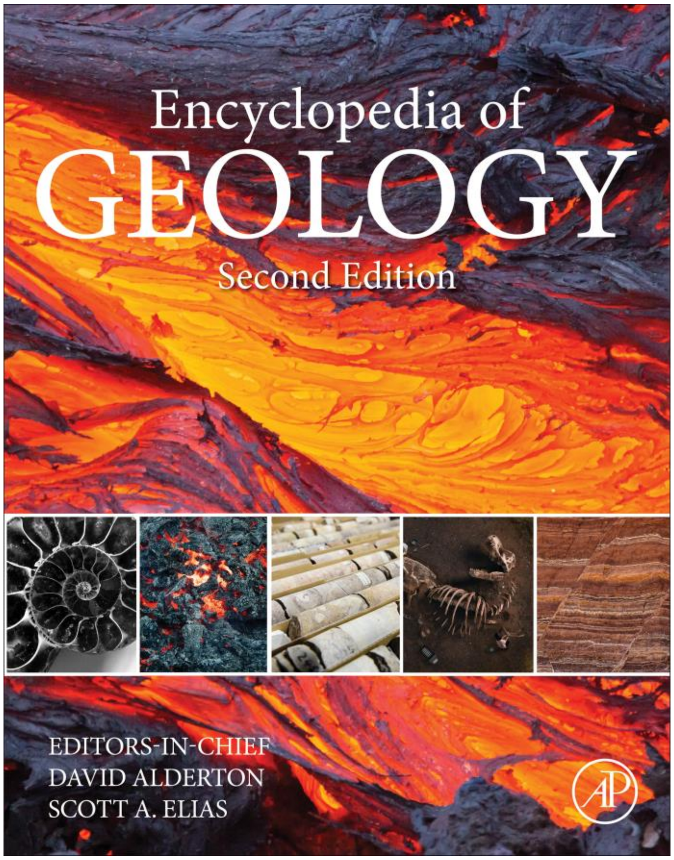

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Subduction Initiation

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Glossary

Byerlee's law In rheology Byerlee's law (also known as Byerlee's friction law) concerns the shear stress required to slide one rock over another. The minimum shear stress needed for sliding along a fault increases approximately linearly with the normal stress on the fault (that is close to pressure, which typically increases with depth below the surface). Byerlee's law applies to cool rocks ($<\sim 500\ ^{\circ}$C) but temperature controls rocks strength at higher temperatures. For this reason, Byerlee's law only controls rock strength in the upper part of the lithosphere.

Corona These features are best known from Venus, where these approximately circular structures range in diameter from 60 to >1000 km. Nearly all coronae have associated volcanic and tectonic features, including abundant small (<50 km diameter) volcanoes, extensive flow deposits, radial and concentric fractures and ridges.

Forearc At a convergent plate margin, the forearc lies between the trench and the volcanic arc. Forearc crust may be blanketed in sediment (common near continents) or may be exposed (naked forearcs, common away from continents). Naked forearcs are 100–150 km wide and expose igneous rocks that form during subduction initiation.

Friction coefficient The coefficient of friction (COF), often symbolized by the Greek letter μ, is a dimensionless scalar value which describes the ratio of the force of friction between two bodies and the force pressing them together. The coefficient of friction depends on the materials used; for example, ice on steel has a low coefficient of friction, while rubber on pavement has a high coefficient of friction. In geology, COF is useful for describing the strength of a fault. COFs for this range from near zero (e.g., talc or overpressured fluidi in a fault zone) to one (fresh peridotite on either side of a fault).

International Ocean Discovery Project (IODP) IODP is an international marine research program. The program used heavy drilling equipment mounted aboard ships to monitor and sample sub-seafloor environments. With this research, the IODP documented environmental change, Earth processes and effects, the biosphere, solid earth cycles, and geodynamics. IODP is the latest version of scientific ocean drilling; the first version was called the Deep Sea Drilling Project. See video https://www.youtube.com/watch?v=lZ7IeblAb9g.

Izu-Bonin-Mariana (IBM) The IBM convergent plate margin stretches 3000 km from Japan to Guam, USA. The peaks of the largest volcanoes make small islands but most of the IBM system lies deep beneath the ocean.

Numerical modeling Numerical modeling applies partial differential equations (PDE) of continuum mechanics to describe the physical conditions and time evolution of geological scenarios using values for rock properties (for example, viscosity and density). The PDE are impossible to solve analytically in a general case. Therefore, numerical approaches such as finite difference methods (FDM) or finite element method (FEM) are used to approximate the solutions of the PDE in form of large systems of linearized equations. Powerful computers are then used to solve the systems of equations needed to investigate plausible geological scenarios for various solid Earth systems.

Lithosphere the strong outer shell of the Earth, typically 100–200 km thick and. Consisting of all of the crust and the uppermost mantle. Earth's lithosphere is broken up into plates of various size. Lithosphere lies on top of hotter and weaker asthenosphere.

Obduction The process by which slices of oceanic lithosphere (ophiolites) are emplaced on land.

Ophiolite An ophiolite is a section of the Earth's oceanic crust and the underlying upper mantle that has been uplifted and exposed above sea level and often emplaced onto continental crust. Many ophiolites formed in forearcs during subduction initiation.

Slab Deeply subducted oceanic lithosphere diving into the mantle.

Wilson Cycle The Wilson Cycle is a model where a continental rift breaks one continent into two, opening an ocean basin in between. The separation of the two continents is followed later by formation of one or more subduction zones that closes the ocean basin and leads to continental collision to recombine the two continental blocks. Named for Canadian geoscientist J. Tuzo Wilson (1908–1893) who first proposed the idea to explain the Phanerozoic evolution of the Atlantic Ocean and surrounding regions.

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Introduction

Other tectonically active silicate bodies in the Solar System (Venus, Mars, Io) have lithospheres but only Earth has plate tectonics. This is equivalent to saying that only Earth is capable of systematically forming new self-sustaining subduction zones driving the continuously evolving mosaic of tectonic plates (Note: there are feature surrounding corona on Venus that look like incipient subduction zones but these do not evolve into continuously operating subduction zones). It may or may not be a coincidence that only Earth also developed complex life, but once begun, life has been and is strongly influenced by the onset and operation of modern-style subduction and plate tectonics (Stern, 2016; Pellissier et al., 2017). Earth has two types of crust—oceanic and continental—and therefore two types of lithosphere. Because oceanic lithosphere has thinner crust and is therefore more dense than continental lithosphere, new subduction zones involve this as the sinking plate. The sinking of oceanic lithosphere in subduction zones provides most of the power for driving plate motions, so forming a new subduction zone changes plate motions and—sometimes in tandem with mantle plumes—causes new oceans to open and old oceans to close. We have advanced considerably in our understanding of how mature subduction zones operate (Stern, 2002) but we are much less advanced in our understanding of how new zones form. Part of the reason that subduction initiation (SI) remains enigmatic is because it happens rarely and deep underwater. Consequently, the big breakthrough in our understanding of SI came from marine geologic studies of western Pacific forearcs. New insights come from recognizing evidence of SI preserved on land, especially from studying ophiolite belts, many of which represent fossil forearcs (Stern et al., 2012). SI concepts and models are evolving rapidly as geologists, geodynamicists and experimentalists increasingly collaborate on this central geoscientific problem. Geoscientists are integrating growing amounts of natural data on subduction initiation examples with increasingly robust 2D and 3D numerical geodynamical models, using properties of rocks determined by laboratory experiments and theoretical considerations. Concepts and models of subduction initiation have thus become increasingly robust and realistic in terms of the physics responsible (theory) and the resulting geochemical and rheological responses or products (evidence). This line of inquiry is one of the most exciting fields of modern solid Earth research.

History of Research

The focus of SI-related research has evolved substantially over the 50 years since the term "subduction" became accepted as an important plate tectonic process. In the first 15 years, inquiry focused on compressive failure of oceanic lithosphere and was led by geodynamicists (e.g., McKenzie, 1977). Tectonic scenarios created by many geologists during this time (and continuing today) showed new subduction zones forming and disappearing willy-nilly, without attention to force balance or locations of lithospheric weaknesses. We began to change our thinking after Deep Sea Drilling Project Leg 60 drilled into Mariana forearc crust. The revolution in how we now think about subduction initiation can perhaps be traced back to this statement by Natland and Tarney (1980, p. 895): "In short, we propose that the Mariana fore-arc region is an in situ ophiolite succession with appropriately thin crust, a reasonably typical velocity structure (probably modified by serpentinization and the extensive faulting that has occurred), and the necessary upper pillowed extrusive sequence overlying appropriate plutonic rocks. It was produced during the early stages of arc volcanism and is not a fragment of ocean crust." Shortly thereafter, geodynamicists started exploring how SI could be accompanied by upper plate extension (Matsumoto and Tomoda, 1983). Thinking continued to evolve in the 1990s as geodynamicists began to model extensional failure of the oceanic lithosphere along long lithospheric weak zones, especially transform faults and fracture zones. Key insights came from studies of the Izu-Bonin-Mariana and other forearcs, made possible because of technological advances in deepwater exploration and by the rise of Asian marine geosciences, especially those of Japan.

Geoscientists began to realize that a large proportion of ophiolites probably formed in an oceanic forearc during SI (Pearce, 2003), opening the door to studying SI products on land. In 2014 and 2017, the International Ocean Discovery Program (IODP) specifically targeted studies of SI processes with expeditions to the IBM convergent plate margin (IODP Expeditions 351, and 352) and one expedition to the Tonga-Kermadec convergent margin (IODP Expedition 371). Both subduction systems began ~52 million years ago, coincident with a major change of Pacific plate motion that was possibly triggered by the initiation of new subduction zones (e.g., Bercovici and Ricard, 2014). Expedition 351 drilling in the IBM backarc discovered that much of what would later become the upper plate experienced strong extension during SI. Expedition 352 to the IBM forearc allowed geoscientists to test ideas about SI by coring and studying magmatic rocks. Expedition 371 showed that significant compression accompanied SI in the SW Pacific, in contrast to IBM SI, where no evidence for SI-related compression has been found. The three communities—marine geoscientists, land geoscientists, and geodynamicists- are now working together to better understand how new subduction zones form and how evidence for ancient SI events can be recognized. Controversy today is focused on whether SI can only occur in response to plate convergence (induced SI; horizontal forcing) or if SI can occur spontaneously (spontaneous SI; vertical forcing). The "Induced SI only" camp can be traced back to McKenzie (1977) and the "Induced and Spontaneous SI" camp can be traced back to Matsumoto and Tomoda (1983) (Authors of this article belong to the Induced and Spontaneous SI camp.) Continued advances can be expected from studies of convergent plate margins at sea, ophiolites on land, and development of increasingly realistic numerical experiments, esp. as 2D models are replaced by 3D models. An overview of SI science can be found in Stern and Gerya (2018); a 13.5 min video summary of this paper can be seen at https://www.youtube.com/watch?time_continue=4&v=SF8HMDV3JgU&feature=emb_logo.

Physical Constraints and Considerations

SI is a physical process and the laws of physics determine its behavior. Most important are physical constraints on rock density and rock strength. Five considerations are especially important: (1) Density of oceanic lithosphere and asthenosphere; (2) Strength of oceanic and continental lithosphere; (3) Presence or formation of long lithospheric weak zones; (4) Rheological weakening processes; and (5) Acting forces. These considerations are explored further below.

1. Density of Lithosphere and Asthenosphere. Plates move mostly because they are pulled by the sinking of oceanic lithosphere in subduction zones (Conrad and Lithgow-Bertelloni, 2004). Hereafter, the terms "buoyant" and "dense" are relative to shallow mantle asthenosphere, which has a characteristic density of $\sim$3250 kg/m^3. Oceanic lithosphere density increases with age because a lithospheric mantle root is progressively added beneath buoyant oceanic crust over time due to cooling and thermal contraction of the aging oceanic plate. For the first few million years after forming at a spreading ridge, oceanic lithosphere is formed mostly of oceanic crust (density of $\sim$2900 kg/m^3); this rests stably on denser asthenosphere. As the lithosphere cools and the mantle root thickens, the density of oceanic lithosphere is increasingly controlled by the thickening and increasing density of its mantle part, which is 1–3% denser than underlying asthenosphere. Lithosphere thus rapidly becomes denser with age and after 10–20 million years is denser than the underlying asthenosphere. Hereafter, oceanic lithosphere is readily subducted (e.g. Korenaga, 2013) except that further key limitations for SI are imposed by the growing strength of the aging lithosphere, as discussed in the next section. The critical subductable age of oceanic lithosphere was likely greater back in geological time due to thicker oceanic crust caused by hotter Earth interior and related larger degree of mantle depletion beneath mid-ocean ridges (e.g., Korenaga, 2013).
2. Strength of oceanic and continental lithosphere. Oceanic lithosphere becomes stronger with age, making it increasingly difficult to bend and break to form a new subduction zone. Already in the late 1970s, the geodynamic community began to quantitatively address the influence of lithospheric strength on SI. The physics of the process was initially considered from the point of view of a plate under compression (e.g., McKenzie, 1977; Mueller and Phillips, 1991) by estimating the minimum force required to start subduction along a pre-existing fault that follows Byerlee's frictional resistance law. These calculations showed that in most cases, the force necessary to overcome the strength of the lithosphere would be nearly an order of magnitude greater than likely geologic stresses. This in turn suggests that subduction would be almost impossible to initiate under compression unless some rheological weakening mechanisms and/or pre-existing weak zones (discussed in the next sections) exist to facilitate SI. It has also been suggested that subduction can start without compression and by breaking of weakened continental rather than ambient oceanic lithosphere (e.g., Nikolaeva et al., 2010).
3. Lithospheric weak zones. Given the strength of oceanic lithosphere, the only way that SI can start is along a lithospheric weakness such as a transform fault or fracture zone. A large mantle plume head could also create a long enough weak zone. The lithospheric weakness must be long because the plate must flex in three dimensions in order for asthenosphere to flood over it at the earliest stages of SI (Zhou et al., 2018). The minimum length of this weakness is 500–1000 km (see animations from Zhou et al., 2018: https://www.geosociety.org/datarepository/2018/2018208%20Animation%20DR1.mp4; https://www.geosociety.org/datarepository/2018/2018208%20Animation%20DR2.mp4; https://www.geosociety.org/datarepository/2018/2018208%20Animation%20DR3.mp4).

   The weakness must also be favorably oriented.

   Subduction initiation across a pre-existing weak zone was initially proposed by Toth and Gurnis (1998) who showed that induced SI can occur with reasonable plate forces if the shear strength of the inherited fault is on the order of 5 MPa or less, which is comparable to the low strength of mature subduction interfaces. Such weakness is significantly lower than that measured for common crustal and mantle rock types and may be explained by the presence of deep percolating pressurized fluids within long-lived fracture zones (e.g., Dymkova and Gerya, 2013) and/or other rheological weakening mechanisms discussed in the next section.
4. Rheological weakening processes. It has been repeatedly suggested that the presence of liquid water on the surface and deep lithosphere hydration are key factors that enable and stabilize subduction on Earth (e.g., Regenauer-Lieb et al., 2001; Hirauchi et al., 2016; Dymkova and Gerya, 2013). Experimental data suggest that friction coefficients of the weakest minerals (sheet silicates such as talc and serpentine) that form by alteration and metamorphism in deep lithospheric faults are significantly larger than required for induced SI (Hirauchi et al., 2016). Somewhat lower friction coefficients have been determined by laboratory experiments for mantle peridotites affected by hydration reactions-induced rheological weakening (Hirauchi et al., 2016). Very low frictional resistance has also been explained by the presence of pressurized percolating fluids (Dymkova and Gerya, 2013) that can drastically reduce effective normal stress on faults. Other proposed rheological weakening mechanisms include thermal weakening of passive continental margins (Nikolaeva et al., 2010), shear heating (e.g., Thielmann and Kaus, 2012; Kiss et al., 2020), grain size reduction (Mulyukova and Bercovici, 2018), seismic weakening (Rice, 2006) and melt-induced weakening (Gerya et al., 2015). In nature, all these weakening mechanisms are likely to combine, thus leading to a composite rheological behavior of the deforming fault rocks driven by multiple feedback mechanisms. Significant fault weakness must exist before SI but further weakening is likely to accompany the process.
5. Acting forces. Forces acting during SI are of key importance since at this early stage there is no yet significant slab pull to drive subduction. Based on acting forces, Stern (2004) subdivided SI mechanisms into induced (i.e., caused by far-field forcing

ongoing plate motion, or changes in plate motion caused by changes in force balance away from the SI site) and spontaneous (i.e., cause by local forcing originating at the SI site and not elsewhere). This classification has been further elaborated by Stern and Gerya (2018 and references therein) as follows:

A) SI induced by far-field forcing from ongoing plate motions and their changes. Two general subclassses of induced SI are envisioned: (A1) compression-induced SI. Styles of induced SI include rupture within an oceanic plate or at a passive margin along a pre-existing or newly formed lithospheric-scale weakness, subduction polarity reversal induced by attempted subduction of buoyant lithosphere, subduction zone transference or "trench jump" following collision and accretion of an arc or oceanic plateau, compression-induced conversion of oceanic transform faults, fracture zones, or STEP (subduction-transform edge propagator) faults into trenches, inversion of spreading ridges to trenches; and (A2) extension-induced SI (tensile decoupling of the continental and oceanic lithosphere due to rifting). A1 forces the lithosphere down whereas A2 allows the dense lithosphere to sink in a manner that is similar to spontaneous SI except that in the first case extension precedes SI whereas in the second case it follows it. Two examples of compressional SI are shown on the left side of Fig. 1. In the case of Transference, collision destroys an existing subduction zone and the existing plate forces cause the oceanic plate on the other side of the colliding block to form a new subduction zone. There are no Cenozoic examples of SI by transference, suggesting that the strength of oceanic lithosphere is too great. The collision of India with Asia beginning ~50 Ma might be expected to have caused a new subduction zone to form southwards in the Indian Ocean but the strength of this oceanic lithosphere has made it easier for India to continue to collide with Asia rather than form a new subduction zone by transference. Indeed, recent migration of compressional deformation to central India has been suggested (Koulakov et al., 2018), as the result of growing resistance inside the Himalayan-Tibetan system. Transference is especially difficult to reproduce with numerical experiments (Tetreault and Buiter, 2012; Vogt and Gerya, 2014). On the other hand, Polarity Reversal seems to happen easily, as supported by reconstruction of geologic events during and after the Miocene collision of the Ontong-Java Plateau with the Solomon Arc. This collision shut down the S-dipping Vitiaz subduction zone along the north flank of the New Hebrides archipelago and formed the New Hebrides trench and the associated N-dipping subduction zone (Cooper and Taylor, 1985).

B) SI caused by local forcing, also called spontaneous SI. Five general subclasses exist: (B1) sedimentary or topographic loading near the continent-oceanic transition (passive margin collapse), (B2) gravitational collapse along an oceanic transform fault or fracture zone caused by a lateral buoyancy contrast between adjacent plates of contrasting thermal and/or compositional structures, (B3) plate loading by convection in the sub-lithospheric mantle, (B4) plate loading and weakening by tectono-magmatic plume-lithosphere interaction, (B5) large meteorite impacts. Meteorites large enough to cause SI were only likely very early in Earth history, in Hadean and perhaps Archean time. Three examples of spontaneous SI are shown on the right side of Fig. 1. A short video about B2 can be watched at https://www.youtube.com/watch?v=Gkx8ldVEgJ8&feature=share&fbclid=IwAR2yMPV0CwfAon1N3JFqfYCKDURfA53rziupke_coy6OBN7mQ1L929RWgFg . A short video about B4 can be watched at https://www.youtube.com/watch?v=Hb47L8S7fMU.

Induced (compressional) SI and spontaneous SI may be distinguished by what happens before one plate begins to subduct beneath another. Because induced SI is caused by existing lateral compression, it should be associated with early compression, uplift, and

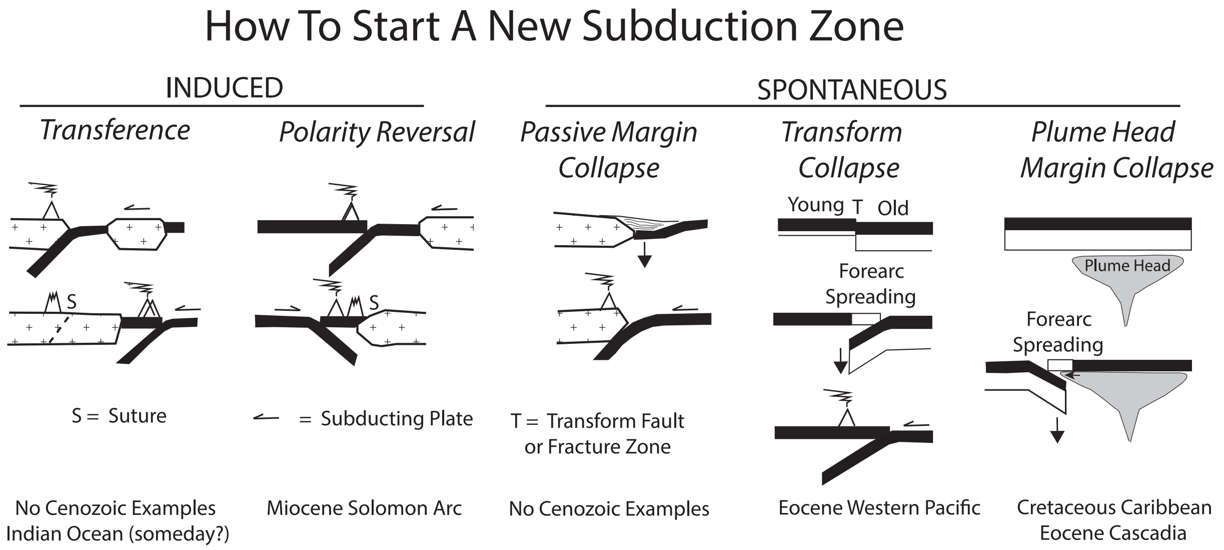

Fig. 1 General classes, subclasses and examples of how subduction zones form. From Stern RJ and Gerya T (2018) Subduction initiation in nature and models: A review. *Tectonophysics* 746: 173–198.

erosion. Early compression does not accompany spontaneous SI; instead, the early stages are strongly extensional, to the point of seafloor spreading above the sinking plate. In nature, acting forces may combine to activate local "sweet spots" where subduction initiation is eased by combination of available forces and lithospheric weaknesses and rheological feedback mechanisms. In modern plate tectonics, such sweet spots are invariably located in oceans or along ocean-continent transitions (Gurnis et al., 2004; Dymkova and Gerya, 2013) as is further discussed in the next section.

The Ease and Difficulty of Making New Subduction Zones

There is a large range of opinions concerning the ease and difficulty of making new subduction zones. Predictions from simple analytical and numerical models based on experimentally defined flow laws emphasize difficulties in creating new subduction zones (e.g., McKenzie, 1977; Mueller and Phillips, 1991), whereas field observations suggest frequent (yet episodic) initiation of new subduction zones in nature via a broad spectrum of SI scenarios. In this respect, a key observation is that of Gurnis et al. (2004), who noted that about a third of all active subduction zones formed in the last 65 Ma, during the Cenozoic. Fig. 2 shows regions where SI has occurred from the Jurassic Period (~200 Ma) and may be occurring today; note that some of these are no longer active subduction zones because continental collision has occurred. This implies that oceanic subduction initiation must be an inherent "easily and frequently" starting process of modern-style plate tectonics. This is an extremely useful thing to know, because we have a high-resolution record of plate motions during this time and so have a better chance to infer the sequence of SI-related processes than can be done for earlier times. We have robust reconstructions of global plate motions extending back to the beginning of the Cenozoic Era (66 Ma) and even earlier (Müller et al., 2016), and these can be interrogated for information concerning the timing and location of subduction zone formation; specifically, the longer the region where SI occurs, the larger the effect on the motion of especially the subducted plate.

Two things are clear from insights: first, that SI is a relatively frequent episodic process in which the net resisting force can be overcome during the normal evolution of oceanic lithosphere; and second, that finding the geologic evidence for understanding how subduction zones formed in the Cenozoic coupled with what we know about the history of global plate motions can provide powerful insights to create realistic, quantitative and predictive global and regional SI models.

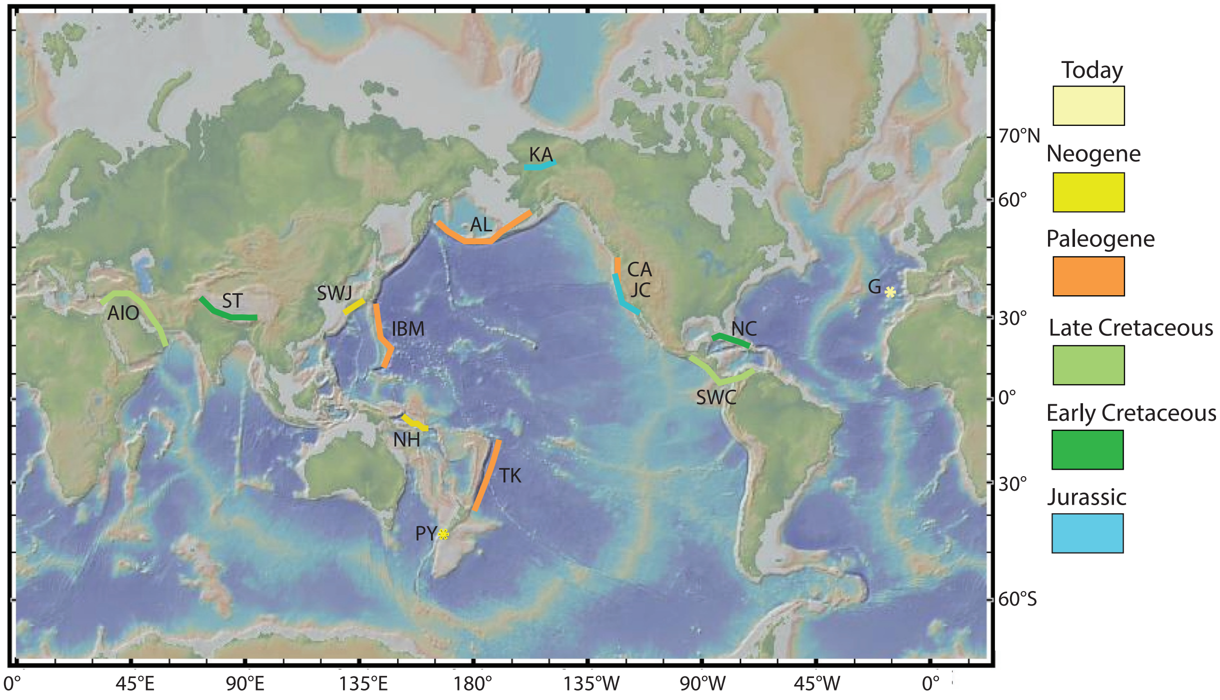

Fig. 2 Examples of subduction initiation, Jurassic and younger, both on land and at sea. *AIO*: Anatolia-Iran-Oman SI, ~100 Ma; *AL*: Aleutian SI, ~46 Ma; *CA*: Cascadia SI, 55 Ma; *G*: Gibraltar SI, today; *IBM*: Izu-Bonin-Mariana SI, 50 Ma; *KA*: Koyukuk SI, 170 Ma; *JC*: Jurassic California SI, 165 Ma; *NC*: North Caribbean SI, ~126 Ma; *NH*: New Hebrides SI, Miocene; *PY*: Puysegur SI, ~10 Ma; *ST*: South Tibet SI, ~125 Ma; *SWC*: SW Caribbean SI, ~100 Ma; *SWJ*: SW Japan SI, 17 Ma; *TK*: Tonga-Kermadec SI, ~50 Ma.

Suggestions for Future Research

Many difficulties exist in both recognizing and characterizing subduction initiation processes in nature. These are related to both poor data accessibility and incomplete understanding of dynamics, signatures, and physical controls of SI, which are very different from those of mature convergent margins. Another complication is that SI happens deep underwater, which is a much more difficult place to study geologically than on land. Another source of uncertainty comes from the fact that very many (>10) potential SI mechanisms have been proposed with only some having been systematically tested in terms of their physical consistency, controlling parameters and observable signatures (e.g., review by Stern and Gerya, 2018 and references therein). One possible solution to these complexities has been recently suggested as a concerted effort of creating the global Subduction Zones Initiation (SZI) database (https://www.szidatabase.org), in which observational data and existing correlations of subduction in initiation sites with surrounding plates structures and kinematic parameters are summarized (Crameri et al., 2020). The database that can be further maintained, updated and explored by systematic high-resolution numerical modeling effort aimed at testing of observed and proposed subduction initiation scenarios (Stern and Gerya, 2018) by realistic 3D high-resolution numerical modeling based on physical properties of mantle and crustal rocks determined from both experimental data (e.g., Hirauchi et al., 2016) and geodynamic inversion calculations (e.g. Baumann and Kaus, 2015). This cross-disciplinary data plus modeling approaches can be used for identifying future prospective SI observation sites (including new IODP drilling locations) that can provide key insights into the governing physics, chemistry and dynamics of past and present subduction initiation processes.

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Further Reading

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