What Initiated the Flood Cataclysm?

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Abstract

We report results from a parametric study of various weakening mechanisms that can occur in olivine aggregate materials to help understand how an episode of runaway subduction could be initiated. We use a finite element analysis employing an internal state variable plasticity/damage model to show that temperature contrasts, loading rate, crystallographic damage, water content, and initial anisotropy can all induce significant mechanical instability in olivine rock. Our results indicate that each of these weakening/localization effects may have played an important role in fashioning an initial state for the Earth from which the Flood cataclysm could easily emerge.

Keywords

Localization, Instability, Subduction, Anisotropy, Olivine, Internal State Variable, Constitutive Law

Introduction

Baumgardner (1986, 1990, 1994a, 1994b) has advanced the proposition that the essential process responsible for the large-scale tectonic changes contemporaneous with the Genesis Flood was runaway subduction of the pre-Flood oceanic lithosphere. Precursory to the runaway would be some pattern of stress concentration and shear zone formation in the pre-Flood lithosphere, concentrated at plate boundaries, from which a large-scale runaway event could readily emerge. The question we pose and try to address is: Did God during creation week fashion the earth's lithosphere with built-in internal stresses, zones of weakness, and slow deformations pre-calculated to unleash global tectonic catastrophe on precisely the day Noah and his family would board the Ark, or did God employ other special means to initiate the Flood cataclysm? The question relates to the timing of God's special action. The point here is that God's intervention has frequently been assumed to occur just at the moment of the Flood, for example, near collision of a large comet with the earth, asteroids hitting the earth, rapid earth expansion, or something of that sort. Although some type of catastrophic event *could* have initiated the runaway subduction at the required moment, we illustrate in this paper that finite deformation and creep effects alone, established by God at creation, can account for the onset of the catastrophe. Figure 1 shows the stress-strain relation of a test specimen that has experienced the localization instability and subsequent shear banding and failure. It also shows the corollary to the instability proposed by Baumgardner for the global Flood event. From a material science standpoint the deformational history is very similar for a small specimen test and for the large-scale geodynamical

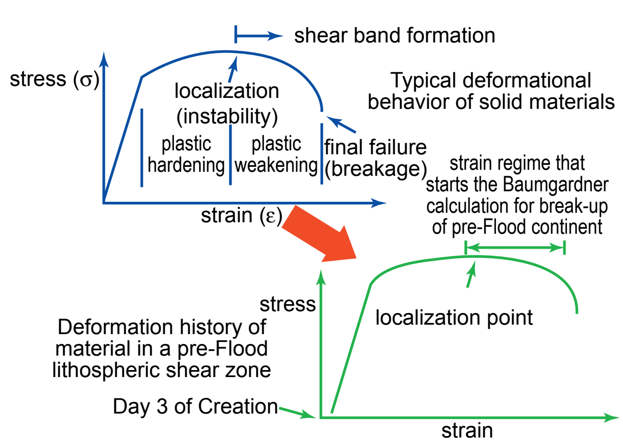

Figure 1. Stress-strain curve illustrating the relationship between how a typical solid deforms under increasing stress and the localization event associated with the onset of catastrophic plate tectonics

event. In this paper, we evaluate mechanisms related to a possible initial stress/strain regime for the mantle that could later have led to mantle runaway. For such built-in conditions at Creation, we quantify the relative strength of various mineral physics instability mechanisms that may have played a role in initiating runaway subduction.

Crucial to our understanding of the nature of the instability is the phenomenon known as **localization**. Localization refers to formation of one or more zones of weakness when a solid is subjected to increasing deformation. When localization takes place, deformation, instead of being more or less uniformly distributed, becomes concentrated in narrow weak zones, sometimes known as shear bands. If deformation proceeds far enough, these localization zones become progressively weaker until the solid fails or breaks. Localization can be associated with at least three phenomena. The first involves thermal softening. This thermo-mechanical instability can arise because deformation results in heating, and heating results in weakening, and weakening results in a focusing of deformation with still higher rates of heating and weakening. The other two mechanisms involve geometric instabilities. One arises from anisotropy, or variation in material properties as a function of direction, that can result from variations in polycrystalline texture. Within a narrow band, one crystallographic slip system can be more favorably oriented for easy deformation than the slip systems in the adjacent material, and that band can become weaker and weaker with increasing deformation. The other arises from the fact that dislocation substructures in the crystalline lattices can coalesce to form microbands that in turn develop into macroscale localization zones, again, with increasing deformation.

Figure 2 shows the relation of a pre-Flood continent, an adjacent zone of subduction, and a local volume of material involved with initiation of the instability. It is this local volume that is the focus of our numerical simulations. Several mechanisms could play a prominent role in this environment. One mechanism involves a temperature differential in adjacent zones with corresponding differences in strain rates despite similar levels of stress. Other mechanisms arise from inhomogeneities common in geomaterials. Differences in mineralogy, grain size, water content, levels of anisotropy, density of lattice defects all can result in a localized focusing of deformation.

Simple material models such as power-law forms, though nonlinear, generally are not robust enough to capture the physical phenomena, particularly localization, that dominate the behavior of solids in many real world situations. By contrast, more complex models, such as the history-dependent internal state variable (ISV) model, are demonstrating considerable success in solving complex boundary value problems in a wide variety of important engineering applications. In this paper we examine the mineral physics instability mechanisms by employing the ISV model embedded in a finite element code (cf. Horstemeyer, 1998). We organize our set of numerical experiments using a typical analysis of variance statistical method called design of experiments (DOE). We then perform the calculations in a simple geometry to quantify effects of the various mechanisms that lead to localization instability.

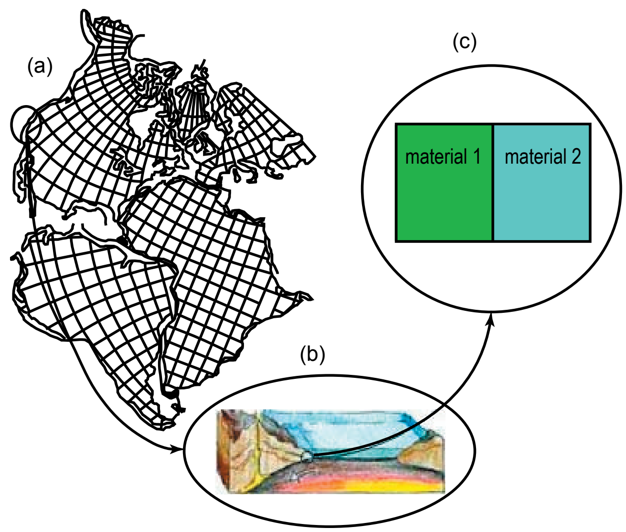

Figure 2. Illustrations of (a) pre-Flood continent, (b) subduction zone, and (c) local material differences at subduction zone.

Parametric Study

To understand the relative importance of the various instability mechanisms that could have induced runaway subduction, we performed a statistical design of experiments study using an L8 orthogonal array. The L8 represents a linear set of equations representing eight "experiments." The L8 array allows up to seven independent parameters with two values for each parameter. The parameters considered in this study were the following: temperature, applied loading rate, whether damage is allowed to develop or not, water content, and initial amount of anisotropy. For the temperature parameter, for example, we assign the two values of 700 K and 900 K.

The earliest works that relate statistical procedures to physical experiments came from Sir Ronald Fisher (1935a, 1935b). In this present DOE study, the "experiments" are not physical but numerical in nature. Statistical numerical studies of this sort have been performed by Horstemeyer (1993) to determine failure using penetration mechanics and by Horstemeyer, McDowell, & McGinty, (1999) to determine parametric effects in a large scale, finite

Table 1. Calculation array showing the parameters for material 2.

Calculation	Temperature	Loading Rate	Damage	Water	Pre-strain
1	900K	1e-4/s	yes	wet	50%
2	900K	1e-6/s	no	dry	50%
3	700K	1e-4/s	no	wet	50%
4	700K	1e-6/s	yes	dry	50%
5	900K	1e-6/s	yes	wet	none
6	900K	1e-4/s	no	dry	none
7	700K	1e-6/s	no	wet	none
8	700K	1e-4/s	yes	dry	none

deformation, visco-plasticity finite element problem.

Figure 3(a) shows the 2-D problem domain for the numerical calculations that consists of two regions containing the same material (polycrystalline olivine) with each region characterized by different properties. This "test sample" undergoes uniaxial tensile loads and is pulled at a uniform rate. Figure 3(b) shows the point in the finite element calculations when, because of developing variations in material strength, the localization instability first appears. At the beginning of the calculation, both regions can be entirely isotropic and homogeneous. But as deformation proceeds, microheterogeneities arise that eventually lead to most of the deformation being concentrated in a narrow zone in the lower region and to dramatic overall weakening of the sample. The deformation history captured in these numerical experiments is intended to relate to the deformation that occurred in the rocks of the earth's lithosphere and mantle from early in creation week until the onset of the Flood cataclysm. In other words, these calculations deal with the history of the rocks *prior* to when Baumgardner (1994b) began his runaway modeling.

Parameters

In this section we describe each of the parameters

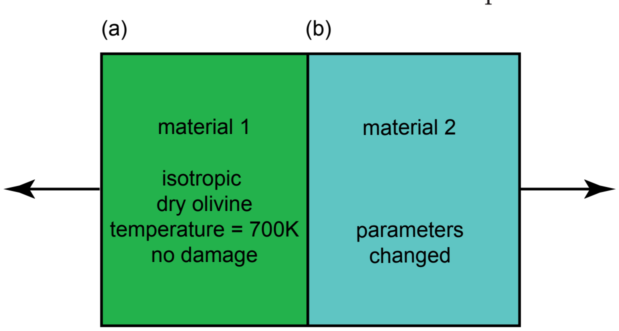

Figure 3. (a) Schematic of finite element calculation with boundary conditions and (b) an example of a results showing the shear stress contours for design of experiment calculation #3 to illustration localization and the following shear band for olivine aggregates at the subduction zone initiation site.

in more detail. Table 1 summarizes each of the parameter values for material 2 shown in Figure 3. We assume material 1 to be isotropic dry olivine with no damage and at a temperature of 700K. Material 1 can therefore be understood to represent a portion of a subducting lithospheric slab and material 2 to represent a portion of an adjacent shear zone. In Baumgardner's simulations, at least two orders of magnitude in strain rate variation are needed to initiate runaway subduction. These studies were conducted with the motivation of comparing mechanisms that could yield such orders of magnitude differences in strain rate.

Temperature

For our parametric study, we assume a 200K differential between material 1 and material 2 for one state and zero difference for the other. This allows us to evaluate the influence a relatively modest 200K differential has on the emergence of localization behavior.

Loading Rate

We chose two mechanical loading rates that vary by two orders of magnitude for this study. Instabilities generally arise from strain rate mismatches in adjacent material, so this parameter was deemed very important to include. We note that our loading rates correspond to inelastic creep rates often quoted in the literature. This point is clarified in Horstemeyer (1999).

A recent study by Albert, Phillips, Dombard, & Brown (2000) examined how varying the loading rate affected the initiation of subduction. These authors used different pressure loads (100 and 150MPa) with three different ramp times to see if subduction could be initiated. For the material model, they used an elasto-visco-plastic model for the lithosphere that was 700km long and 40km thick beneath an elastic lid, with a temperature variation of 273K at the surface to 1073K at the bottom. Their stress state, obtained from their assumed pressure loading histories, yielded strain rates ranging from 1×10^{-16}/sec to 1×10^{-19}/sec. They found 41Myr were required for subduction to occur. These authors did not consider any microstructural variations, such as, water, texture, damage, or pre-strain levels. Their long time requirement emphasizes the urgency for including these mechanisms and accounting for the fact they result in such a strong tendency for instability and consequently a dramatically reduced timescale.

Damage

Okamoto (1989) observed that when a liquid phase exists at mineral grain boundaries or triple junctions, damage growth commonly occurs. Within the context of their study damage refers to porosity, cracks, defects, free water inclusions, or melt phases of olivine. Raj & Chyung (1981) attempted to model damage growth in terms of a modified diffusional creep, but we explicitly include these effects in a phenomenological manner in the ISV model (Horstemeyer, 1998). In geomaterials damage is function of grain rotation, deformation, and breakage of grains (Tada, 1989).

In material 2, we include calculations with and without damage evolution. The damage evolution was assumed to occur as nucleation and growth arising from inelastic (both plasticity and creep) behavior. Although damage itself will not cause instability, it can heighten the ability for material to localize in combination with other mechanisms. Damage does soften the material state though and is itself enhanced when localization occurs.

Water

Polycrystalline olivine can absorb a significant amount of water (cf. Beran & Putnis, 1983) which results in mechanical perturbations in the case of water inclusions and chemical perturbations in the cases of oxygen entering O-sites, leaving free protons that can themselves be trapped at M-site and Si-site vacancies. Whatever the chemical or mechanical setting, water has been shown to significantly increase the strain rate in creep tests (cf. Chopra & Paterson, 1981, 1984; Karato, Paterson, & Fitzgerald, 1986; Mackwell, Kohlstedt, & Paterson, 1985). Paterson (1989) summarized how water can affect rock strength in three different contexts: (a) molecular water aggregates that serve as reservoirs of water that can alter the global stress state, (b) water in solid solution promoting diffusion and hence recovery mechanisms, and (c) water in dislocation cores facilitating glide mobility. All of these water effects are captured phenomenologically in the yield functions, hardening moduli, and dynamic recovery functions of the Bammann ISV model. The material constants for the Bammann ISV model for wet and dry Anita Bay dunite (Chopra & Paterson) have been measured and are given in Horstemeyer (1998).

We apply the experimentally based constants for wet and dry olivine in our parametric study for material (b). There is strong evidence for the presence of water in the subducting oceanic crust as well as in the asthenosphere of today's earth. If this was also true for the pre-Flood world, then it is essential to include these effects of water in our evaluation of localization-induced instability.

In a similar vein, Regenauer-Lieb, Yuen, & Branlund, (2001) studied the importance of water for initiating subduction in relation to sediment piles at passive margins. In their model, the only variable parameter was water content. Their strain rate includes three components: Peierls stress, power-law creep, and diffusional creep that was related to water, temperature, and pressure dependent. Their sediment loading simulations demonstrate the possibility of subduction initiation when the lithosphere is wet. The lower plastic part of the lithosphere could deform as a coupled entity with the elastic upper part when the upper part was wet, whereas when the upper lithosphere was dry, this did not occur. Strain rates in their simulations ranged from 1×10^{-14}/sec to 1×10^{-16}/sec depending on the dry and wet conditions. Their study included only the thermal-mechanical feedback, but further studies could include void-volatile interactions and dynamic recrystallization, which they claim could also induce the subduction instability over time. Hence, they strongly argue that the subduction initiation event required water and this coupled with the thermal-mechanical feedback mechanism could generate a narrow (<600 m) low viscosity shear zone that cuts through the lithosphere.

Pre-strain

When a metal deforms, the complex interactions of the grain structure, lattice orientation, and dislocation substructure produce anisotropy. Of course, some materials such as composite materials or pearlitic steels are inherently anisotropic.

Seismic anisotropy of the earth's mantle has been observed in various tectonic regions (Ando 1984; Fukao 1984; cf. Raitt, Shor, Francis, & Morris, 1969; Shimamura et al., 1983). This anisotropy is a reflection of texture (or fabric) and subgrain formation from dislocation substructures, both of which are caused by deformation of the material. Microstructural studies of deformed olivine and pyroxenes have revealed strongly anisotropic behavior. Karato (1989) concluded that discernable anisotropic behavior occurs from the earth's crust down through the upper mantle and transition zone. An initially isotropic material can develop anisotropic behavior that couples both elasticity and inelastic behavior; hence, when deformations are large, anisotropy can be large as well. Furthermore, various materials in the earth will give rise to different responses under the same deformation; thus, different levels of anisotropy can arise depending on the material. Because of the heterogeneity in the earth, adjacent zones could have different anisotropic states. At a larger scale, for example, say between the lithosphere and asthenosphere, different anisotropic effects can also arise. The anisotropic effects can play a notable role in the stress and strain behavior of the material. One can imagine significant anisotropy existing in the pre-Flood earth, especially as a result of God gathering the waters together into one place and having the dry land appear on Day 3 of creation.

In this study, we assume either no pre-strain and isotropy in material 2, or a level of anisotropy corresponding to 50% initial strain. Pre-Flood continental basement rocks show widespread evidence for huge total deformations, much more than the 50% strain levels that we employ in this study. If deformations were more than 50% strain, then one might expect even stronger effects anisotropic effects than we include.

Results

Figure 4 shows a typical stress-strain curve for the case in which material 2 is wet olivine. The beginning of the simulation (point a) represents the local strain state sometime before Day 3 of creation week with only a small local applied stress. As the applied stress increases, from points a to b to c, one can observe the progressive increase of localization strain. Point c represents a candidate stress state for the end of creation week, probably even at the end of Day 3. The time between creation and the Flood moves the state into the region of localization and instability. This region is where the slope of the stress vs. strain curve is negative. As the stress-strain curve drops off, the weakening has started and the local straining increases as evidenced by point d in Figure 4. This calculation clearly illustrates the weakening effect water plays in the deformational behavior of olivine.

Now that we understand the progression of the localization instability, let us next evaluate the relative importance of the various parameters. Figure 5 shows the normalized values of the localization strains related to the influence of each parameter in the study. Figure 5 illustrates that the loading rate and presence of water give the largest influence in causing instability. Since the loading rate was highest, we can normalize the results by its value such that the loading rate effect corresponds to 1.00 and the effect of water 0.99. The 200 K temperature yields a 0.83 effect, the damage parameter 0.62, and the initial anisotropy 0.59. These results, of course, depend critically on the original parameter values we selected. Had we chosen a 500 K for our temperature difference, temperature would have been the most important parameter. If the pre-strain were assumed to be much larger than 50%, then that parameter might have had the greatest effect.

The motivation for this study was to evaluate the relative importance of various instability mechanisms. Since the weakest had about 0.6 the impact of the strongest, one conclude that all these phenomena can play a comparable role and may

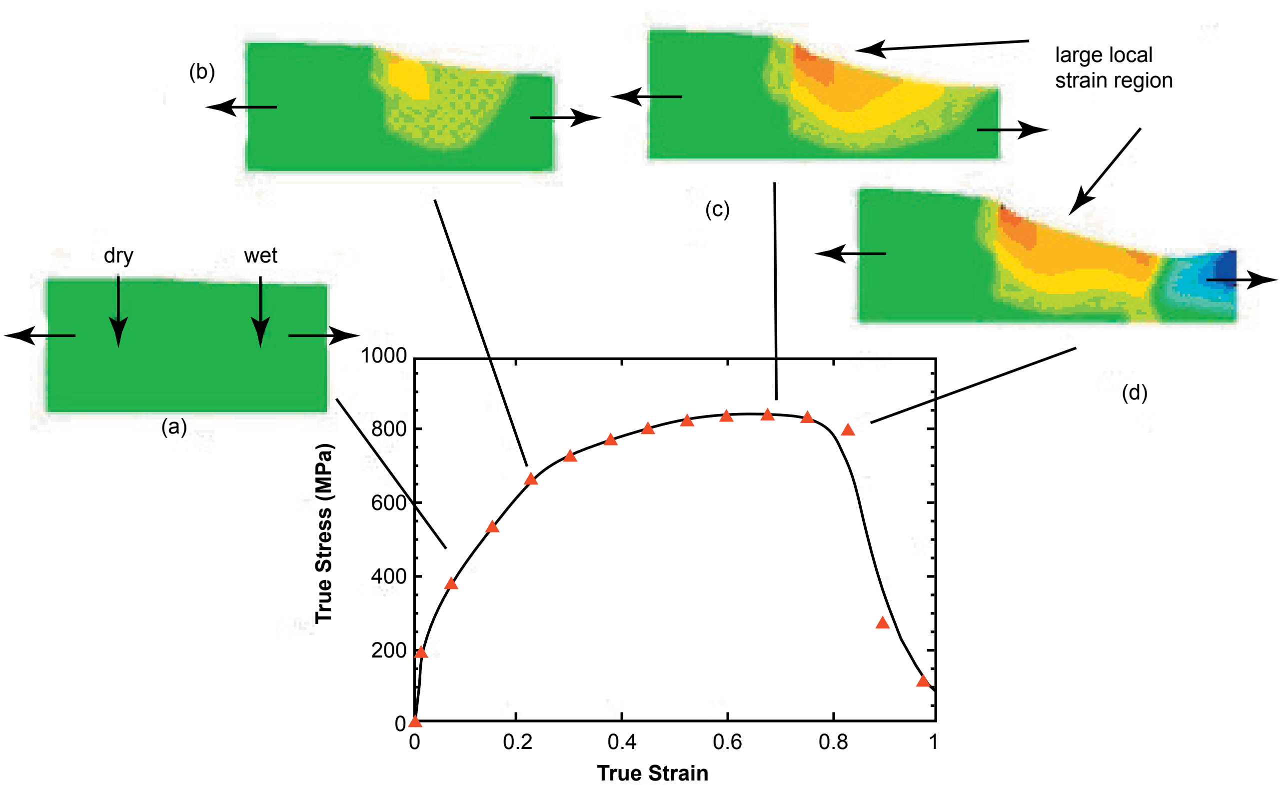

Figure 4. Stress-strain response of local region with dry/wet material with the corresponding strain contours. This illustrates the progression of localized shearing that could have occurred from (a) early period just after Day 3 of Creation Week (b) period represented before global Flood, (c) localization to initiate global Flood, and (d) incipient shear band to start runaway subduction.

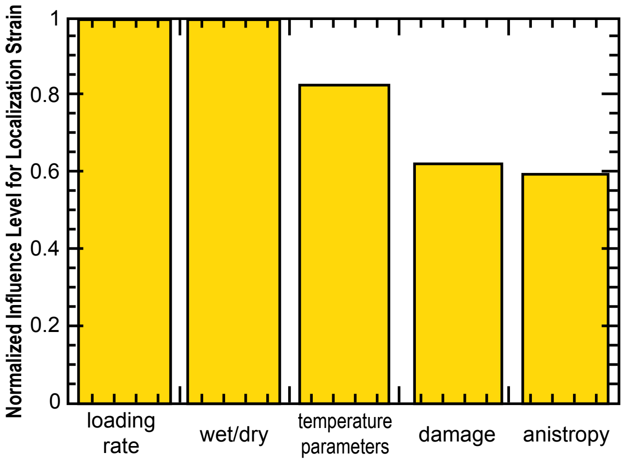

Figure 5. Design of experiments parametric results illustrating the relative importance of each parameter with respect to each other. Note that since all of the parametric effects were on the order of two orders of magnitude difference in strain rate with adjacent material, all of the parameters approximately equally could initiate localization of the subduction zone.

all have contributed to the mechanics of the Flood catastrophe. It is important to remember that each of these effects occurs naturally, with no requirement for special divine intervention. One could imagine that one or a combination of these parameters influenced the localization and subsequent runaway subduction of the lithospheric plates to cause the Genesis Flood. In engineering practice, one, two, or three of these effects typically act in concert to induce localization and failure of the material. We should also emphasize that the mechanisms described in this study also enhance the rate of the immediate post-localization deformation, that is, the rate of the subduction runaway itself.

Mechanisms not included in this study also can enhance instability and post-instability behavior. One such mechanism is that of dynamic recrystallization. Constitutive modeling to date has not incorporated the detailed cause-and-effects of this process. Dynamic recrystallization can indeed occur in the mantle, and when it does, it reduces the grain size. This grain size reduction results in local softening. Yet another mechanism not considered in this study is that of rocks of different mineralogical composition lying adjacent to one another. This also can generate local strength variation and promote instability.

Conclusions

We have shown numerically that several mechanisms can enhance the potential for instability that ultimately led to the Genesis Flood. Recall our question at the beginning: Did God establish conditions in the earth during creation week such that catastrophic plate tectonics would eventually occur at the precise time Noah's day, or did He have to employ additional special means to initiate the cataclysm? Our study suggests it is plausible from a material science standpoint that the earth, as originally created by God, could have been close to the point of instability as far as the state of its lithosphere was concerned, and that during the period between creation and the time of Noah slow deformation was taking place that eventually caused the system to cross the boundary into the regime of full-blown instability and catastrophe. In this case no additional special action was required on God's part for the Flood cataclysm to unfold.

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