Initiation of subduction in nature and models

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The process of subduction initiation remains enigmatic and controversial. Certain scenarios must lead to subduction initiation and a recent review [1 and references therein] proposes two such scenarios ("induced" and "spontaneous") based on both theoretical considerations and natural data. Induced subduction nucleation may follow continued plate convergence after the jamming of a previously active subduction zone (e.g. due to the arrival of a buoyant crust to the trench). This produces regional compression, uplift and underthrusting that may yield a new subduction zone in a new location. Two subtypes of induced initiation, transference and polarity reversal, are distinguished [1 and references therein]. Transference initiation moves the new subduction zone outboard of the failed one. Polarity reversal initiation also follows collision, but continued convergence in this case results in a new subduction zone forming behind the magmatic arc. Spontaneous nucleation results from the inherent gravitational instability of a sufficiently old oceanic lithosphere compared to the underlying mantle. It is widely accepted [1 and references therein] that subduction can initiate spontaneously either at a transform/fracture zone or at a passive continental/arc margin, in a fashion similar to lithospheric delamination.

Numerous hypotheses have been proposed to explain the physical mechanisms of induced and spontaneous subduction initiation, which largely depend on the tectonic setting [2 and references therein]:

(1) Plate rupture within an oceanic plate or at a passive margin.
(2) Polarity reversal of an existing subduction zone.
(3) Sediment or other topographic loading at continental/arc margins.
(4) Conversion of oceanic transform faults/fracture zones into trenches by forced convergence.
(5) Spontaneous initiation of retreating subduction due to a lateral thermal buoyancy contrast at oceanic fracture zones separating oceanic plates of contrasting ages.
(6) Tensile decoupling of the continental and oceanic lithosphere due to rifting.
(7) Rayleigh-Taylor instability growth due to a lateral thermal/compositional buoyancy contrast within the lithosphere.
(8) Addition of water into the lithosphere.
(9) Spontaneous thrusting of the buoyant continental/arc crust over the oceanic plate.
(10) Small-scale convection in the sub-lithospheric mantle.
(11) Interaction of thermal-chemical plumes with the lithosphere.
(12) Large asteroid impacts.
(13) Shear-heating induced localization along spontaneously forming lithospheric-scale fracture zones.

Indeed, only some of these hypotheses were tested numerically and ambiguity remains about physical consistency of some of the proposed mechanisms. In particular, the problem of subduction initiation at passive margins remains among the long-standing and controversial problems in plate tectonics. Although such initiation features in the classical Willson Cycle description, interestingly there is no irrefutable natural example of such subduction initiation. The numerical experiments of [3,4] suggest that a typical passive margin, with a rifted continental crust thinner than 30-35 km, could transform into an active margin only if its lithosphere is unusually thin (¡ 65-75 km). Combining this conclusion with the finding from [3] that the subduction initiation process is indifferent to the age of the oceanic lithosphere past 20 Ma, one can conclude that passive margins can most easily convert to the active shortly (within some 20 Myr) after break-up, when its lithosphere is still thin and hot. If subduction initiation does not happen during this stage it is unlikely to occur

later due to the cooling and thickening of the lithosphere along the margin wand. This sequence of events explains why mature passive margins are typically very stable [4].

The issue of induced versus spontaneous subduction initiation also remains partially controversial in both nature and within numerical models. As summarized by [5], nearly half of all active subduction zones initiated during the Cenozoic. Furthermore, all subduction zones associated with active back arc extension have initiated since the Eocene, hinting that back arc extension may be intimately associated with an interval (several tens of Myr) following subduction initiation [5]. That such a large proportion of subduction zones are young indicates that subduction initiation is a continuous process during the normal evolution of moving plates [5]. This eludes to the fact that induced subduction initiation should play a dominant role [5], and would be difficult to avoid if tectonic plates remain dynamic. Although they occur within different tectonic settings, four known subduction initiation events (Izu-Bonin-Mariana along a fracture zone, Tonga-Kermadec along an extinct subduction boundary, New Hebrides within a back arc, and Puysegur-Fiordland along a spreading center) were typified by rapid uplift within the forearc, followed by sudden subsidence [5]. This correlates well with the results of 2D numerical experiments that explored incipient compression across a pre-existing plate boundary, and found that the formation of a through-going fault is associated with rapid uplift on the hanging wall and subsidence on the footwall [5]. On the other hand, a number of other thermomechanical models [2 and references therein] suggest that an initial stage of compression is not a prerequisite for the initiation of self-sustaining, retreating subduction, given a sufficient age contrast between plates and width of the weak plate boundary. Further complications may come from three-dimensional aspects of the plate structure near pre-existing fracture zones such as transform faults.

The record of deformation left on the overriding plates can potentially distinguish spontaneous and induced subduction. Induced nucleation begins with strong compression and uplift, whereas a spontaneous nucleation begins with rifting and seafloor spreading [1,5]. However, a lack of known locations for active subduction initiations provides a major obstacle to directly investigating subduction initiation by observation of overriding plate deformation. According to numerical experiments [3,4] subduction initiation at passive continental margins is a long-term process and often has a "hidden" phase of initial slow movements (overthrusting), which are not expressed in typical subduction features such as a pronounced trench and magmatic arc. The main future challenge is, therefore, to identify possible subduction initiation localities worldwide by numerically evaluating the probability of subduction initiation (Figure) at various passive margins and oceanic plate boundaries based on local lithospheric structures and acting tectonic forces [4]. Simulated dynamics of unstable margins and plate boundaries can then be analyzed in order to understand and constrain the key natural observables which should be monitored. In particular, an interesting question concerning subduction initiation is what mechanism can lead to subduction of the Atlantic oceanic lithosphere. Future technical advances will likely be directed toward modeling of subduction initiation in 3D with realistic high-resolution global [6] and regional [7,8] models, including free plate surfaces that can take into account actual plate configurations, the geometry of passive margin, oceanic transform/fracture zones and the distribution of continental/oceanic topography.

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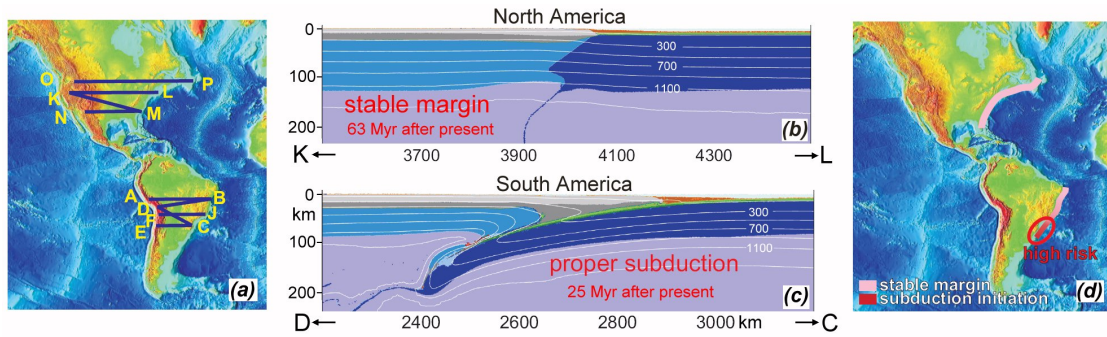
Figure 1: Evaluation of subduction evaluation risk along the Atlantic American margins [4].