Why do some subduction zones have M9 earthquakes and others less than M7.5? Composition and state variations on the subduction thrust

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The maximum size of subduction earthquakes is an important scientific question and a critical earthquake hazard issue. Some subduction zones have had M~9 earthquakes, NE Japan, Chile, Sumatra, etc. and some M<7.5 such as the Mariana and several other west Pacific island arcs. Of course we need to be cautious a M7.5 maximum (Mx) based on known past events since M9 earthquakes can have return times of over 600 yrs (i.e, recent NE Japan megathrust). We could be more confident if we are able to identify a physical explanation for the two Mx types. With this caution I will assume that the estimates of maximum magnitude difference are valid. At the end I give a few notes on addressing this question by drilling, seismic surveys, and other studies off New Zealand, Cascadia, and elsewhere. This topic addresses GeoPRISMS objectives of: societal impacts, and under Subduction Cycles and Deformation, "strain buildup and release along the plate boundary" and "release of volatiles such as H2O and CO2".

Seismic Coupling and Seismic Efficiency

Two expressions are closely related to maximum magnitude, "seismic coupling ratio" or seismic efficiency, and the downdip extent of the seismogenic zone. Seismic coupling (see Wang and Dixon, 2004 EOS) here is defined as the fraction of the plate convergence that is accommodated by thrust earthquakes (i.e., seismic moment) compared to aseismic motion (the degree of "locking" is another sometimes confusing expression). I note the problem of tsunami earthquakes, where rupture is too slow for much seismic energy but that can generate large tsunamis. The coupling ratio involves a down-dip seismogenic width, sometimes taken to be from the trench to a common observed limit of 30-40 km. In fact, the seismogenic width can vary considerably (discussion below) and a low coupling ratio can simply be the result of a very shallow downdip limit. The main other way of viewing a low seismic coupling is that there are patches on the thrust that are seismic and areas that move aseismically. For lower coupling subduction zones, there are several suggestions for variable seismic and aseismic patches. There may be slippery material like serpentinite/talc on the thrust (discussed below) with "coupled" patches such as subducted seamounts (see Wang and Bilek, 2011, Geology; Kodaira

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et al., 2000, Science), or there may be areas of higher and lower pore pressure. The subduction zone stress regime also has been suggested as an important factor. However, it is now recognized that most if not all subduction thrusts are very weak, similar to San Andreas fault, so regional tectonic stress variations are unlikely to be a critical factor.

GPS and other geodetic data are now giving us some indication of "coupling" for the landward parts of an increasing number of subduction zones. The majority of margins that have had M9 earthquakes appear to be mainly "fully coupled", although there are interesting exceptions. For example the central part of the M9 1964 Alaska earthquake that had less slip than adjacent areas has less inferred "coupling" based on GPS data. Unfortunately, most west Pacific island arcs like the Mariana where there have been only <M7.5 earthquakes have backarc spreading and it is difficult to separate steady spreading motion from elastic strain buildup in the GPS signal. However, it should be possible to separate the two signals with careful analysis of land data; this is well worth pursuing. Difficult seafloor GPS is the sure way to allow the separation of the two signals.

Updip and Downdip Limits of Seismogenic Zone

The updip and downdip limits of the seismogenic zone are an important control of maximum magnitude. Also, the downdip limit represents the closest approach of the seismic source and therefore the ground motion and earthquake hazard at near coastal cities. The updip limit strongly affects the tsunami generation. Most subduction zones that have had M9 earthquakes appear to have a deep downdip limit, 30-40 km, whereas the Mariana and other island arcs with Mx<7.5 appear to have shallow maximum depth thrust events, less than 10 km for Mariana (see Pacheco et al., 1993, JGR). If the downdip limit is so shallow that it approachs or overlaps the updip limit, very large thrust earthquakes are not possible. This is one explanation for the small maximum magnitude of these island arc subduction zones (see Hyndman,Yamano, Oleskevich, 2006, Island Arc).

The updip limit of great earthquake rupture (usually defined by aftershocks) is commonly some 10's of km landward of the trench. The first reasonable explanation was that the accretionary prism may be aseismic, but it is now recognized that some great earthquakes occur completely under the accretionary prisms. The second explanation was that the limit was controlled by the smectite-illite clay transition, but this too has been discounted (e.g. Saffer and Marone, 2003, EPSL). So we still do not have a satisfactory explanation but downdip temperature-dependent physical and chemical changes are likely the origin of this limit.
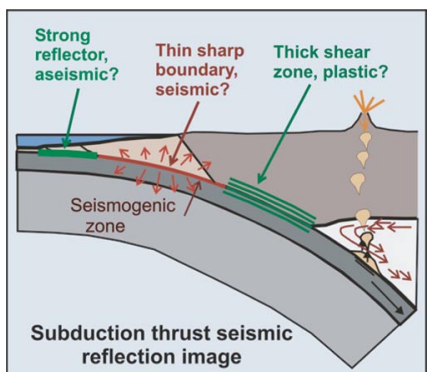
For the downdip limit, there are a number of possibilities, several are: (1) Maximum temperature for seismic behaviour in felsic rocks of about 350C from laboratory data. This temperature seems to apply for the San Andreas and other continental faults. The temperature is reached at great depth for most subduction zones with the exception of those that are subducting young and hot

oceanic plates such as SW Japan, Cascadia, Mexico, etc. where it is at 20-30 km depth. For these, it is probably the controlling mechanism. For one area of Cascadia there appears to be a change in thrust character from thin seismic to thick ductile (Nedimovic et al., 2003, Science), as sometimes observed at the thermally controlled "brittle-ductile" transition in exposed continental faults. Bell et al., (2009, GJI) examined the reflection character of the Hikurangi thrust and found substantial spatial variations. However, the Cascadia-type downdip transition is not expected in this cool subduction zone.
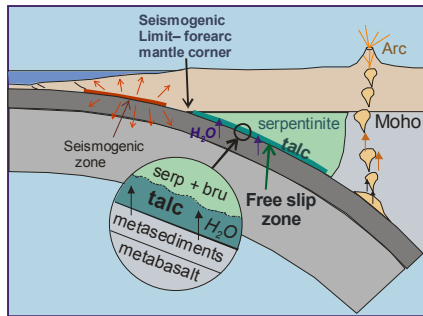
(2) The forearc mantle corner. At this point the thrust is overlain by forearc mantle that is expected to be serpentinized by fluids being driven off the downgoing plate by increasing heat and pressure (e.g., Peacock and Hyndman, 1999, GRL). The structure of serpentinite suggests that it is aseismic, but this is still debated. However, the rising fluids also should be silica saturated resulting in talc on the thrust; talc is exceptionally weak and is unlikely to be able to support elastic strain build-up and earthquake rupture. An important observation has been serpentinite and talc on the San Andreas fault, notably in the SAFOD borehole where the fault is creeping.The forearc mantle corner is usually poorly determined but generally is at a depth of 30-40 km, a common maximum depth for great thrust earthquake rupture. Several subduction zones appear to have seismic behaviour to slightly greater depths but it is not clear if this is due to structural complexity or areas such as subducted seamounts were there is not serpentinite/talc on the thrust. There is now some evidence that the updip limit of ETS slow slip occurs at the forearc mantle corner. The slow slip therefore may be associated with the serpentinite/talc.

In west Pacific subduction zones like Mariana where the maximum magnitude if often less than M7.5, it has been argued that the updip limit and downdip limit may overlap so there is a minimal seismogenic zone (e.g., Hyndman et al., 2006, Island Arc). This is because these may have oceanic crust in the forearc (perhaps thickened) only 5-10 km thick, so the forearc mantle corner may be this shallow and the downdip seismogenic limit very shallow. An important observation in several of these subduction zones is serpentinite diapirs reaching the surface a few 10's km from the trench. They may be over the shallow forearc mantle corner. In any case, their occurrence indicates the likelihood of serpentinite/talc on the thrust only a short distance downdip landward from the trench. With a common width updip aseismic zone, the seismogenic zone is very narrow and only small maximum magnitudes are possible.

Short Margin-Parallel Extent for Subduction Thrust Earthquakes

The maximum magnitude of subduction thrust earthquakes is limited by the along-margin extent. Some margins have events that extend long distances along the margin (Cascadia is a good example) whereas others have short lateral extents not much more than the downdip extent. Some possibilities for the difference are stress concentrators due to roughness of the incoming plate, seamounts, normal faulting structures, aseismic ridges, etc. (see Wang and Bilek, 2011, Geology; Kodaira et al., 2000, Science). Large accretionary sedimentary prisms may provide a smooth thrust surface with few stress concentrators that start and stop rupture.

Patchy Seismic and Aseismic Zones on the Subduction Thrust

The other way that small maximum magnitudes may be explained is through patchy seismic and aseismic zones on the subduction thrust. The "patchy" locked and rupture areas
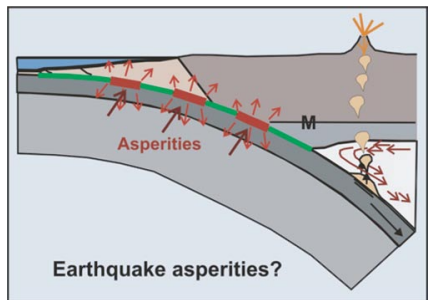
may be small fraction of total area that is mainly aseismic. Sheared off seamounts are one type of localization. Subducted sediments also may isolate the thrust from aseismic mantle serpentinite/talc. One possibility is that the incoming oceanic crust contains substantial serpentinite that may be in the footwall of the subduction thrust and that is smeared out along the thrust making it largely aseismic. Peridotite and serpentinite are surprisingly common in DSDP/ODP/IODP ocean crustal core samples. Only a few small special areas then may be seismic, rather like the situation of the creeping section of the San Andreas fault which exhibits numerous small earthquakes.

For a previous relevant discussion see: Hyndman, 2007, The seismogenic zone of subduction thrust faults: What we know and don't know, Columbia Univ. Press.

New Zealand Tests of Hypotheses for Maximum Magnitude Controls.

1. 3D multichannel seismic reflection surveys to map in detail variations in thrust interface character associated with inferred seismic ("locked") and aseismic areas (creeping?) (extension of Bell et al., 2009, GJI, Hikurangi thrust reflection character study).

2. Drilling of subduction thrust to see if serpentinite/talc is present in aseismic area, as found for creeping section of San Andreas fault (in SAFOD borehole; Moore and Rymer,2007, *Nature* **448**, 795-797)) compared to inferred locked Hikurangi area.

3. Detailed mapping and sampling of the incoming oceanic plate to see if there are occurrences of serpentinite in the crust.

4. Detailed mapping of location of forearc mantle corner, compared to landward limit of GPS-inferred locked zone.