In situ stress and pore pressure magnitude along subduction zone megathrusts: Integration of laboratory, drilling, geophysical and numerical modeling approaches

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At subduction zones, mechanical loading due to burial and tectonic compression, in combination with the release of bound fluids by dehydration, can drive fluid pressures significantly in excess of hydrostatic. The resulting fluid overpressure drives flow and volatile transport through the forearc, and ultimately affects the strength of fault zones and wall rock, thus mediating in situ stress magnitudes, seismic behavior, and deformation style. Recent advances in documenting pore fluid pressure and effective stress magnitudes at convergent margins have come from drilling, seismic reflection surveys, and numerical modeling. Boreholes penetrating across the plate boundary at several subduction complexes, including Nankai, Costa Rica, and Barbados, have allowed quantification of effective stress and pore fluid pressure from observed compaction state and from laboratory reconsolidation tests on core samples. Likewise, drilling efforts coupled with laboratory measurements of rock strength have also yielded new estimates of in situ horizontal stress magnitude defined on the basis of wellbore failures and direct hydrofracturing experiments. At larger scales, pore pressure and horizontal stress magnitudes have been quantified using P-wave interval velocities from seismic reflection surveys, by application of laboratory- and field-based transforms linking velocity, porosity, and stress state. Numerical models, constrained by laboratory and drilling measurements, provide additional independent constraints on regional-scale pore pressure distribution. Finally, new and ongoing sub-seafloor observatory installations provide direct in situ measurements that serve as essential “ground truth”, while also documenting temporal variations in stress, strain, and pressure.

In total, these approaches show that low effective stress and highly elevated pore pressure (pore pressure ratios of $\lambda = \sim 0.70–0.95$) are common in the vicinity of the subduction megathrust at several margins, and that these conditions extend at least 30-40 km landward of the trench. In some cases, increased seismic reflectivity along the plate boundary is also correlated with regions of expected dehydration reactions or locations of high pore pressure estimated from numerical models, although this link remains unquantified and the underlying cause of the reflectivity is not fully understood. A simple non-dimensional analysis suggests that, globally, elevated pore pressure – and thus mechanical weakness - results from a dynamic balance between (a) geologic forcing that acts to drive pore pressure generation, and (b) hydraulic conductivity and drainage path length, which mediate fluid escape. Taken together, these findings provide a robust, quantifiable, and universal framework for understanding the role of fluids in the absolute strength of subduction megathrusts beneath the outer forearc. The high excess pore pressures and concomitant low effective stresses should suppress the nucleation of unstable slip, consistent with observations of fault failure by slow slip, afterslip, and very low-frequency earthquakes (VLFE) common to this region. Additionally, the low absolute strength of the plate boundary near its trenchward edge may offer an explanation for the propagation of rupture from below, potentially allowing coseismic slip all the way to the trench. Finally, in situ indicators of stress magnitude and orientation suggest that both horizontal stresses and slip on splay thrust faults are transient, and likely tied to the seismic cycle.

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