Class Notes

on

Wadati Benioff zone and related stress states

Part of subject GPM 202 Seismology

by

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General

Studies of the seismic activities on the surface of the earth have contributed significantly to recent theory of global tectonics. Seismic phenomena are generally explained as a result of interaction of lithospheric plates. Subduction zones are the most seismically active areas on the earth. Earthquakes occur to depths of up to 700 km (upper to lower mantle transition); the distribution of earthquakes is used to define the shape of the subducting slab. In Island arc, the seismic activity is observed to be dipping to depth up to 700 km. This phenomenon was first pointed out by Berrioff and hence the dipping zone of subducting slab is called the *Benioff zone*. The distribution of hypocentre of earthquakes > 400 km indicates that the subducting zone i.e. lithospheric slab is deformed at these depths. The nature of the subducted lithospheric slab is shown in Figs 1-4. The stronger the interaction of colliding plates the higher seismic activity would be expected. The number of earthquakes observed in the Benioff zone may be controlled by-

1. The plate convergence rate
2. Age of the subduction plate
3. The Barrioff Zone dip angle
4. The length of the slab

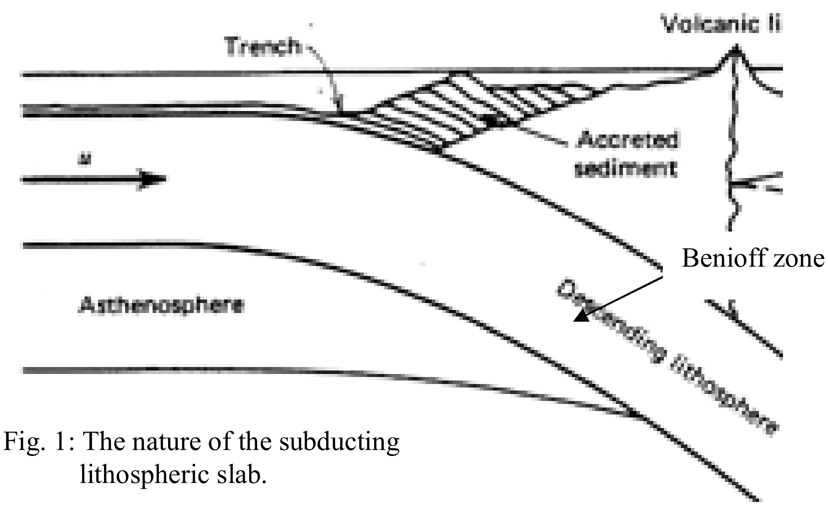

Fig. 1: The nature of the subducting lithospheric slab.

Note that

- the geometry of Benioff zones is very variable and depends on the age of the subducting lithosphere, the geological setting at the surface of the subduction zone and the plate speed; and
- both compressional and extensional earthquakes are observed.

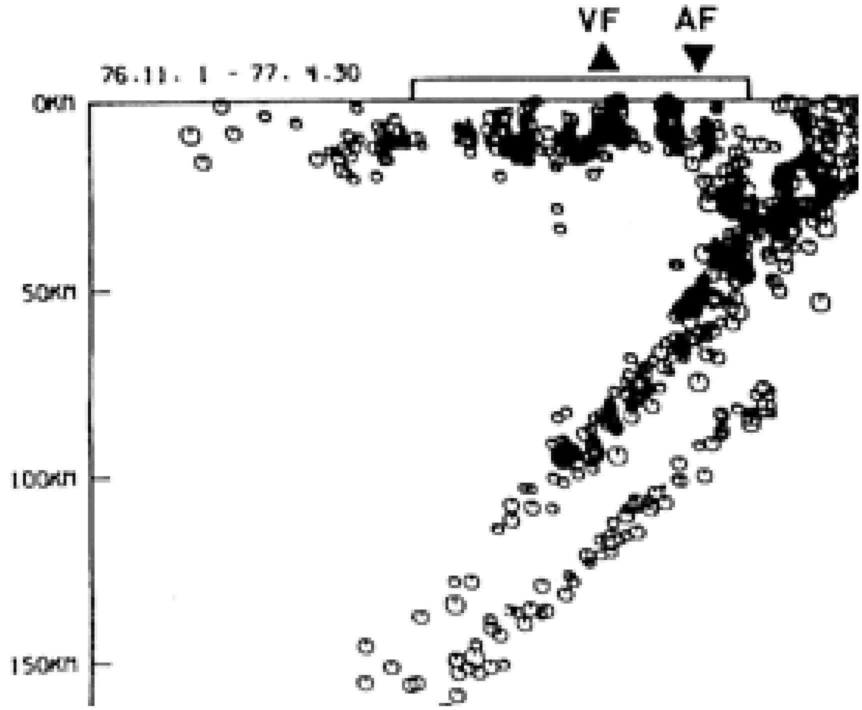

Fig. 2: The Wadati-Benioff zone under northern Honshu, Japan, showing two parallel planes of earthquake loci. VF indicates the volcanic front, at the center of the land area (from Hasegawa, 1989).

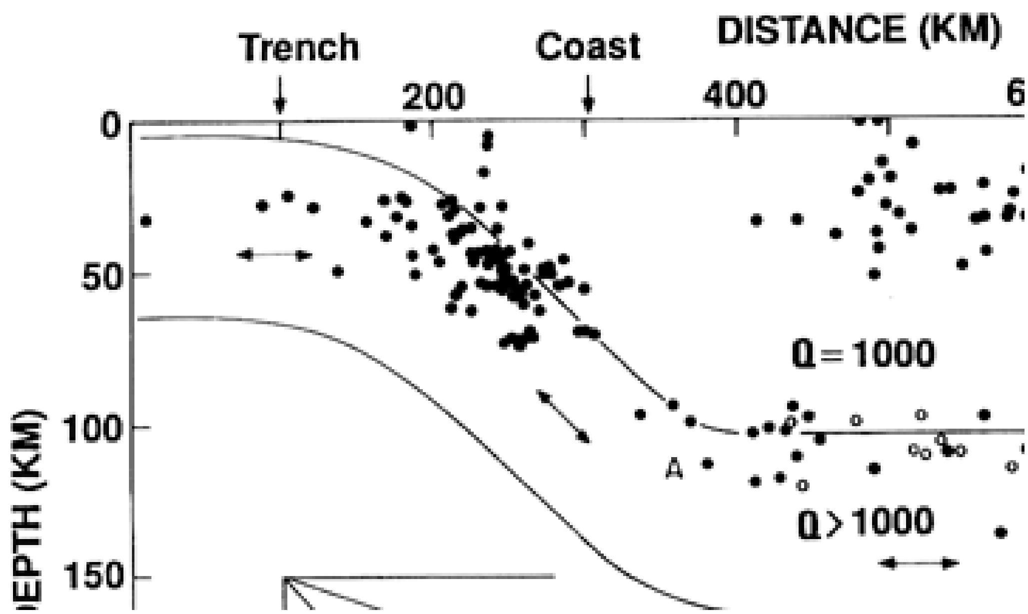

Fig. 3: A cross-section of the Wadati-Benioff zone under central Peru, showing evidence of 300 km of "horizontal subduction" (from Shneider and Sacks, 1992).

The fact that the Nazca plate which is plunging under Central Peru is relatively young and, therefore, less negatively buoyant than more mature lithospehre, may partly explain the pattern of subduction (Fig. 3). Along the top plane, compression is dominant which corresponds to the top of the subduction slab experiencing drag from the overlying mantle; along the lower plane, extension is dominant which corresponds to the middle part of the slab failing in extension due to its negative buoyancy.

Stress distribution in descending lithosphere slab

Usually compressive mechanisms dominate for the deepest earthquakes (depths > 300-350 km). This is due in part to the increased resistance to slab penetration in response to higher mantle viscosity; and in part to the presence of the olivine-spinel phase change. Stresses acting on subducting lithospheric plate are shown in Fig. 4. In (a), (b) and (d), the extensional stresses in the upper part of the plate are due to the slab being pulled into the low strength Asthermosphere. In the second case i.e. (b) the resistance of the more rigid layer under the asthermosphere causes compressions within the lower part of the slab. If the plate sinks further down, the stress becomes compressional throughout as in (c). In some cases as in (d), the deeper part of the lower slab may break off.

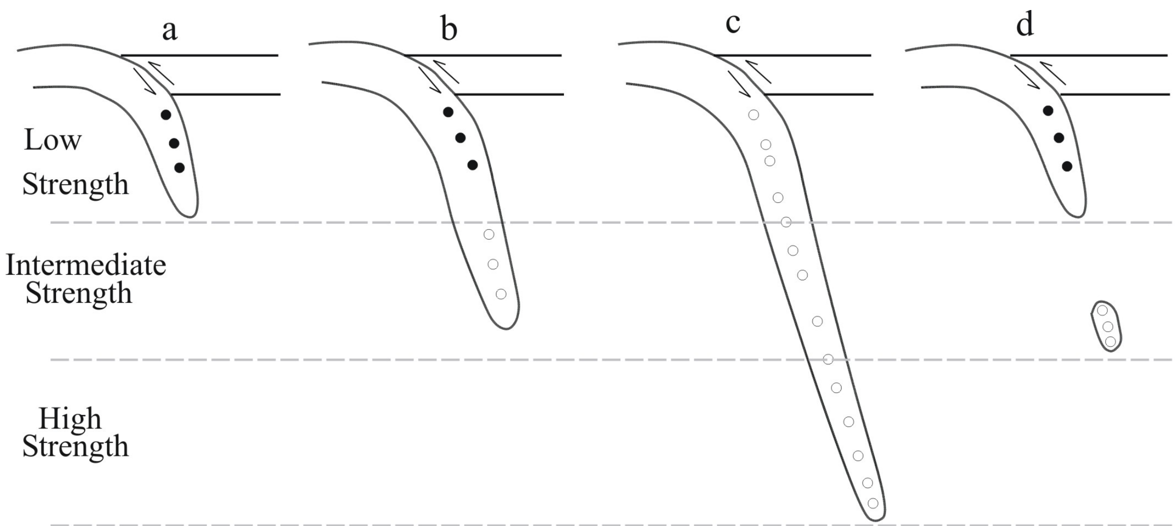

Fig. 4: The stresses acting on subducting lithospheric plate. Solid circle denotes extension and open circles compressions.

The earthquake activity of the downgoing slab occurs as a result of three distinct processes as shown in Fig. 6. In region 'a' earthquakes are generated in response to the bending of the lithosphere as it begins its descent. Downward flexure of the lithosphere throws the upper surface of the plate into tension, and the normal faulting associated with this stress regime gives rise to the observed earthquakes, which occur to depths of up to 25 km. The region 'b' is characterized by earthquakes generated from thrust faulting along the contact between overriding and underthrusting plates. In this process, the overriding plate suffers compressional deformation for several tens of kilometers to the landward side of trench. The 'b' portion of the downgoing slab is associated with thrust type of faulting. The 'c' portion is the Benioff zone of the downgoing slab. The earthquakes occurring in this part of the Benioff zone at depths greater than the thickness of the lithosphere at the surface are not generated by thrusting at the top of the descending plate, because the asthenosphere in contact with the plate is too weak to support the stresses necessary for extensive faulting. At these depths, earthquakes occur as a result of the internal deformation of the strong descending slab of lithosphere, so that the majority of events lie about 30-40 km beneath the top of the slab. The presence of earthquakes at depths in excess of 70 km is paradoxical because below this level the high pressure causes materials to flow rather than fracture. From 70 to 300 km, it appears that faulting occurs during the rapid dehydration of *serpentinite*. Below 300 km the earthquake mechanism is believed to be the sudden phase change from olivine to spinel, known *as transformational* or *anticrack faulting*. The change to spinel is probably complete by a depth of about 700 km, explaining the termination of subduction zone seismicity at this depth. Unlike the shallow events of region 'a' and 'b' in Fig. 6 where principal stress directions are horizontal or vertical, the deep events of region 'c' are characterized by principal stress directions which are either parallel or orthogonal to the dip of the descending plate (Fig. 7).

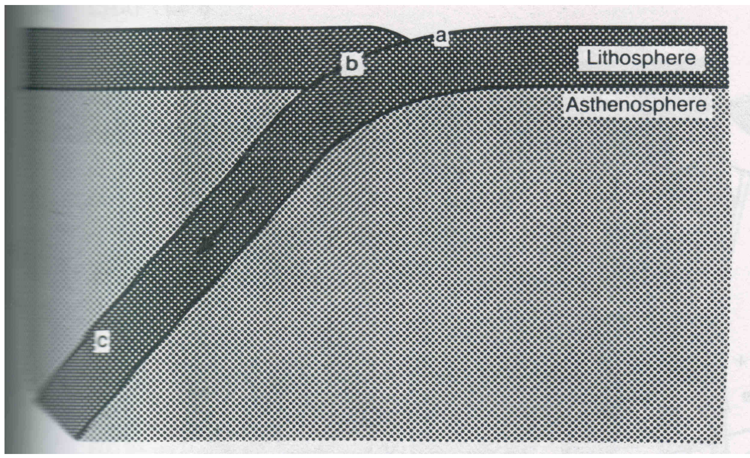

Fig. 6: Plate model of subduction zones: a, b and c indicate regions of distinctive focal mechanism solutions.

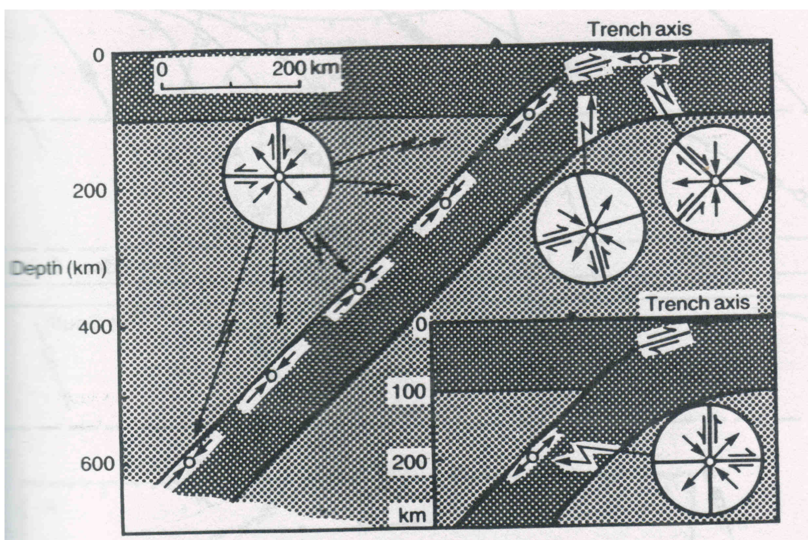

Fig. 7: Schematic focal mechanism solution distribution on a section perpendicular to an island arc. Inset shows alternative intermediate depth mechanism.

References:
Lowrie: Fundamentals of Geophysics
Gubbins: Seismology and plate tectonics