LECTURE 2 THE GEOMETRIES OF FAULTS

LECTURE PLAN

1) CLASSIFICATION AND DESCRIPTION OF FAULTS
2) FAULT DISPLACEMENTS
3) EXTENSIONAL FAULTS

1) CLASSIFICATION AND DESCRIPTION OF FAULTS

Faults are important structures because they are responsible for earthquakes, control the distribution of minerals and hydrocarbon accumulations and offset stratigraphy. They are widespread on the Earth and occur on other rocky planets. In this lecture we will learn about the geometries of faults and the terminology used to describe them.

Normal faults with the largest offsetting an impact crater in the Beta Regio region of Venus

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Normal faults with the largest offsetting an impact crater in the Beta Regio region of Venus
Normal faulting in the Afar region at the termination of the Carlsberg Ridge seen on a digital elevation model (DEM) collected by the Space Shuttle (SRTM data). Normal faults offsetting Pliocene-Recent basalt flows. Note the displacement gradients on these faults.
Strike-slip and normal faulting seen on a digital elevation model (DEM) collected by the Space Shuttle (SRTM data).

Termination of the East Pacific Rise

Extension across normal faults in the Basin and Range

Extension across normal faults in the Basin and Range

San Francisco

San Andreas Fault

San Andreas Fault

Termination of the East Pacific Rise

Continental Margin

San Andreas Fault

Los Angeles
Faults are planar discontinuities along which significant displacement has occurred. Form generally in the top 10-15km of the crust.

- Faults do not continue in all directions forever, but their displacement dies out along tip lines (like tears in a piece of paper). This decrease in displacement produces a displacement gradient.

- Faults are "penny-shaped" dislocations within rocks surrounded by a area of ductile deformation known as a ductile bead. The propagation of fault through the ductile bead produces what appear to be "drag folds", although they have not been dragged because they were formed before the fault grew.

The area above a fault is said to be in the hanging-wall (because it hangs over you if you stand on the fault).

The area below a fault is said to be in the footwall (because it lies by your foot if you stand on the fault).

The classification of faults is based on the dip of the fault plane and the direction of slip relative to a horizontal plane.

However:- It is often not possible to find the exact displacement, as this requires knowledge of the location of matching points on either side of the fault plane. It is not easy
When the lengths and displacements for faults are collated for all measured faults on the Earth a clear relationship between small and large faults emerges. They all share the same displacement (d) to length (L) ratio ($d/L = 0.03$). The $d/L$ ratio is a measure of the stiffness of the material that contains the faults. Stiff material (say like glass) has very long faults with very small displacements ($d/L = 0.001$). Less stiff material (say like toffee at room temperature) has faults whose length is similar or just longer than the displacement ($d/L = 0.1-1.0$). Thus, the fact that all faults on the Earth have $d/L$ ratios that are similar implies that the Earth's crust has a similar stiffness at whatever scale it is viewed.

Another way to consider these data is in terms of fault growth. If a fault increases in displacement, then it must also increase its length (otherwise the $d/L$ ratio would not be 0.03). Thus, the data imply that faults grow by adding displacement (usually during earthquakes, although some faults creep), which causes an increase in fault length by lateral propagation.
Faults increase their displacements during earthquakes. For example during the 1983 Borah Peak Earthquake in the U.S.A., the fault slipped by about 1.5 metres, of which about 300 mm was footwall uplift and 1200 mm was hangingwall subsidence. This examples shows how uplift/subsidence measured geodetically can be linked with the geology of the fault and with the focal mechanism of the earthquake.

Geodetic and geological data from the 1983 Borah Peak earthquake (Ms = 7.3), which occurred on the Lost River fault, western United States. (a) Coseismic deformation (dots) associated with the earthquake, measured by resurveying a levelling line across the fault. The model fit to the data (solid line) was calculated assuming a planar fault in an elastic medium. (b) Geological cross-section across the Lost River fault. Qu = Quaternary alluvium, V = Tertiary volcanics, shading = Palaeozoic and older. (c) Seismological data for the 1983 earthquake sequence. Error bars bracket the mainshock location, with the focal mechanism shown at the hypocentre. Small circles indicate the aftershock locations. The 'model fault' is that used to generate the geodetic curve (solid) in (a). Redrawn from Stein et al. (1988).
Some faults break the surface and others (blind faults) do not.

The first diagram shows an elastic model of a normal fault whose upper tip extends to a contemporary free surface. Note that hangingwall subsidence is very much greater than footwall uplift. (b) Displacement contours in the deformed volume around the model fault, calibrated relative to the displacement at the fault centre. Arrows show gross displacement directions. Note the asymmetry in the strain field across the fault, in particular the larger area of high strain in the hangingwall.

The second diagram shows a model of a blind normal fault confined within an elastic medium. The fault has a maximum displacement at its centre which decreases gradually to zero at the tip. Fault length is equal to its down-dip dimension. Note that the strain is partitioned equally and oppositely into footwall uplift and hangingwall subsidence. (b) Displacement contours in the deformed volume around the model fault, calibrated relative to the displacement at the fault centre. Arrows show gross displacement directions. Note the symmetry in the strain field across the fault.
The North Sea is a classic area with segmented normal faults seen here using seismic data.

This map shows the oil fields around the North Viking Graben.

This cross-section illustrates the styles of faulting as seen on a deep seismic reflection profile.

This is a shaded image of the top pre-rift horizon compiled using 3D seismic data. It is like looking at the buried topography under the synrift and postrift. Note the segmented nature of the faults, and the fact that the Gullfaks oilfield is in the crest of the footwall.

This is an example of high resolution seismic reflection data from which the faults are interpreted. Note the thickening into the fault that indicates that the fault was active in Heather time (mid-Jurassic).
2) FAULT DISPLACEMENTS

Along most faults the following features can be recognised:-

a) Direction of movement

Lineations on the fault plane give the azimuth or bearing along which displacement has occurred. Corrugations, grooves, striations, stretched crystal fibres and slickolites are types of lineation.

These lineations should be plotted on field maps as close as possible to the trace of the fault.

b) Sense of movement and stratigraphic separation

Determined by stratigraphic relationships and from the apparent offset of marker units such as dykes or other faults.

The stratigraphic separation across faults is as follows:-

- Extensional faults place younger rocks on top of older rocks and cause an omission of stratigraphy (see below).
- Contractional faults place older rocks on top of younger rocks and cause a repetition of stratigraphy (see below).
- Strike-slip faults do not produce a stratigraphic separation.
Stratigraphic separation must vary along the strike of a fault and this can be viewed on a stratigraphic separation diagram. To produce such a diagram, plot the elevation of the cut-off of particular stratigraphic horizon in both the footwall and the hanging-wall against distance along the fault. The vertical distance between the footwall and hanging-wall cut-offs is known as the stratigraphic separation.

c) The relationship between heave, throw and displacement

The displacement is the distance by which a particular feature (e.g. a bedding horizon) is offset across the fault measured along the fault surface.

The throw is the vertical distance that a point moves during faulting.

The heave is the horizontal distance that a point moves moves during faulting.

3) EXTENSIONAL FAULTS

Found in extensional tectonic regimes. Generally propagate at around 60° to the stratigraphy. Associated with crustal thinning, elevation of crustal isotherms and the upward migration of magmas.
A number of normals faults dipping in opposite directions may form horst and graben structures whilst a number of normal faults with the same dip direction form half graben.

Normal faults may be listric (concave upwards) or planar and this is the subject of much debate.

a) Models of fault geometry

i) Domino Model:- Planar extensional faults bounding rigid blocks. The faults and the blocks both rotate during deformation. Gaps at the edges of the block are filled with extensional basins and ductile flow of the lower crust at the lower end. May be associated with a basal detachment horizon.

ii) Listric faults and detachments:- Listric faults have curved profiles which are concave upwards. The shallow into detachment horizons. Geometrically necessary folds in the hanging-wall are forced by the presence of curved fault planes. Roll-over anticlines may be cut by antithetic normal faults. These second order faults accommodate strain in the growing anticline. Note that these are not compressional folds.

The same terms as used in thrusts can be used to describe Footwall ramps, flats and cut-offs, Hanging-wall ramps, flats and cut-offs (see later).

The faults produce sedimentary basins and topography on the basin margins so that growth faults with stratigraphic thickening are the result.
Folds associated with normal faults

Movement over listric faults produces a type of fault bend fold known as a roll-over anticline. Displacement gradients may also produce folds around normal faults. Roll-overs and displacement gradients may both produce reverse drag and complex strain patterns around the terminations of the faults.

Synthetic and antithetic faults may occur around the major fault.

3-D Geometry of normal faults

Faults are surrounded by tip lines where the displacement accommodated by the fault dies to zero. Faults are generally found en echelon and are separated by transfer zones where displacement is transferred between the faults. Fault Bridges and relay ramps occur in these regions. Transfer faults (strike-slip) may also occur between offset fault strands.

b) Basic Rules for extensional faults

1) Normal faults bring younger rocks over older rocks.
2) Normal fault cut down section in their movement direction.
3) Younger normal faults occur in the hanging-wall of older extensional faults.
4) Fault blocks bound by planar normal faults (domino) must rotate during deformation. Also, rotation occurs in the hanging-wall for the case of listric faults.
FURTHER READING AVAILABLE FROM THE ELECTRONIC LIBRARY


Steven E. Schulz and James P. Evans, 2000, Mesoscopic structure of the Punchbowl Fault, Southern California and the geologic and geophysical structure of active strike-slip faults, *Journal of Structural Geology*, 22, 913-930


Claudia J. LewisJoann M. Stock, 1998. Late Miocene to Recent transtensional tectonics in the Sierra San Fermín, northeastern Baja California, Mexico, *Journal of Structural Geology*, 20, 1043-1063
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Michel Corsini Alain Vauchez Renaud Caby, 1996. Ductile duplexing at a bend of a continental-scale strike-slip shear zone: example from NE Brazil, Journal of Structural Geology, 18, 385-394


David A. Ferrill, John A. Stamatakos and Darrell Sims, *Normal fault corrugation: implications for growth and seismicity of active normal faults*, *Journal of Structural Geology*, 21, 1027-1038


A. Nicol, J. J. Walsh, J. Watterson and P. A. Gillespie, 1996. Fault size distributions -- are they really power-law?, *Journal of Structural Geology*, 18, 191-197 Note all the other papers in this issue!