LECTURE 10 THE PLATE TECTONIC SETTING OF STRUCTURES AND DEFORMATION

LECTURE PLAN

1) SITES OF CRUSTAL DEFORMATION
2) STRUCTURES AT CONSTRUCTIVE PLATE BOUNDARIES
3) STRUCTURES AT DESTRUCTIVE PLATE BOUNDARIES
4) STRUCTURES AT CONSERVATIVE PLATE BOUNDARIES

1) SITES OF CRUSTAL DEFORMATION

Global seismicity is generally confined to very thin zones known as plate boundaries. The seismicity tells us where deformation and the formation of new structures is occurring today. The zones of seismicity occur within four main areas:-

a) the centres of oceans (ocean ridges) marked by shallow earthquakes down to around 65km. Vulcanicity produces new crustal material which forms "new magnetic stripes".

b) between convergent plates such as:-
- areas of continental collision which have distributed seismicity with shallow earthquakes from detachment faults and deep earthquakes from basement culminations.
- subduction zones. Deep earthquakes of over 0-600km. Zone of earthquakes defines a zone known as a Benioff Zone.

[Diagram of plate tectonics with labels for different types of tectonic settings and processes]
c) Some seismicity occurs within continental areas in the world’s intra-continental rifts. Shallow earthquakes (<15-20 km) and some volcanic activity is common.

d) Along conservative plate boundaries such as,
   - Oceanic transform faults; these are really part of the mid-ocean ridge system.
   - Continental strike-slip faults at plate boundaries or within plates. These are marked by shallow earthquakes which may include normal, reverse and strike-slip focal mechanisms.

Away from these zones, stable areas (cratons) exist with sparse tectonic activity.

We know that tectonic activity has not resulted in intense deformation of the stable areas as these areas contain long-lived geological features which have maintained their shape since Triassic times.

Examples:-

a) The opposing coastlines of Africa and the America still fit together after 180Ma and 4000km of drift, so that the interiors of the continents must also be undeformed.

b) The magnetic stripes in the oceans have maintained their shape for up to 180Ma.

- The link between seismicity and present-day tectonic activity suggests that seismic zones must represent the boundaries to the stable, slowly-deforming areas. The areas bounded by the zones of seismicity and vulcanicity are plates. The zones of seismicity and vulcanicity are termed plate boundaries.
**Surface features:** Maps showing global topography of the Earth show that elevations fall into two main areas (see next page). The oceans are generally low in elevation whilst the continents are higher in elevation. The reason for this is that the crust has a different composition and thickness in these 2 areas. The ocean crust is basic in composition. This ocean crust is quite thin, ranging between 5-15 km in thickness. The continental crust is thicker, with a normal thickness of 35 km, but having greater thickness in mountain ranges (e.g. 70 km under the Tibetan Plateau). It is composed predominantly of the minerals quartz and feldspar, so that it is said to be acid in composition. Acid crust is less dense than basic crust. The lower density and greater thickness of continental crust, and the fact that it is floating on the mantle, means the continental crust floats higher than ocean crust, explaining the higher topography of the former. (Note, as an aside, the high, and smooth topography of Greenland and Antarctica which are to due to the presence of thick icesheets).

However, the edges of the continents are not the edges of the Earth’s Plates. The global distribution of earthquakes shows where the the crust is being deformed. Areas of rapid deformation are marked by concentrations of earthquakes, which reveal the edges of the plates. Thus, the mid-ocean ridges are plate boundaries, as are the deep ocean trenches around the Pacific. The areas between the zones of earthquakes are rigid, lacking deformation related to earthquakes. These are the Earth’s tectonic plates. For example, the African plate is composed of African continental crust plus ocean crust from the eastern Atlantic and western Indian Oceans.
Uniformitarianism suggests that the styles of structures that characterise modern plate margins may also characterise ancient plate margins. Thus, by comparison, we may be able to characterise the ancient tectonic setting of areas by examining their structures. This is one of the major goals of structural geology.

So we will now examine the structures found at modern-day plate margins and compare them with ancient examples.

2) CONSTRUCTIVE PLATE BOUNDARIES-

Plates are moving apart. Called constructive as new material in the form of volcanic and igneous rocks infiltrate the boundary to fill the gap and form new crust. 2 main types:

a) Mid-Ocean Ridges exist within ocean crust. Basalt dykes, gabbro intrusions and ocean floor basalt pillow lavas.

Modern examples- Mid-Atlantic Ridge and the Iceland Hot Spot. Features include normal faulting and fissuring (dykes), seismicity, high heat flow (magma chambers) and basaltic lava flows. The Carlsberg Ridge in the Indian Ocean.

Ancient example- Now seen in obducted ophiolites such as the Lizard Complex or the Semail Ophiolite of the Oman.
Ocean crust is everywhere less than c. 180 Ma due to subduction of older ocean crust.
The strike of the ridge can be oblique to the spreading direction. Transform faults form to accommodate these motions. Plate motion vectors are parallel to transform faults which form small circles about the Euler poles of rotation of each plate (see earlier lectures).
Oceanic Fracture Zones (Oceanic Transforms)

- offset of the ridge by strike-slip fault movement
- faults penetrate the Moho
- typical of slow-spreading ridges

They form to accommodate lateral variations in spreading rates.
The East Pacific Rise is an example of a fast-spreading centre (upto 80mm/yr). It shows the typical axial uplift morphology (sonar data).
The Mid-Atlantic Ridge is a slow-spreading centre (<22 mm/yr). It has the typical axial depression (rift) morphology.
Overlapping Spreading Centres (OSCs)

- The geometry of OSCs is unstable, one rift tip will eventually link with the other ...

The old OSC is preserved as a discontinuity in the crust
Hydrothermal Activity

Ocean waters circulate through the oceanic crust due to convection and become enriched in sulphides and causing metasomatisation of the ocean crust (serpentinites form). The sulphide enriched waters emerge as black-smokers.
Vents at Black Smokers on Earth have fauna that derive their energy from the hydrothermal activity rather than the sun. NASA believes that such fauna may have developed on other planets/moons where ice blots out the sun and where large gravitational forces cause tidal heating and volcanism, e.g. on Europa, where they intend to drill through ice to access underlying oceans.
b) **Continental rift-zones** are incipient constructive boundaries which are the first stage of continental break-up. They have varied vulcanicity because rising magmas interact with continental crust of widely varying composition.

Modern example- **Afro-Arabian Rift System.** The Gulf of Aden has been opening over the last 20Ma along a continuation of the Carlsberg Ridge spreading axis. Gulf of Suez lies at the NW end of the Red Sea. Tilted fault blocks occur associated with large normal faults and sedimentary basins. Rifts may be associated with **out-pourings of tholeitic basalts** and dyke swarms situated above "mantle hot spots" e.g. East African Rift.

An ancient example- **North Sea Basin.** Periods of rifting occurred from the Devonian to the Cretaceous. Doming and uplift in mid-Jurassic times was related to high heat flows and a volcanic centre. Note:- thinned continental crust characterises the area.

The structures of continental rifts may become stranded on the opposing sides of a new ocean. These continent-ocean junctions are no longer areas of seismicity and therefore cannot be plate margins. They are known as passive continental margins.

Modern example- **The Atlantic coastlines.** Contain tilted fault-blocks bound by normal faults.

Ancient examples- These are commonly found on the telescoped margins of former oceans which are now preserved in continent-continent collision zones. The former passive margin on the NW side of Tethys now lies within the telescoped Western Alps.
There are two models for the structure of rifts (and sedimentary basins in general).

1) the pure shear model was proposed by McKenzie (1978), and involves brittle failure of the upper crust and ductile stretching of the lower crust and lithospheric upper mantle. The rift takes on a symmetrical geometry. The amount of stretching in the lithosphere is called the $\beta$ factor. $\beta$ factors of 1.5 - 2.0 are computed for several aulacogens and basins, e.g. Central Graben of the North Sea.

2) the simple shear model proposed by Wernicke (1985) who considered that the whole of the lithosphere is stretched by simple shear along low-angle detachment faults. This model was applied to the Basin and Range Province (W USA) and to the East African Rift system.
The Basin and Range extensional province lies inboard of the San Andreas fault which is a transform fault. GPS data show rates and directions of extension that indicate that extension is due to the drag of the Pacific Plate as it passes to the NW past North America. Rifting is induced by lateral forces from the transform. The northward continuation of the East Pacific Rise lies beneath the Basin and Range (a subducted ridge). Perhaps the heatflow was enough to weaken the continental lithosphere facilitating the distributed extension.

(see Bennett et al. 2003)
The c.N–S ridges are active normal faults that are spaced tens of kilometres apart. Extension is distributed across 600–800 km of the North American Continent. Active volcanism is relatively minor compared to East Africa.
The East African Rift System lies where the Carlsberg Ridge spreading centre comes onshore. It has therefore formed due to upwelling mantle at a constructive plate boundary. It has caused continental break-up as Arabia is now a separate plate. Extensive volcanism accompanies the rifting due to upwelling mantle.
The Afar regions lies at the junction of the Gulf of Aden, the Red Sea, and the East African Rift system. The Gulf of Aden appears to have propagated into this region to form the triple junction. Note how localised the rift systems are (especially individual branches of the East African Rift. The rifting is accompanied by extension volcanism. The high resolution of this digital elevation model allows one to see individual rift faults in the coastal region of Djibouti. See next page for more detail.
Offshore, the rift is extremely localised (<40 km across), whilst onshore tens of small-scale faults are spaced only a few kilometres (<10 km) apart. (From Manighetti et al. 1997). The rift has propagated onshore during its evolution, rifting continental crust.

Plate 1. Finite geometry of Arabia-Somalia plate boundary at threshold of Afar [from Manighetti et al., 1997]. Faults are from analysis of bathymetric contour patterns, field work, and SPOT and aerial image analysis. Main active rift faults are in red. AR/SOM plate motion is from Chase [1978]. M is Maskali transform. Other letters identify successive ridge segments (discussed by Manighetti et al. [1997]). Numbers indicate age of most recent basalts (from Tables 1 and 2), and ORSTOM [1983, 1985].
3) DESTRUCTIVE PLATE BOUNDARIES-

Plates are converging. Termed destructive as crust is subducted reducing the surface area of the plate. 3 main types:-

a) Ocean-Ocean Subduction. A section of oceanic crust intervenes between the subduction zone and the nearest continent. Composed of:- a partially submerged volcanic mountain chain 50-100km wide which a deep ocean trench around 50 to 250km away on the convex side of the arc.

Features include:-
  i) Oceanic crust with a cover of pelagic sedimentary rocks descending into a deep oceanic trench.

  ii) Accretionary complex or accretionary prism which is off-scraped sedimentary cover of the subducted crust which has compressional thrusts and folds.

  iii) Fore-arc basin formed between the topographic highs of the growing pile of off-scraped sediment in the accretionary complex and the magmatic arc.

  iv) The magmatic arc where magmas derived from the subducted slab travel upwards to form volcanic islands.

  v) Back-arc basin where subsidence and sedimentation are controlled by extensional faults which form due to the gravitational effects of the subducted slab.
The scale of subduction zones (Stern 2002)

Figure 1. Subduction zones and convergent plate margins. (a) Location of convergent plate margins on Earth (modified after Lallemand [1999]). Active back arc basins are also shown. (b) Schematic section through an upper 140 km of a subduction zone, showing the principal crustal and upper mantle components and their interactions. Note that the location of the “mantle wedge” (unlabeled) is that part of the mantle beneath the overriding plate and between the trench and the most distal part of the arc where subduction-related igneous or fluid activity is found. MF stands for magmatic front. (c) Schematic section through the center of the Earth, which shows better the scale of subduction zones. Subducted lithosphere is shown both penetrating the 660 km discontinuity (right) and stagnating above the discontinuity (left). A mantle plume is shown ascending from the site of an ancient subducted slab. Dashed box shows the approximate dimensions of the shallow subduction zone of Figure 1b.
The effects of the age of subducted material (Sterns 2002).

**Figure 4.** End-member types of subduction zones, based on the age of lithosphere being subducted (modified after Uyeda and Kanamori [1979]).
The fate of subducted slabs of oceanic crust is largely to dehydrate and melt, and leave a residue of very dense eclogite (metamorphosed basalt) and harzburgite (oceanic lithospheric mantle), which slowly absorbs heat from the surrounding asthenosphere and heats up until equilibrium with the surrounding mantle has been achieved. Most earth scientists think that this occurs above the 670km discontinuity, and that slabs do not normally penetrate through this level. However, seismic tomography has shown that in some instances, the cold slab can be imaged passing through the discontinuity into the lower mantle.

This debate has profound implications for the nature of convection in the mantle. Many geochemists consider that convection is of a "two-layered" type, with the regions above and below the 670km discontinuity convecting separately. The only material which passes between the two is considered to be (in an upwards direction) heat and primordial helium gas, associated with very large mantle plumes such as Hawaii. The return flow may be via these very deep subduction zones and may enrich the lower mantle in an unusual mixture of strongly depleted mantle and eclogitic-facies basic rocks and even sediments.

Reading
Wilson, M. Igneous Petrogenesis, Chapters 6 and 7.
Figure 2. Structure of subducted slabs as inferred from mantle tomography (from Karason and van der Hilst [2000]). Red lines show the surface projection of each section. The base of each section is the core–mantle boundary (CMB); dashed lines show the location of mantle discontinuities at 410, 660, and 1700 km. Red and blue colors in each section denote regions where P-wave velocities are relatively slow and fast, respectively, compared to average mantle at the same depth. Fast regions are most easily interpreted as relatively cool areas corresponding to the subducted slab and its viscous mantle blanket. This allows the cool, subducted slab to be traced well below the deepest earthquake. Note that some slabs penetrate the 660 km discontinuity and descend into the lower mantle (e.g., Central America, central Japan, and Indonesia), while other slabs seem to stagnate in the upper mantle (such as Izu–Bonin). The subducted slab beneath Tonga seems to stagnate at the 660 km discontinuity for a while, then cascade into the lower mantle. 

(Sterns 2002)
Modern example- The Lesser Antilles Subduction Zone where the Atlantic ocean crust passes beneath the small Caribbean Plate. The Barbados ridge is the accretionary complex associated with the Lesser Antilles Volcanic Arc and the Grenada back-arc basin. The subduction zone passes into c. east-west oriented strike-slip transform faults in the north and south. Areas close to the transform faults experience strike-slip deformation.

Ancient examples are often complexly deformed, have a low preservation potential and are difficult to recognise. Some possible examples have been found along the suture zones in the Himalayas (see below).

b) Certain subduction zones border a continent

Modern example- Peru Trench associated with the South American Cordillera exposed within the Andes Mountains, west side of south America). Volcanic belt situated within the continent such as in the Andean Granites and volcanoes.

Ancient example- Southern Uplands Accretionary Prism, U.K., is composed of imbricated Lower Palaeozoic Rocks such as the Moffat Shales. The Lake District is probably an ancient magmatic Arc.
The surface area of the African Plate is being reduced by subduction beneath Eurasia along the Hellenic and Calabrian Subduction zones. Extension occurs in the over-riding plate.
c) Continental Collision Zones are the result of continued plate convergence after the subduction of all the oceanic crust which exists between two continents. This results in the deformation and shortening of the continents involved. Imbrication of the two continents involved leads to the development of thickened crust which can achieve thicknesses of 50-70km e.g. Tibet, with high mountains.

Modern example- Central Asian Collision Zone which form the Himalayan Mountain Chain.

Collision between Indian and Eurasian Plates occurred from the Eocene to Recent. Pre-collision velocities of 10-18cm/year existed with movement towards the NNE. At 38Ma the rate slowed to 5cm/year and rotated towards the north. This probably indicates the initiation of collision of the two continents at 38Ma. 1500km of convergence has taken place since then indicated by the ocean floor magnetic stripes.

Plate Boundaries include:-

a) Indus Suture is the southern boundary to the Eurasian Plate, which marks the former position of the subduction zone which existed between the converging plates. The ocean between the continents was called Tethys and remnants of Tethyan Oceanic Crust exist just south of the Indus Suture such as basic and ultra-basic igneous complex associated with pillow lavas and greywackes of the Kohistan Complex. Remnants of accretionary complexes appear to be located along these boundaries.
b) Indian Plate is bound to the east and west by two major strike-slip faults, the Quetta-Chaman strike-slip fault and a major strike-slip fault running through Burma.

Deformation of the Eurasian Plate involves thrust fault systems and strike-slip fault systems. Local extensional basins occur.

Examples- Himalayan Frontal Thrust, the Red River Strike Slip Fault and the Baikal Rift System.

Indentation Tectonics:- Deformation of the continental interiors by strike-slip fault systems due to the collision of a rigid continental indentor may occur. The strike-slip faults arising in the Himalayas and continuing into S.E. Asia may be examples of this.

An ancient example- of a continental collision zone would be the Moine Thrust Belt of NW Scotland formed during closure of the Iapetus Ocean.
4) CONSERVATIVE BOUNDARIES-

Plates are moving horizontally past each other with a strike-slip sense of movement. Material is neither created or destroyed but conserved. Steep strike-slip faults zones. 2 main types:-

a) Transform Faults- Offset mid-ocean ridges, and therefore separate neighbouring plates. Modern example- Discovery Fracture Zone along the East Pacific Rise. Ancient examples exist within obducted ophiolites.

b) Continental Strike-Slip Faults-

Example- The Dead Sea Transform Fault

Example- San Andreas Fault System which separates the Pacific Plate from the North American Plate. This is a strike-slip fault systems which is composed of anatomising fault strands which form zone 100km wide zone. Parallel faults exist such as the Imperial Valley, San Jacinto and Elsinore Faults. Faults are associated with en echelon folds such as in the Santa Maria Oilfields. Local bends in strike-slip faults are associated with localised areas of thrust faulting and growing highland topography (e.g. Near Santa Barbara) and localised extensional "pull-apart" basins containing extensional faults which are the site of subsiding lowland areas.
FURTHER READING AVAILABLE FROM THE ELECTRONIC LIBRARY


Christoph Gaedicke, Boris Baranov, Nikolay Seliverstov, Dmitry Alexeiev, Nikolay Tsukanov and Ralf Freitag 2000, Structure of an active arc-continent collision area: the Aleutian-Kamchatka junction, *Tectonophysics*, 325, 63-85

Y. Rolland, A. Pécher and C. Picard, 2000, Middle Cretaceous back-arc formation and arc evolution along the Asian margin: the Shyok Suture Zone in northern Ladakh (NW Himalaya), *Tectonophysics*, 325, 145-173