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Megathrust Earthquake Cycles: Linking Paleogeodesy Observations with Geodynamic Models

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The use of geologic records of crustal motions (Paleogeodesy) is becoming a more important component of earthquake hazard analyses in subduction zone systems. Inherent in the linking of these data with geodynamic models of the earthquake cycle to unravel details of plate boundary coupling is (a) an understanding of the conditions under which the geologic record is produced and preserved, and (b) how the expected pattern of vertical motions vary in time and space within the upper plate of subduction zones. Recent geodynamic models of crustal deformation in response to the earthquake cycle in megathrust systems show that small variations in the location of the observing site and the time scale implicit in those observations will have a large effect on the nature of the signal and its utility in defining megathrust processes such as coupling and rupture. The earthquake cycle produces distinctive patterns of crustal displacements - typically observable in the upper plate of the system - that reflect details of the pattern of plate coupling and rupture behavior. Patterns of horizontal deformation are relatively simple with the distribution of trenchward and landward motions depending on the interplay between the elastic loading/unloading signal combined with a transient post earthquake signal resulting from visco-elastic relaxation. The patterns of the vertical motions are more complex with the direction of motion (up/down), its amplitude, and rate varying in space and time as the system proceeds through the earthquake cycle. In contrast to horizontal motions, which tend to be smoothly varying, vertical motions undergo abrupt changes in character depending on position (particularly with respect to the down-dip extent of locking - both interseismic and co-seismic). This makes observations of vertical motions complicated but potentially more diagnostic of parameters such as interface coupling and rupture. Observed vertical motions, preserved in the geologic record, reflect some combination of coseismic and short-term post-seismic motions (including after-slip and early viscous relaxation), both of which vary significantly in the upper plate in the vicinity of the down-dip limit on the megathrust of coupling and rupture. Models utilizing only elastic models of co-seismic motions are likely to mis-estimate fault slip or the extent of fault rupture. Here we explore the implications of these effects for recent analyses of paleo-geodesy from great earthquake events such as 1700 Cascadia, 2004 Banda Aceh, and 2011 Tohoku.