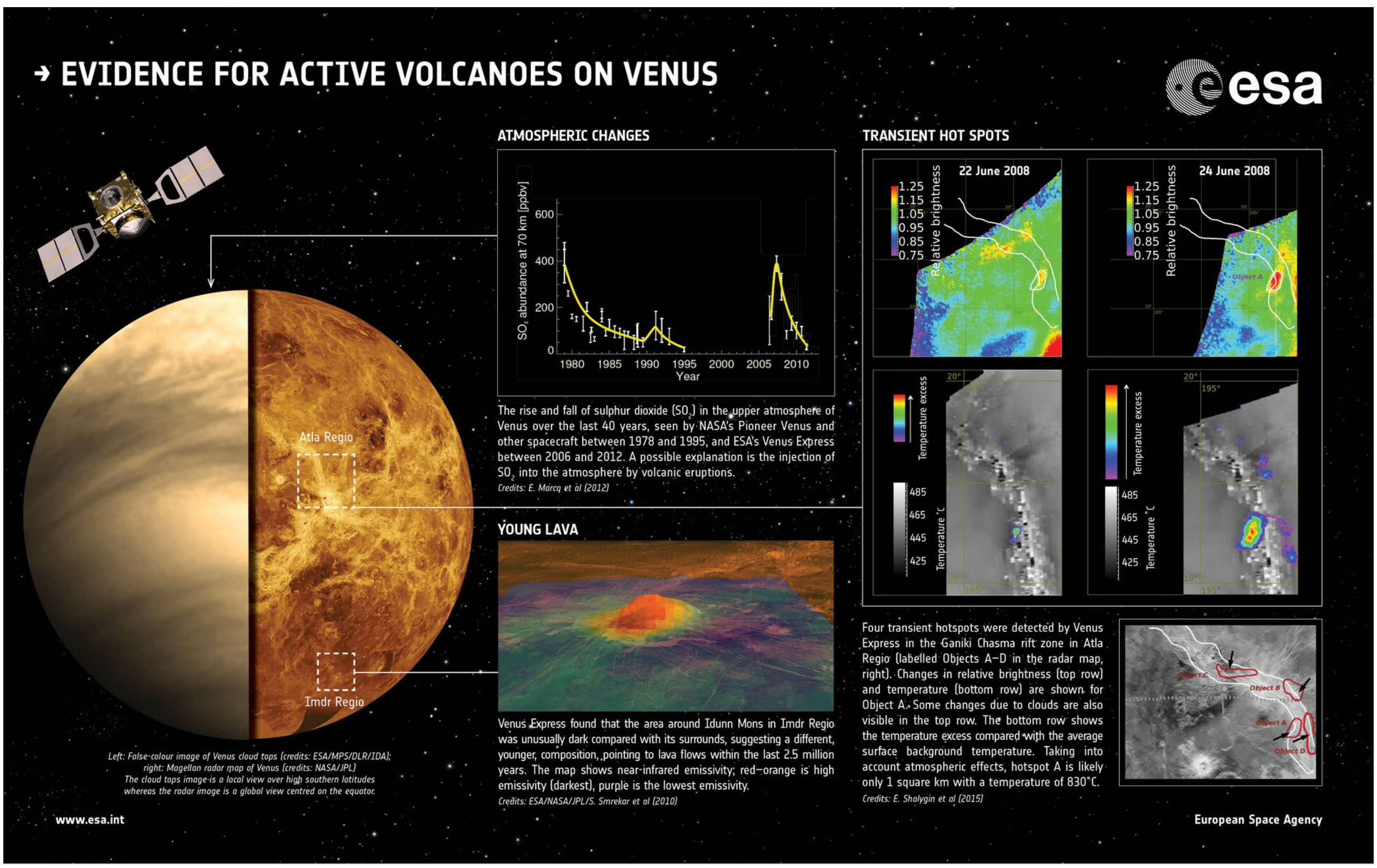
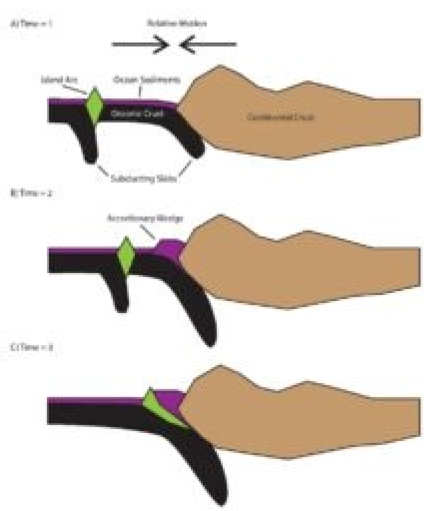


Diagram summarizing evidence for active volcanism on Venus.
ESA graphic

In some ways, the first rocks that existed on Earth are fairly straightforward, even though no direct evidence of their existence has ever been found. After coalescing via impacts, the material that would become the Earth was basically a hot ball of magma. The densest (metallic) material sunk down to form the core, and lighter (silicate) material floated upwards, eventually cooling enough to form the first rocks: most likely a very mafic veneer on a magma ocean. At this time, Earth may have more resembled modern Venus, with no significant tectonic movements and volcanism as the driver which shapes the surface. So, how does an Earth-like tectonic system with subduction start on a planet with no plates? Also, since continental material today is made via processes like subduction, how does continental crust evolve on a planet without tectonics? Even on Earth today, the process of how a subduction zone initiates is a bit of an enigma. How do we solve the seemingly unanswerable question of how subduction started on Earth billions of years ago? For details on these beginning steps, please review the case study on Earth's Oldest Rocks.

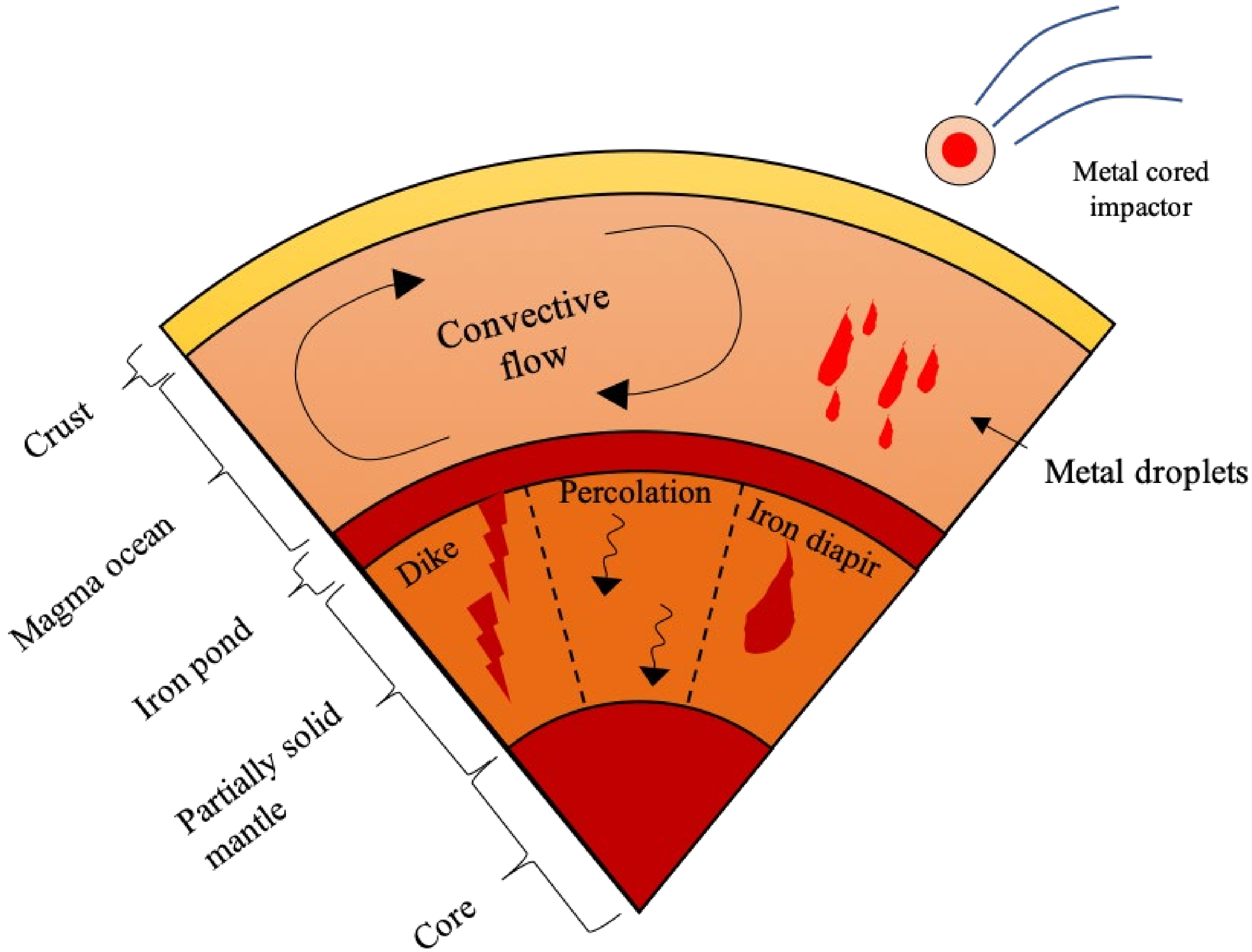


Cartoon showing the general process of accretion in growing continents.

Graphic: BZenith via Wikimedia.

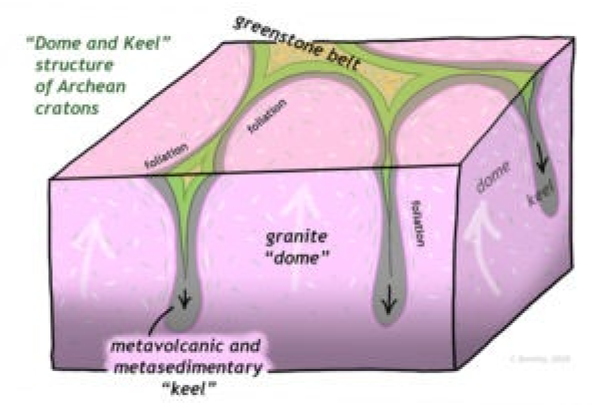
Why is the start of subduction so important for understanding the start of plate tectonics? There are two main reasons: First, subduction is an important driver of plate movement today. In fact, some would argue it is the ***main*** driver. Once subduction begins, other processes, like the building of continents through collisions and the creation of new seafloor at oceanic ridge systems can also begin. Secondly, some models of early Earth focus on subduction, and use it as an assembly process for Earth's first continental cores. Basically, subduction would create an island arc, and island arcs would accrete to make the first continents. Though this model has fallen somewhat out of favor (e.g. Bedard and Harris, 2014) in place of models discussed below, it is still a possible mechanism for Earth's early history, and should be considered. The only rocks we have from the Hadean and Archean eons are found in buoyant continental cratons, and thus, are the only rocks you can use to directly surmise the start of plate tectonics. While subduction is a driver of felsic magmatism today (the makings of the continental crust), is it proper to assume that subduction is the main process that made it in the past? Lastly, subduction also causes the initiation of many geochemical cycles (deep water cycle, many chemical and isotopic heterogeneities) which are used to understand the mantle. If the mantle has evolved over time via tectonic movement or other methods, it is important to have a time constraint on this mixing process.

Hot Stuff, Coming Through



Hypothetical core-mantle differentiation processes: Percolation, diking, and diapirism. After Rubie et al. (2015).

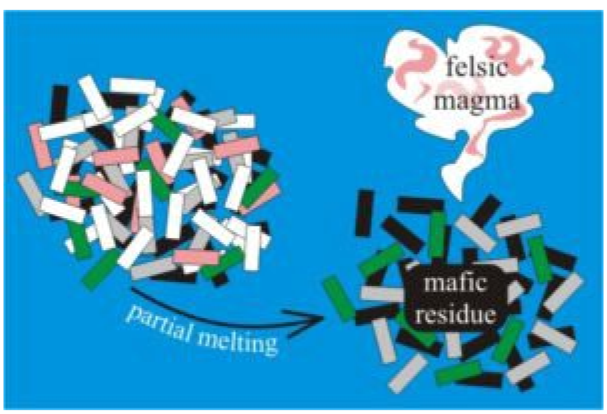
One of the biggest issues with modern tectonics and subduction is the heat the early Earth possessed. It is speculated that the internal heat of the early Earth was much higher than today (as much as 300 degrees Celsius), suggesting both a higher heat flow out of the planet, and thus a warmer lithosphere. Modelling has shown that this heat would have made the lithosphere weaker, more prone to breaking. A trigger, like the extra heat that comes with a mantle plume (Greya *et al.*, 2015) or even an extraterrestrial impact (*e.g.*, O'Neil et al, 2019) may have weakened the lithosphere enough to start the subduction process.



Block diagram showing the structure of a typical Archean craton, such as the Pilbara. Arrows show relative motion of the granite "domes" relative to the metavolcanic & metasedimentary "keels."
Callan Bentley cartoon

Early models for the movement of material within Earth, *i.e.* a proto-tectonics, have focused on [vertical tectonics, found within these greenstone belts]: upward moving plumes and diapirs and downward-moving delamination or "drip" tectonics. The extra heat in the mantle could have driven a more-active plume system all over the planet. Each plume could have been a place where the lithosphere was heated and weakened. This is known as plume-lid tectonics—the rising material from plumes was somewhat capped by the young, hot, but continuous lithosphere. Another part of this plume-lid model has to do with a rock known as eclogite. Models predict a thicker oceanic crust during this time; much thicker than today's. At about 40 km, basalt metamorphoses to eclogite, which is much denser type of rock. This dense lower part of the crust would "peel off" in a process known as delamination, or 'drip' downward. This is a possible way material can cycle before the beginning of plate tectonics.

The Chicken and Egg Problem of Making Continents



Partial melting makes magmas that are more felsic than their source rocks, and leaves behind solid rocks that are more mafic.
Cartoon by Callan Bentley.

The process of making continental material on modern Earth with plate tectonics has one major requirement: continental material. So, how can you make a continent before you have a continent? With modern tectonics, [the making of felsic continental rock that composes the thicker continental plates], involves the differentiation of partially melted mantle material through the subduction process and partial melting. This results in diapirs (magma chambers) of more felsic magma rising through the pre-existing crust, becoming increasingly more felsic as the buoyant magma melts surrounding rock in its journey toward the surface. Models that predict a thicker mafic crust early in Earth's history can allow for more magmatic differentiation as magma rises in a plume (or otherwise) than would happen within oceanic plates on Earth today. Another factor is felsic input directly into magmas, a major part of today's formation of continents. Through partial melting of host rock, which pulls more felsic components out of the host than mafic components, and assimilation, in which felsic material can enter a melt and drive the overall composition of it towards being more felsic (less mafic), large portions of recent continental material has been made. The problem is both of these methods require felsic host rocks present in the beginning of the process to work properly in large quantities. Even without plate tectonics as we know it today, there certainly is a propensity for making some felsic material, or at least material that is more felsic than the average crust at the time, in a variety of ways. And perhaps that is all that is needed; a slight increase in felsic material in a section of the crust might have been enough at the time to make it buoyant and start the more complex processes described above and make full-fledged continents. It seems that if this is the case, plume-lid volcanism or early subduction or both may have seeded the first continents. One final piece of the modern subduction story may come down to something as simple as sediment (Sobolev and Brown, 2019). It turns out the sediment is a great lubricator of slab movement, and the amount of sediment even affects modern slab descent. The problem is this: without a continent to supply sediment to lubricate subduction, it may be slow or inhibited. Sobolev and Brown suggest only after continents form and provide sediment as lubrication (such as with the post-Archean, 2.4-2.1 billion year old Huronian Glaciation), does subduction really take off.

A fragment of the Acasta Gneiss, the oldest known rock on our planet. In exhibition at the Natural History Museum in Vienna.

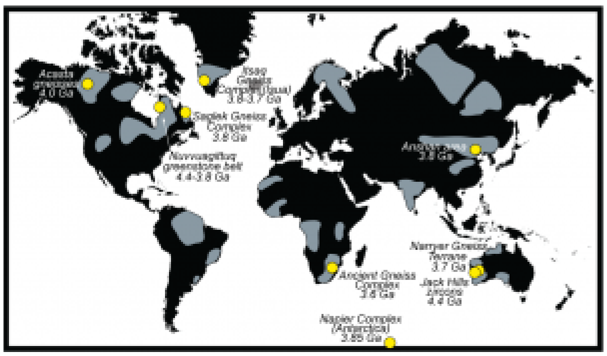
[Archean continental rocks]() may be hinting at a different process in their formation. This is due to a high concentration of rocks which are only rarely produced in tectonic settings today: [the tonalite-trondhjemite-granodiorite (TTG) suite of intrusive igneous rocks]() and their metamorphosed descendants/equivalents, like the [Acasta Gneiss](). TTGs are superficially similar to normal crustal granites, but typically have a much lower amount of potassium feldspar from a lower overall elemental potassium content. According to modeling, TTGs are only formed via partial melting of metamorphically altered mafic rocks, which seems to be less common today than in the past. One thing TTGs cannot tell us is the source of this melting metamorphic mafic rock. It could come from a melting subducting slab, or it could come from lower crust delamination. It is helpful to remember that slabs today do not really melt to produce magma, but rather introduce volatiles to produce flux melting in the mantle wedge. If slabs were melting in the past this would be a clear difference between early Earth and modern tectonics. Water is also an important factor in TTG formation according to geochemical models, which does lend some credence to an early but not fully modern subduction-like process. Since water is needed to form TTGs, some process like subduction should have brought water down into the zone of formation of TTG rocks. Trace elements also support the argument that mantle mixing (with water also helping mantle convection by making it more ductile) happened with the formation of TTGs (Hastie et al, 2016). Again, a plume could also be creating weaknesses, inducing subduction (Beas et al, 2020), but either way, it appears material was moving from the surface to depth.

A Very Different Archean

Blueschist cobble (with white vein) on Kayak Beach, Angel Island, California.
Callan Bentley photo

"Starting tectonics and making continents by Matt Affolter (2021), excerpted from *Historical Geology*, a free online text"book" by Matt Affolter, Callan Bentley, Shelley Jaye, Russ Kohrs, Karen Layou, and Brian Ricketts.

There are several things that occurred in the Archean that did not occur afterwards. Perhaps the most famous example is komatiite, the ultramafic lava that does not erupt out of today's volcanoes. Another example, TTG rocks are only in high abundance in cratonic rocks dated from the Archean and are rarely formed today. A third example has to do with certain metamorphic rocks that are not present in Archean rocks. These include UHPM (ultra-high pressure metamorphic rocks) and blueschists. Both of these are only formed with the lower temperature/higher pressure conditions in subduction. Two conditions must be true to form these rocks: buoyant continents and strong plates, which could explain the lack of blueschists and UHPM rocks before the late Archean is the evidence used, according to Brown and Johnson (2018). Additionally, as mentioned earlier, these melting broken slabs may be the source for the TTG suite of rocks. Finally, various geochemical isotope signatures (Dhuime *et al.*, 2012, Tush *et al.*, 2020) show that looking at rocks before 3 billion years ago and after 3 billion years ago, processes were just different. Isotopes of hafnium, oxygen, and tungsten show dramatic changes occurred in mantle mixing processes around 3 billion years ago. Oceanic basalts also show concentrations of trace elements that shift around this time (Condie 2015). These are significant enough to convince many scientists that the true start of modern tectonics occurred at this time. At a recent conference on the origins and evolution of plate tectonics, a majority of the researchers put the start of plate tectonics at 3 billion years ago. Some are still convinced that it could have started as early as 4.2 billion years ago, others as recent as 1 billion years ago. It should be noted that there are qualifiers, where some scientists say a different tectonic paradigm existed earlier, whereas only modern plate tectonics, like we know, started later. Evidence for this includes kimberlites, rocks that bring up diamonds that may owe their origin to modern tectonics. While some are old, many more are found within the last billion years of the rock record (Stern *et al.*, 2016). Also, since the oldest blueschist is 780 million years old in China, the oldest UHPM rock is 620 million years old in Mali, it could mean a much more recent start to modern tectonics. Ophiolites are similar in their record, and are a clear indicator of modern tectonics. There are a few ophiolites that are much older, close to 2 billion years old, but the vast majority are less than 1 billion years old. Of course, the incompleteness of the rock record, especially as one ventures further into the past, should be considered. It is certainly possible that the lack of these rocks going back in time is due to destruction via the rock cycle and tectonics.



Archean Cratons (light grey) and locations of Earth's oldest rocks on a world map.
By Jonathan O'Neil, with permission, from: UOttawa Early Earth Blog

Whenever it started, it is clear that by the end of the Archean, most of the cratons on Earth had formed, though the growth of continental cores like cratons has been shown to be episodic (McCulloch and Bennett, 1994), even in the Archean, meaning some sort of process must have periodically added felsic crust. The Wilson Cycle can help explain this pattern today and in the recent past. It is not as useful for a time before tectonics, nor at explaining that most cratons are dated to ~3 billion years old and older. One last item to consider: most of the cores of all modern cratons are Archean and subsequent rifting has mostly gone around them, not through them, presumably due to their strength. Were the processes that occurred before 2.5 billion years ago so fundamentally different, in that the only time in Earth history where cratons could form (known as 'cratonization'), was in the Archean? Some difference in how the Earth constructs its surface, from before the Archean to after, appears to be true. If true, it would be a significant exception to the idea of uniformitarianism.

Conclusion

The geodynamics of the early Earth are controversial and difficult to ascertain. There are a few things that are certainly known:

1) Early on, Earth would have developed a magma ocean, cooling on its surface to form a very mafic crust.

2) Continents started to form early in Earth's history, by a process different than modern continental formation, indicated by somewhat strange early rocks.

3) The date when subduction began is highly debated, with the most commonly referenced time frame being around 3 billion years ago.

4) The start of modern tectonics is also debated, with most scientists agreeing that subduction might have been different in the Archean, including more slab break-offs.

5) This different 'tectonics' in the Archean includes TTGs formed via melting slabs and a lack of blueschists/UHPM rocks.

With this list of (relatively) known quantities, a picture of early Earth's tectonics (or lack thereof) is starting to take shape, though much remains to be resolved.

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