Controls on Subduction Thrust Earthquakes: Downdip Changes in Composition and State

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MARGINS Theoretical Institute:"Rheology and Deformation of the Lithosphere at Continental Margins"

A. Introduction

In this presentation I discuss changes downdip on the subduction thrust interface that control whether or not the thrust plane is seismogenic. Of special importance are the controls of the updip limit and downdip limits to the seismogenic zone. The updip or seaward limit is important for tsunami generation. The downdip limit represents the nearest approach of the seismic source zone so is an important factor for earthquake hazard at near coastal cities. The downdip extent of the seismogenic zone (between updip and downdip limits) is the primary control to the maximum magnitude earthquake. A wide seismogenic zone allow great earthquakes such as the S. Alaska M~ 9 earthquake of 1964. A narrow seismogenic zone allows only intermediate magnitude thrust earthquakes such as for the Mariana arc where there are few events larger than about M=7.5. The downdip width of the seismogenic zone also is an important control on the seismic coupling factor, i.e., the fraction of the plate convergence that appears to be accommodated in thrust earthquakes. A related topic is the strength and stress transfer of the subduction thrust.

B. The Limits to the Seismogenic Part of the Subduction Thrust

Figure 1. Composition and temperature limits to the subduction thrust seismogenic zone that generates great earthquakes.

The convergence

between plates at subduction zones is concentrated in a narrow zone at the thrust interface. We conclude that the composition and state of the material along this interface control the seismic behaviour, including great earthquakes and the stress transmitted across the margin. We conclude that the most important change in conditions is the increase in temperature downdip. Depth or effective pressure appear to have only indirect effect on the seismogenic limits. There are important changes in composition and state in both the hanging wall and in the foot wall rocks. The composition of the overlying rocks changes from, (1) accreted sediments in the updip region near the trench, (2) forearc crustal rocks at intermediate depths, (3) overlying forearc mantle rocks downdip from the contact with the forearc Moho. The downdip increase in temperature and pressure results in, (1) change in mineralogy due to metamorphic reactions, (2) upward expulsion of large amounts of water and high formation pressures due to porosity collapse and dehydration reactions, (3) temperature controlled changes in rock rheology from "brittle" to "viscous/plastic". Important observations on the behaviour of the subduction thrust are: (1) the thrust is very weak such as to produce no detectable heat flow anomaly due to frictional heating, and only small stress transmission to the forearc region as inferred from earthquake data, (2) thrust earthquakes, including great events, occur only at intermediate depths (**Figure 1**). There is an aseismic updip zone of variable width (0-100 km width, up to ~5 km depth).

The Updip Aseismic Zone

Many explanations have been given for the updip aseismic zone. These include: (a) change in physical properties with depth, especially the change from unconsolidated accretionary prism sediments to forearc crustal rocks, (b) increasing pore pressure with depth, (c) temperature controlled changes in mineralogy, especially the dehydration of stable-sliding clays. Detailed examination of a number of subduction zones has resulted in the conclusion that the updip limits correspond to a critical temperature of 100-150°C, not to depth (pressure) or to changes in the composition of the overlying material. We therefore favour the latter explanation. Stable-sliding clays is our favoured explanation, but there are a number of other possible temperature-controlled chemical/mineralogical changes. This explanation also has been proposed for the aseismic behaviour of the upper part of San Andreas transform fault. Aseismic smectite clays occur either in underthrust sediments or are formed by shearing in the fault gouge zone. Such clays dehydrate to probably seismic chlorite/illite at 100-150°C. This temperature occurs on the thrust near the trench for hot subduction zones such as Cascadia and as much as 100 km landward for margins subducting old cold oceanic crust such as S. Alaska and N. Japan.

The Downdip Aseismic Zone

The subduction thrust is aseismic below a depth that varies from about 10 km to 50 km in different subduction zones. The two main downdip changes that affect seismic behaviour appear to be, (1) temperature-controlled change from seismic (velocity weakening) to aseismic (velocity strengthening) that occurs at about 350°C for crustal composition rocks. This limit is seen in the maximum depth of crustal earthquakes which is commonly where the temperature is estimated to be about 350°C. There may be a transition zone from 350 to 450°C within which rupture, initiated at shallower depth, continues downdip with decreasing slip offset. There is a rapid rise in instantaneous shear strength above about 450°C for felsic rocks. The transition from "brittle" to "ductile" deformation of crustal rocks occurs at approximately 450°C, not at the velocity weakening seismic limit of about 350°C. The 350°C temperature and the seismic limit occur on the thrust as shallow as 15 km for very hot subduction zones and as deep as 100 km for cold subduction zones. (2) Serpentinite and related stable-sliding minerals formed through hydration of the forearc mantle by fluids driven off the downgoing plate. Such hydrated minerals are expected to be weak and aseismic. There also are geochemical arguments for a thin layer of very weak talc at the thrust boundary with the forearc mantle. Hydrated mantle serpentinite will be transformed to talc by the infiltration of SiO_2 in fluids driven from underthrust siliceous underthrust sediments and from the underlying oceanic crust with increasing temperature and pressure. Note the simplification: *"wet crustal rocks are seismic, wet mantle rocks are aseismic"*.

Subduction Thrust Temperatures

Because two of the three suggested seismogenic zone limits are temperature controlled, we have calculated accurate thrust temperatures on profiles across a number of subduction zones including Cascadia, S.W. Japan, N. Japan, Chile, S. Alaska, and the Aleutian arc. There are large variations among subduction zones and along strike for individual subduction zones. Simple analytic solutions to the thermal regime are often not adequate approximations. We have used finite element modelling with careful specification of local model parameters for each subduction zone cross-section. The important model parameters include, (1) the thrust dip profile (planar approximations are not adequate), (2) the age of the subducting plate (and its age history), (3) the subduction rates and durations, (4) the effect of insulating sediment on incoming crust (for example for Cascadia, just landward of the deformation front the thrust is at ~250°C), (5) overlying forearc crust radioactive heat generation, (6) the thermal properties of each of the main geological elements. An example of the cross-section and the model thrust temperatures for the hot N. Cascadia subduction zone is given in the lower figure. The predicted heat flow across the margin is compared to observations in the upper figure. The temperatures for the cold subduction zones such as N. Japan are very much lower, with 350°C being reached at depths as great at

Figure 2 (lower) Cross-section of N. Cascadia showing the positions of the critical temperatures 100-150°C, 350°C and 450°C from numerical model. These temperatures are reached at an unusually shallow depth for this margin because of the young age of the subducting lithosphere. (upper) Heat flow measurements compared to predictions of the numerical model.

100 km. The locations on the thrusts of 100-150°C usually are not well constrained because the isotherms intersect the subduction thrust at a shallow angle. The locations of 350°C are usually better defined.

Subduction Zone Examples; Comparison of Predictions with Observed Rupture Limits

The updip and downdip limits predicted by our models have been compared to the limits of the seismogenic zone in a number of subduction zones, Cascadia, S.W. Japan, N. Japan, Chile, S. Alaska, and the Aleutian arc. The seismogenic limits come from, (1) waveform modelling of great earthquake seismic data, (2) the updip and downdip limits of great earthquake aftershocks, (3) the seaward updip limit from modelling of tsunami wave data, (4)the downdip limit of intermediate magnitude thrust earthquakes, (5) the downdip limit from elastic dislocation modelling of geodetic measurements of coseismic deformation,

(6) dislocation modelling of interseismic data to define the interseismic locked zone that may rupture in future thrust earthquakes. These constraints all measure different things, but the limits from the different methods are very similar. The updip temperature limit of 100-150°C approximately corresponds to the subduction thrust updip seismogenic limits for all of the subduction zones studied, based on earthquake, tsunami and geodetic data. However, the uncertainties are quite large in both the updip part of the thermal models, and the estimated updip seismogenic limits.

Our studies of these margins shows that the downdip limit of thrust earthquake rupture appears to correspond to whichever occurs first, the 350°C crustal thermal limit, or the intersection of the thrust with aseismic hydrated forearc mantle. The forearc mantle is at a depth of 30-50 km for subduction beneath most continents but is as shallow as 10 km for some island arcs such as the Marianas.

The general weakness of subduction thrusts may result from clays in the updip zone, high pore pressure at intermediate depths, and serpentinite and talc at greater depths. On a larger scale, although the forearc crust is strong because of the very low temperatures, the forearc mantle may be weak due to the presence of hydrated mineral assemblages.

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