Introduction to Structural Geology

Workbook 3   **Geological Maps**

Contents

How to use this workbook

This workbook is intended as a refresher course for those who have some previous experience of geological maps. If you are completely new to the subject it is worth having a look at some of the textbooks in the bibliography in conjunction with the workbook.

Introduction to geological maps

Geological maps represent the solid geology at the Earth's surface unconcealed by vegetation, soil or buildings (figure 1a).

Different rock types and formations are illustrated by different colours and/or symbols. Other features such as faults, mineral veins, coal seams, marker horizons and landslips are shown. Bedding and structural features such as cleavage and foliations are indicated by strike and dip or plunge and azimuth symbols (figure 1b).

There are several different types of geological maps, the main ones being solid geology, which show bedrock, and drift maps, which show unconsolidated sediments such as river alluvium, peat and glacial deposits that lie above bedrock.

Geological maps usually include stratigraphic columns and one or more cross section (figure 1c). Stratigraphy columns show the different formations on the map in the order of deposition, with the oldest at the bottom and youngest at the top. They also show their thicknesses and are usually drawn to scale. The cross sections show the sub-surface (and often the above-surface) geology, as predicted from the features mapped at the surface
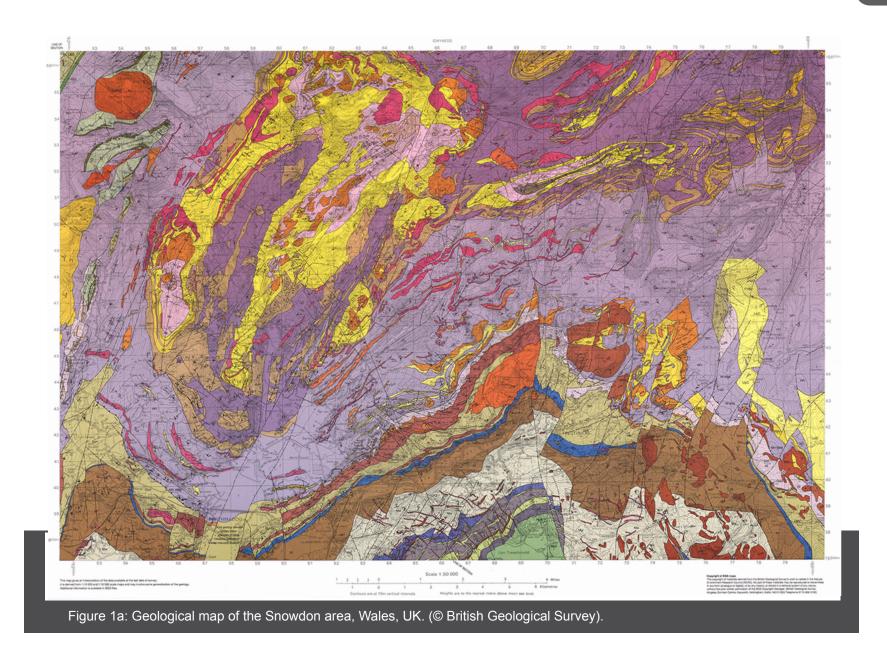
Maps come in a variety of scales depending on the amount of detail needed for different purposes. In all cases, they will show a grid for location (in Britain, the National Grid on land). Points on the map are referred to using coordinates (eastings then northings) which are usually 6 or 8 figure references. The basic grid square covers 100,000 metres, with northings, for example, given as 670000mN, giving an absolute location in metres. When working within a map, it is usual to give 3 figures (e.g. 700N) or 4 figures (e.g. 7000), depending on the scale of the map. Four figure grid references specify locations to within 10 metres. Maps covering a larger area tend to use latitude and longitude in addition or instead. Maps for other countries will use other National Grids.

This workbook looks first at the outcrop patterns on geological maps, which form due to the interaction of the geology with the topography. At how folds, faults and unconformities form consistent outcrop patterns and the information that can be gained about these structures from a map.

It then looks at how to draw cross sections, including dealing with apparent dip. How to use structure contours to construct cross sections and to use structure contours to make accurate and quantitative predictions about subsurface geology.

Working with geological maps enhances the ability to think in 3D and re-enforces the relationships, both temporal and spatial, between different geological units and structures.

Figure 1a: Geological map of the Snowdon area, Wales, UK. (© British Geological Survey).
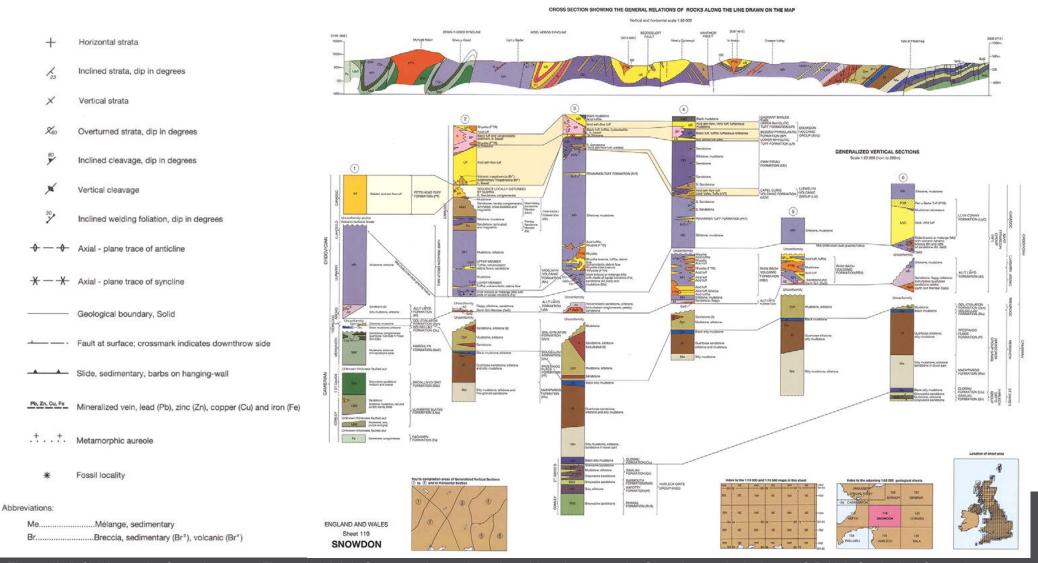
Figure 1b (left): Key to the Snowdon map. Figure 1c (right): Cross section and stratigraphic columns on the Snowdon geological map (© British Geological Survey).

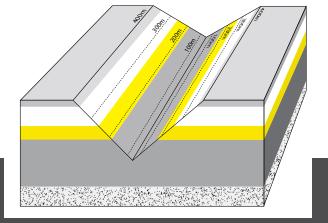# Worksheet 1: Outcrop patterns on geological maps

If the Earth's surface was flat, if there was no topography, then geological maps would be simple. They would be a direct reflection of the underlying geology. However, topography interacts with the geology to produce more complex but predictable patterns.
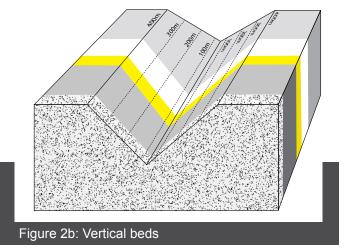
Horizontal and vertical strata:

Horizontal and vertical strata are the most straightforward to interpret on a map. Horizontal outcrops will always follow the topographic contours (figure 2a), whilst vertical layers will always form straight lines (figure 2b).
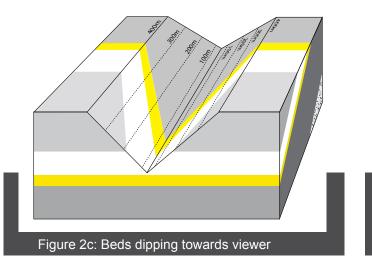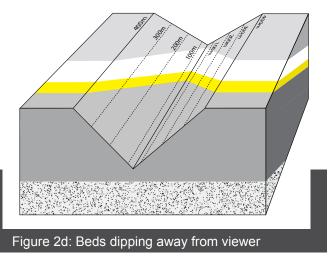
Dipping strata

Dipping layers interact with the topography in predictable ways. In valleys, beds will appear to 'vee' either up or down the valley in the direction of dip (figure 2c and 2d). This is because the valley side acts as an approximate cross section – not always helpful on small scale maps but on large scale maps and in the field this is a useful aid in interpretation.

Figure 2a: Horizontal beds

Figure 2b: Vertical beds

Figure 2c: Beds dipping towards viewer

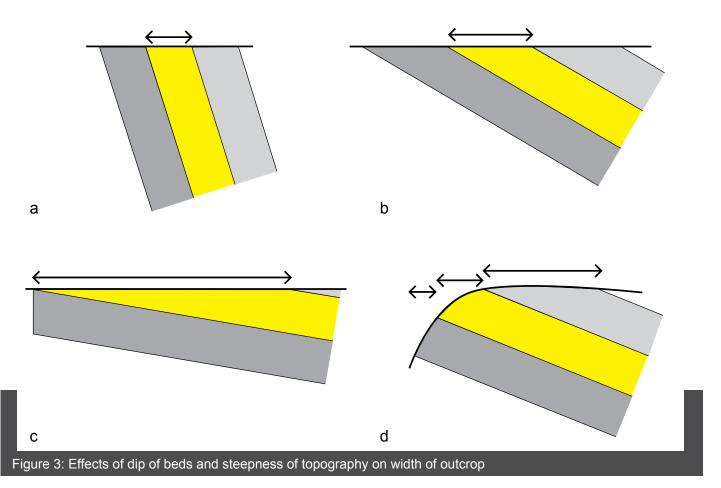Figure 2d: Beds dipping away from viewer

Effects of dip of beds and width of outcrop

The width of outcrop on a map is affected by the dip of the beds and by the steepness of the topography.

All the beds in figure 3 have the same thickness. Figure 3a, 3b and 3c show the effect of dip. As the dip decreases from steeply dipping in Figure 3a to shallowly dipping in figure 3c the outcrop on the map becomes wider and wider.

In figure 3d the beds have the same dip, but the topography varies. Where the topography is steepest on the hillside the outcrop is narrow, where the topography is horizontal along the hill top the outcrop is wider.

Figure 4 shows the Isle of Wight geological map. The Mesozoic sediments have been folded into a monocline with a steep dipping limb and a near horizontal limb. Arrow A points to the shallow dipping limb. Notice how wide the outcrop is here and how closely the geological boundaries

Figure 3: Effects of dip of beds and steepness of topography on width of outcrop

follow the contours, indicative of beds with very low dips. Arrow B points to the steep dipping limb. Notice the narrow outcrop pattern and how the geological boundaries cuts across the topography indicating the steeper dip.
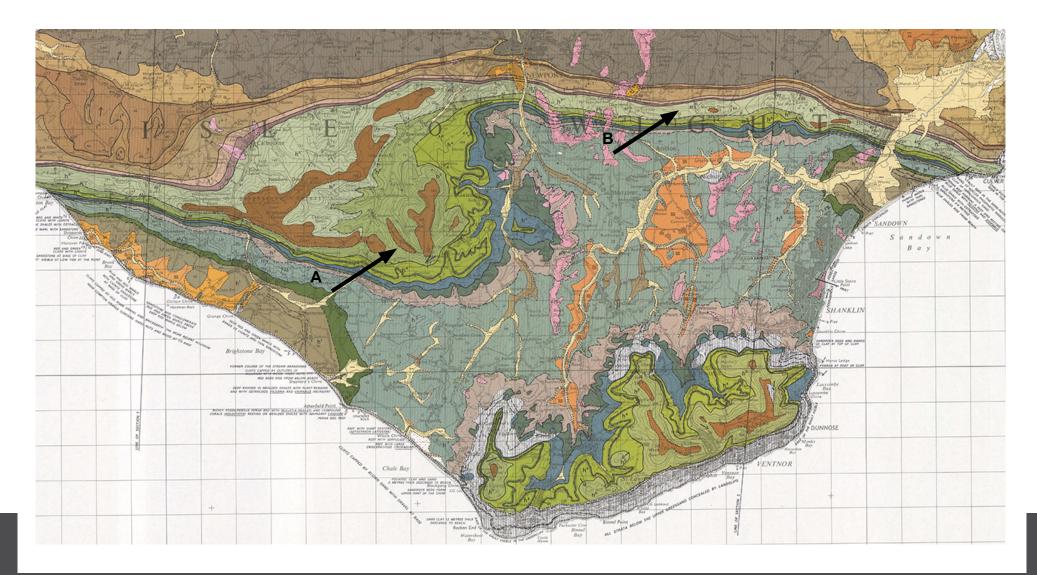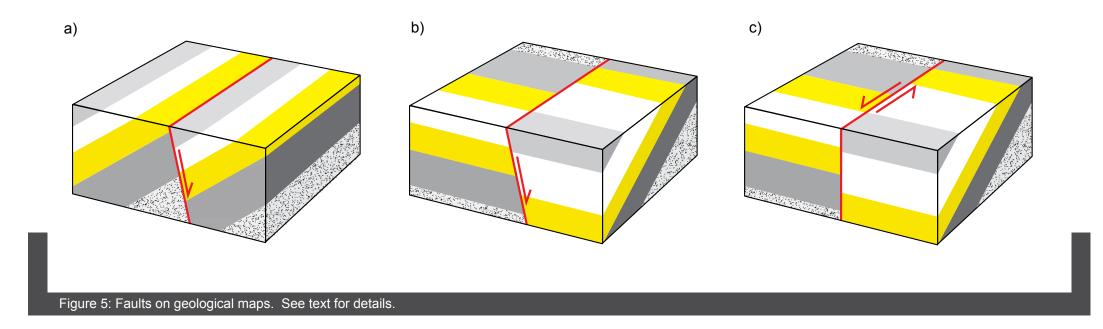
Figure 4: Geological map of the Isle of Wight, southern England, UK. See text for details. © British Geological Survey.

Faults on maps

Faults can occur at any angle with respect to bedding and so the outcrop patterns produced are not unique to any one fault type. Figure 5a and 5b show two potential outcrop patterns for a normal fault.

In a) the fault is parallel to the strike of the beds and in b) the fault is perpendicular to the strike of the beds. Figure 5b and 5c show how the same outcrop pattern can result from different fault movement. Most geological maps include a symbol on the fault indicating the style of faulting.

Figure 6 shows the geological map for Kewick Thrust faults are shown with a filled triangle on their hangingwall. Strike-slip faults with half arrows indicating the direction of movement and normal faults are shown with a tick on the hangingwall. Fold axial traces are also shown on the map.

a)

b)

c)

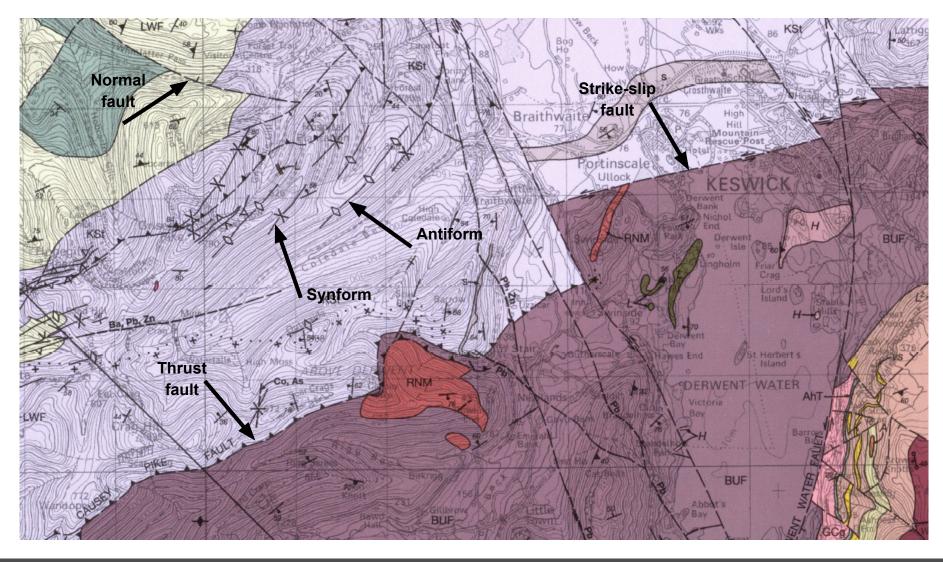Figure 5: Faults on geological maps. See text for details.

Figure 6: Geological map of Keswick, northwest England, showing different types of faults and folds. See text for details. © British Geological Survey.

Fold on maps

Figure 7 shows the different outcrop patterns for folds. The limbs of the folds form a repeating pattern on either side of the axial plane. For anticlines, the oldest rocks are in core of the fold and the rocks get younger away from the axial trace (figure 7a). For synclines, the youngest rocks are in the core and the rocks get older away from the axial trace (figure 7b).

Plunging folds form the same repeating pattern as non-plunging folds, except their limbs converge around the axial traces. The limbs of synclines open in the direction they plunge (figure 7c); whilst the limbs of anticlines close in the direction they plunge (figure 7d).

Figure 8 shows the Pemnbroke geological map and cross section. This shows the repeating pattern of geological units across the map typical of folding. Note the apparent closure of the fold is most likely related to topography as the dips do not change along the axial trace. See figure 10 for an example of a plunging fold.
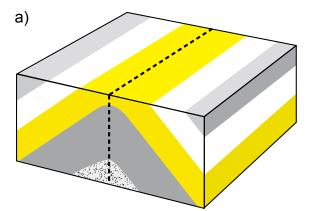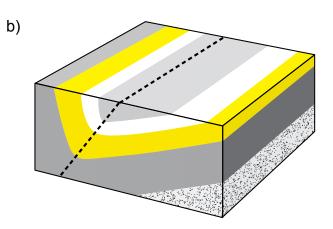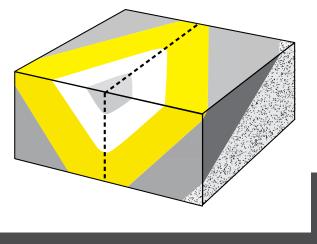
a)

b)

c)

d)

Figure 7: Folds on geological maps. See text for details.

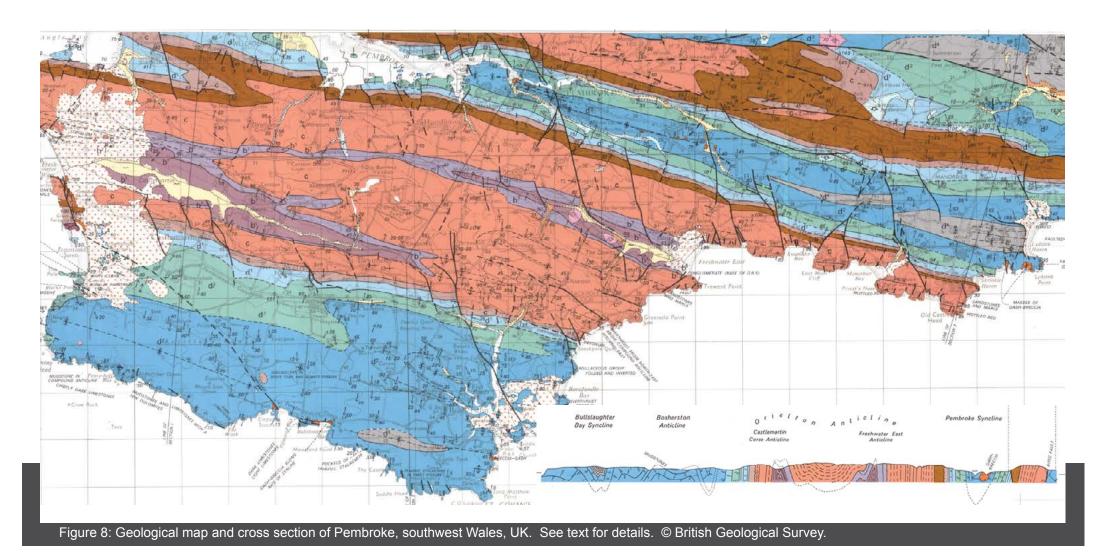Figure 8: Geological map and cross section of Pembroke, southwest Wales, UK. See text for details. © British Geological Survey.

Unconformities

Unconformities represent a break in deposition and a period of uplift and erosion. They can cover tens or hundreds of millions of years and tens or hundreds of metres of strata may be removed.
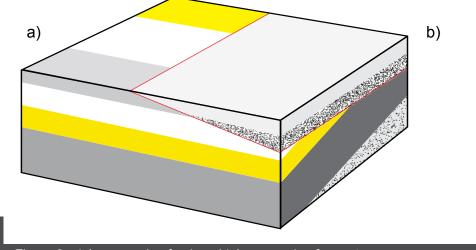
Onlap:

An unconformity where the younger series of rocks progressively onlap the older members of the underlying series. So that younger beds of the series above the unconformity rest directly on the beds beneath the unconformity. Also known as overlap.

Overstep:

Only the lowest bed of series above unconformity rests directly on the beds beneath the unconformity.

Figure 10 is the geological map for Bristol. Here the Triassic (orange/brown) units unconformably over lie the folded Carboniferous (blue) units. The two clearest folds are anticlines and are separated by a narrow syncline largely hidden by the Triassic sediments. The upper anticline plunges to the east and the lower one to the west.
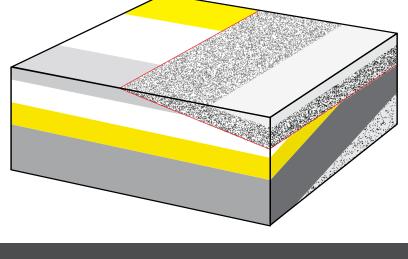
a)   b)

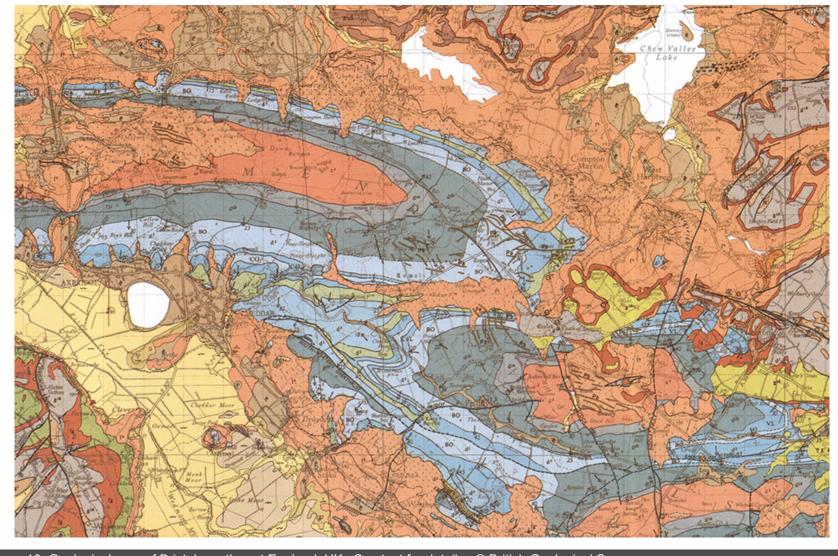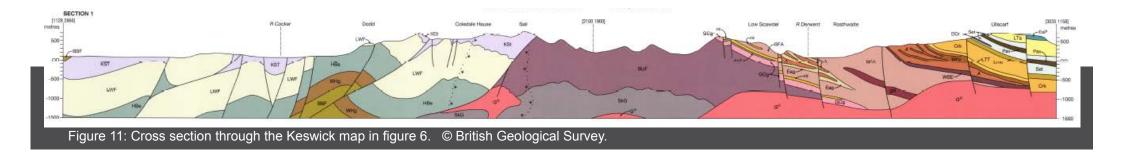Figure 9: a) An example of onlap. b) An example of overstep.

Figure 10: Geological map of Bristol, southwest England, UK. See text for details. © British Geological Survey.

Worksheet 2: Cross sections

A key goal of structural geologists is to understand the three dimensional geometry of the rock layers. A geological map is a two dimensional representation of geological features on the Earth's surface. In order to provide a third dimension, one or more slices through the Earth are needed. Although cross sections are usually vertical, there are instances where it is desirable to project geologic structures on to a dipping plane such as the profile plane of a plunging fold. Cross sections show thicknesses, dip directions, folds, faults, unconformities, sediment thickness changes, igneous intrusions etc.

To draw a cross section, outcrop data from the Earth's surface are projected into the subsurface geology. Sometimes this information can be supplemented with seismic or well data. To be able to draw a geologically realistic cross section an understanding of the geometry and kinematics of structures is needed.

A cross section should be consistent with all the available data, although there are often several viable interpretations of the same data.

Most cross sections are drawn to true scale, that is, where the horizontal scale is the same as the vertical scale. This means the true dip of the rock units are shown. Vertical exaggeration, where the vertical scale is increased relative to the horizontal, is sometimes used to make a cross section clearer. However, it also increases the dips of the rock units exaggerating the geological structures.

Figure 11: Cross section through the Keswick map in figure 6.   © British Geological Survey.
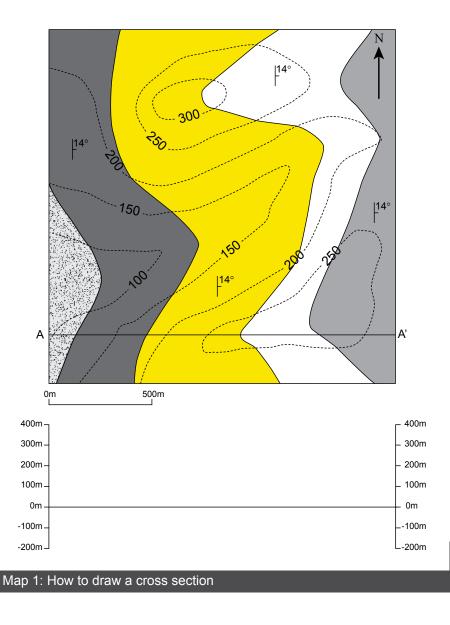
How to draw a cross section:

Step 1:

Determine the line along which to draw the section. The line of section should be representative of the study area, be perpendicular to the major structural feature of the area (e.g. large scale folds or faults), cross as many structural features as possible and run through areas with the most data readings.
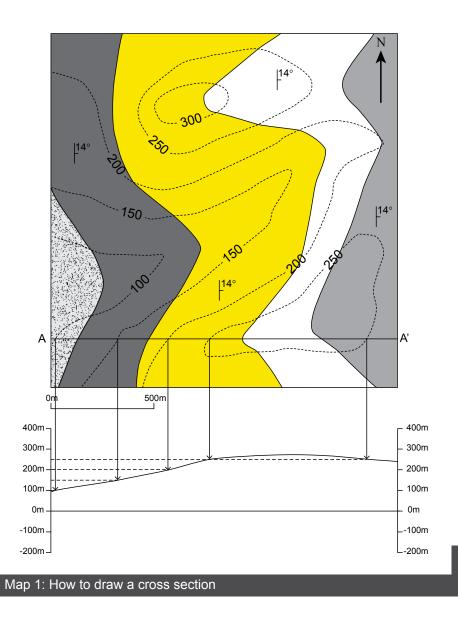
Step 2:

Draw axes of an appropriate scale with the topographic values. Unless there is a reason to do otherwise, draw a true-scale section.

Map 1: How to draw a cross section

How to draw a cross section:

Step 3:

Transfer the topographic information from the map to the section. Project the height of each topographic contour, where it crosses the line of section, on to the section and draw in the topography.
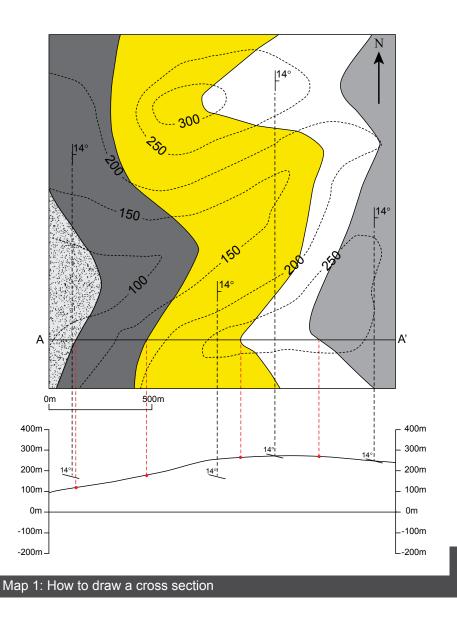

Map 1: How to draw a cross section

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How to draw a cross section:

Step 4:
Transfer the lithological boundaries, faults etc on to the cross section in the same way.

Step 5:
Transfer bedding readings on to the section, correcting for apparent dip if necessary (see figure 12). Plot the readings at the height at which they occur, so where a reading is extrapolated from a greater or lesser height than the topography of the cross section plot it above or below the topography as appropriate.
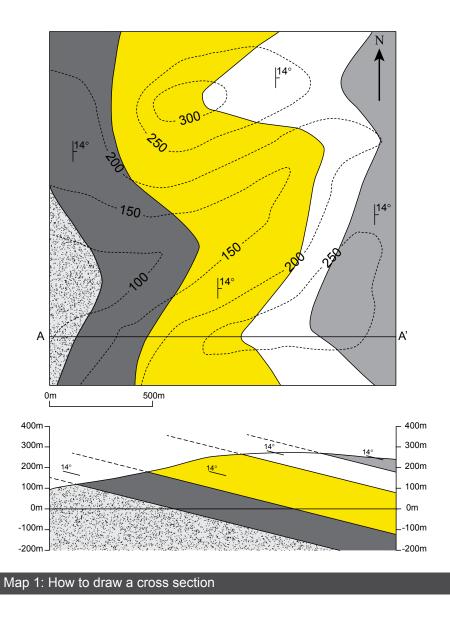

Map 1: How to draw a cross section

How to draw a cross section:

Step 6:

Using the bedding readings as a guide, draw in the lithological boundaries both above and below the surface. Geology extended above the topography is shown by dashed lines. When drawing the section always consider what is geologically reasonable behaviour for the layers e.g. sudden changes in a unit's thickness or dip should be justifiable.
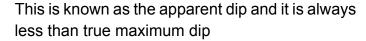
Step 7:

Stand back and admire your work.

Map 1: How to draw a cross section

Apparent dip:

Where a sequence of rocks are cut by a section which is not parallel to the maximum dip of the beds, then the amount of dip will appear to be less.

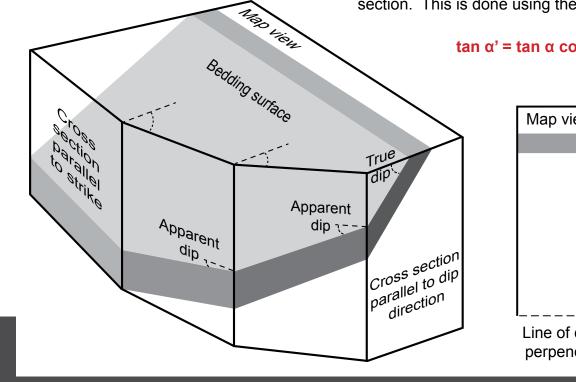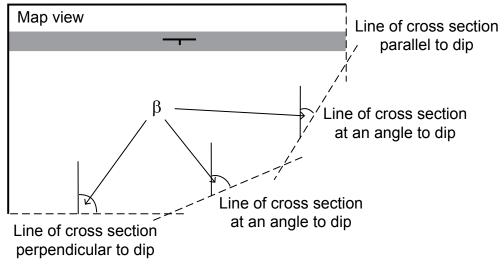This is known as the apparent dip and it is always less than true maximum dip

So to draw an accurate cross section it is necessary to calculate the apparent dip of the beds that do not strike perpendicular to the section. This is done using the equation:

$$\tan \alpha' = \tan \alpha \cos \beta$$

where β is the angle between the dip direction and the cross section; α is the angle of dip and α' is the apparent dip.

As the section becomes more and more oblique to the maximum dip the apparent dip will become less and less until, where the cross section is parallel to strike the beds, it will be zero and the beds will appear horizontal regardless of their true dip.

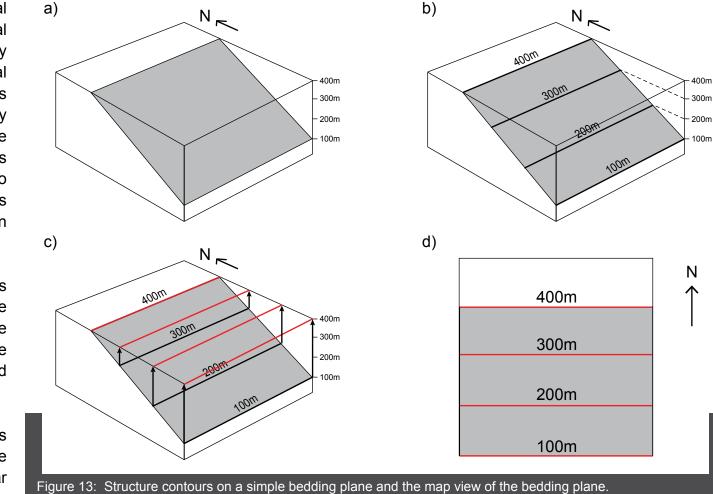Figure 12: Apparent dip illustrated as a block diagram and in map view.

Worksheet 3: Structure contours

Structure contours connect points of equal elevation (i.e. height or depth) on a geological surface (e.g. bedding) in the same way topographic contours connect points of equal height above sea level. Structure contours are also known as strike lines because they run parallel to strike. Structure contours are commonly used to contour subsurface horizons of interest. They can be used in the field to predict geological boundaries and used on maps with no bedding readings to aid cross section construction.

Figure 13a shows a bedding plane and heights above sea level. Figure 13b shows the structure contours as projected on to the plane. Figure 13c shows how these structure contours are projected on to the map view and figure 13d shows the map view.

A plane with a consistent strike and dip has evenly spaced straight structure contours (figure 13), whilst a folded plane or a plane with irregular dip will have folded or varyingly spaced structure contours (figure 15).

Figure 13: Structure contours on a simple bedding plane and the map view of the bedding plane.
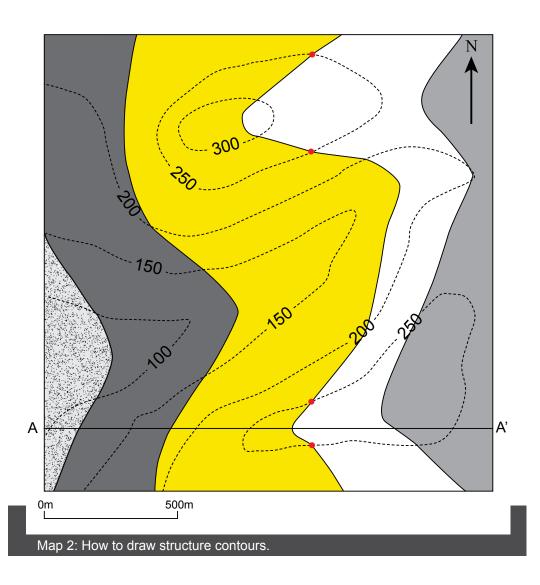
How to draw structure contours:

Where a topographic contours cuts the contact between two rock types it defines the height of the structure contour for the contact at that point.

Where a topographic contour cuts back and forth across a contact it gives several points at the same height.
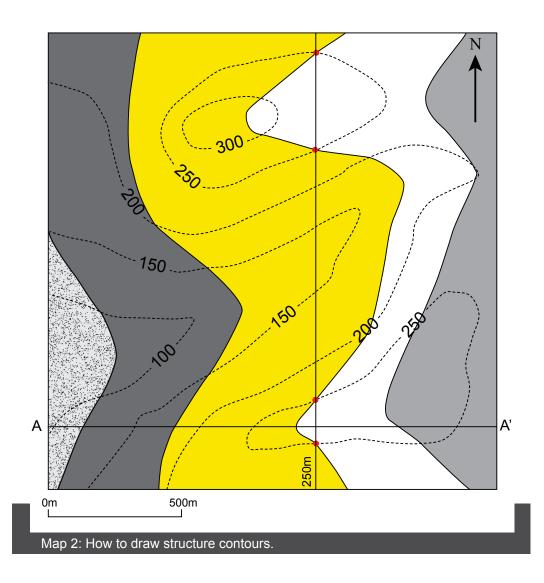
The red dots on map 2 are all at the same height: 250m - and so will all lie on the 250m structure contour for the boundary between the yellow and white units.

Map 2: How to draw structure contours.
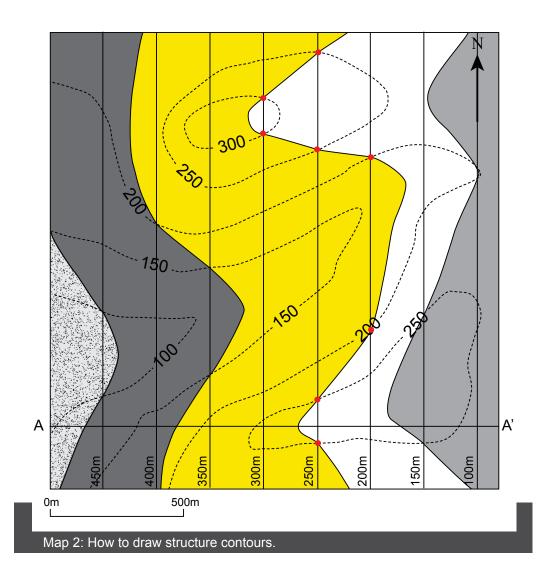
How to draw structure contours:

Assuming that strike does not vary along the boundary then the structure contours will be straight lines, so the points can be joined to form the structure contour for 250m.

At any point along the structure contour the boundary is at 250m. Where the topography is below 250m then boundary will be eroded away. Where the topography is greater than 250m the boundary will be underground.

N

300

250

200

150

150

100

200

250

250m

A   A'

0m   500m

Map 2: How to draw structure contours.
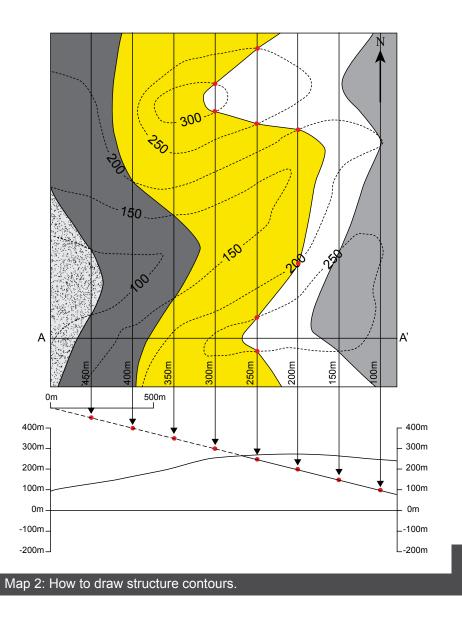
How to draw structure contours:

The process is repeated for the other structure contours. Assuming the boundary has a constant dip then the structure contours will be evenly spaced, meaning the structure contours can be drawn in even where the bed does not outcrop.

Map 2: How to draw structure contours.
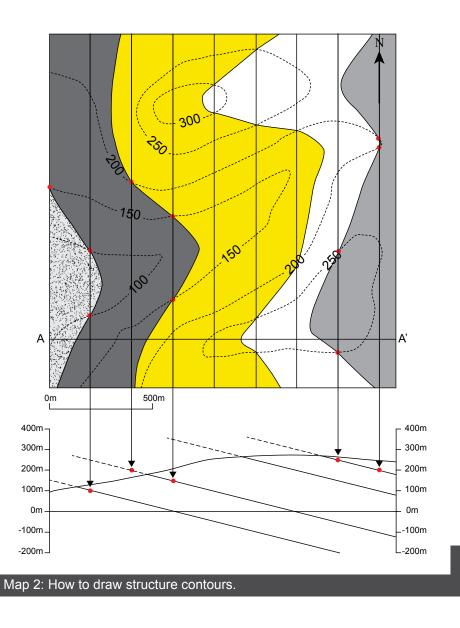
How to draw structure contours:

The structure contours can be used to construct the cross section for the boundary by projecting the heights of the structure contours, where they cross the line of section on the map, to the same height on the section itself.

Map 2: How to draw structure contours.
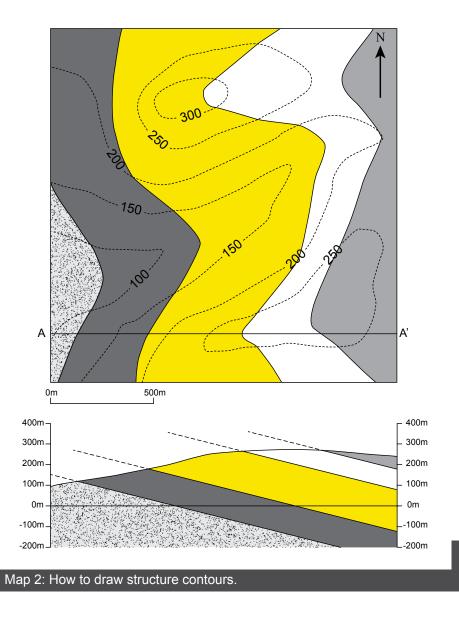
How to draw structure contours:

This process is then repeated for the other boundaries on the map.

Note that in this case, because the units have vertical thicknesses in multiples of 50m, the same spacing as the structure contours, the structure contours for the different boundaries overlie each other.

Map 2: How to draw structure contours.

How to draw structure contours:

The completed cross section drawn using structure contours.

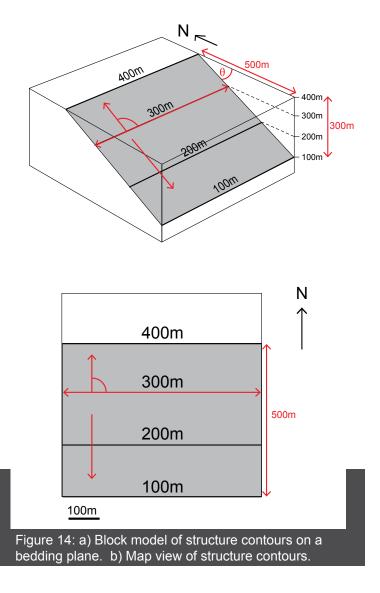Map 2: How to draw structure contours.

How to measure strike and dip from structure contours.

Strike is measured clockwise from north. In figure 14 the structure contours run east - west and so have a strike of 090.

To measure dip trigonometry is used. The horizontal distance is measured from the map and the vertical distance is the difference between the values of structure contours. In figure 14, the horizontal distance is 500m between the 400m and 100m structure contours. The vertical distance the difference between the two structure contours: 300m.
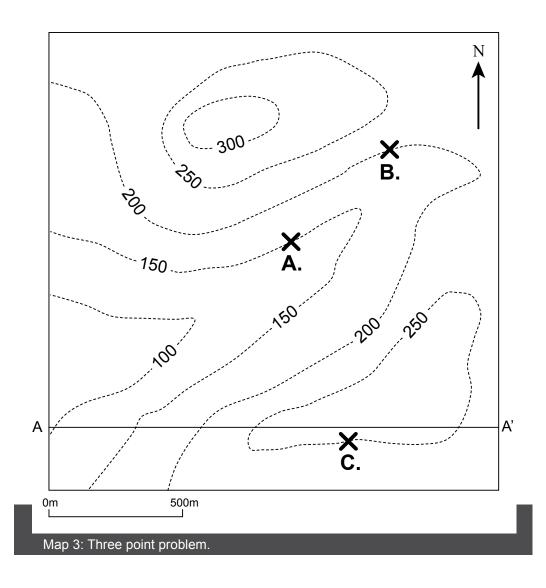
dip θ = tan^{-1}(300/500) = 31°

Figure 14: a) Block model of structure contours on a bedding plane. b) Map view of structure contours.
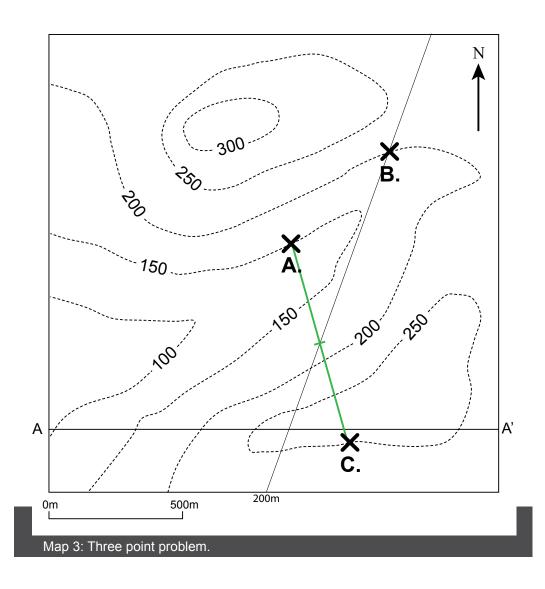
Three point problems

So far to create structure contours we have needed at least two points on a boundary to be able to draw in the contour. The 'three point problem' method allows structure contours to be drawn when only three heights/depths are known on a boundary.

Map 3 shows three small outcrops of a coal seam. Outcrop A is at 150m, outcrop B at 200m and outcrop C at 250m.

Map 3: Three point problem.
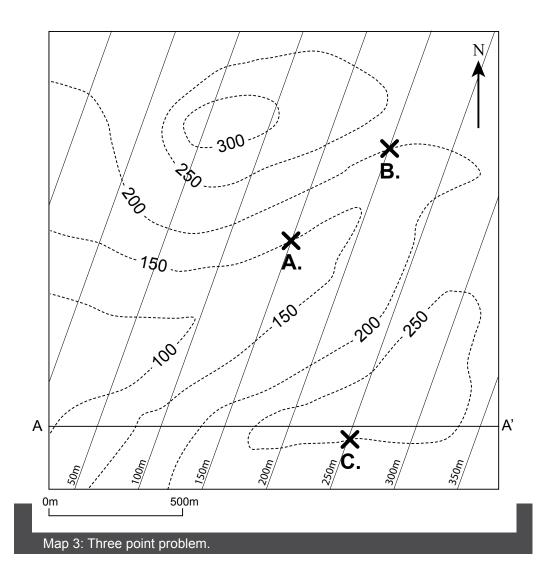
Three point problems

To find the structure contours for the coal seam a line is drawn between A and C. The mid point of this line crosses the 200m structure contour. Outcrop B also lies on the 200m structure contour and therefore this structure contour can be drawn in on the map.

Map 3: Three point problem.
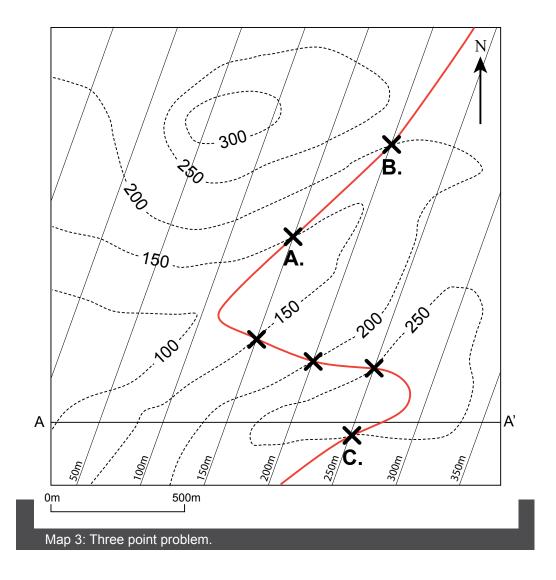
Three point problems

Outcrop A lies on the 150m structure contour and outcrop C on the 250m structure contour. Assuming the coal seam is planar, these structure contours can be drawn in parallel to the 200m structure contour. The rest of the structure contours for the coal seam can be drawn in at the same spacing across the map.

Map 3: Three point problem.
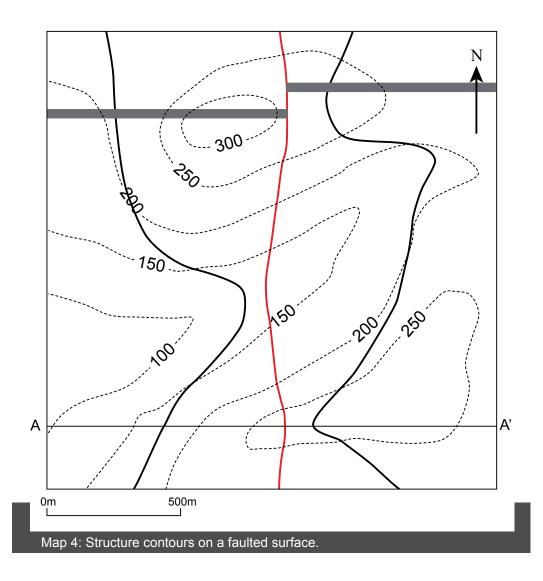
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Three point problems

The outcrop pattern for the coal seam can be constructed by finding where the structure contours and topographic contours of the same value cross. The coal seam can then be drawn in and a cross section drawn in the usual way.

Map 3: Three point problem.
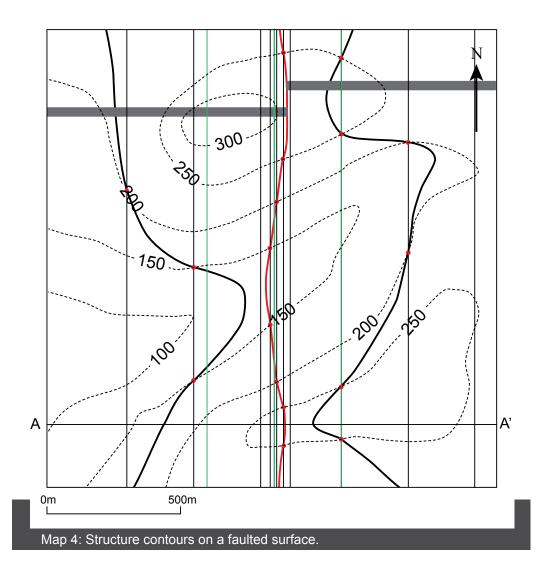
Structure contours on a faulted surface

Structure contours across faulted surfaces can be drawn in the same way as across bedding surface. Map 4 shows a coal seam (thin black line) and a dyke (thick dark grey line) cut by a fault (red line).

Map 4: Structure contours on a faulted surface.
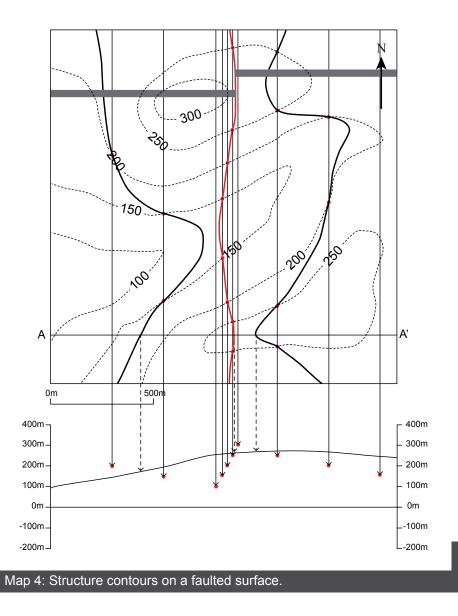
Structure contours on a faulted surface

Structure contours can be drawn on the fault and the coal seam in the usual manner. They could be drawn on the dyke but as it is vertical the structure contours would all lie on top of each other.
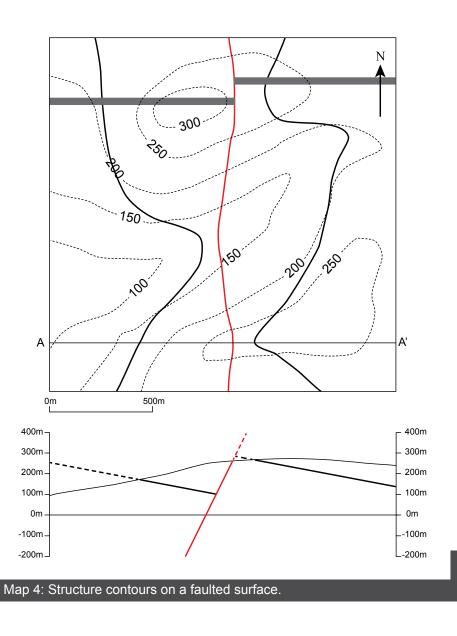

Map 4: Structure contours on a faulted surface.

Structure contours on a faulted surface

The cross section is constructed from the structure contours.

Map 4: Structure contours on a faulted surface.
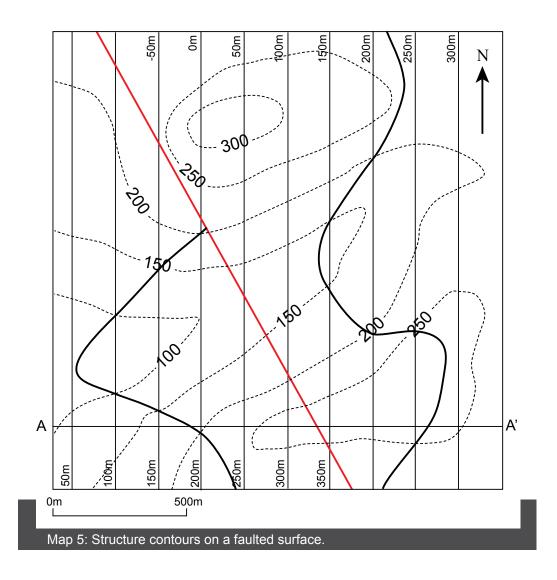
Structure contours on a faulted surface

Provided the section is true scale, the throw of the fault can be measured directly from it. However, a single boundary cannot tell us the displacement on the fault, information from a second boundary is needed. The dyke shows horizontal offset indicating the fault is an oblique sllip fault.

Map 4: Structure contours on a faulted surface.

Structure contours on a faulted surface

Map 5 shows another example of a faulted coal seam. In this case the throw on the fault can be determined from structure contours alone. Note how the value of the coal seam structure contours change by 200m as they cross the fault. The coal seam to the east of the fault is downthrown by 200m relative to the coal seam on the west of the fault. From the map alone it is not possible to work out whether there has been any along strike displacement on the fault.
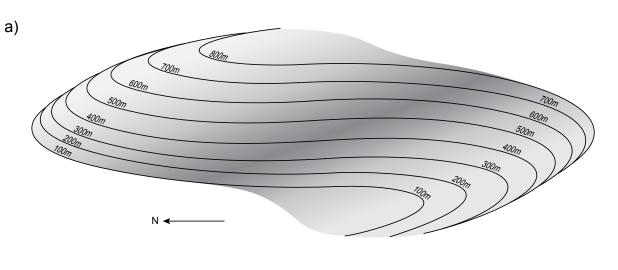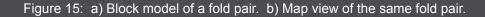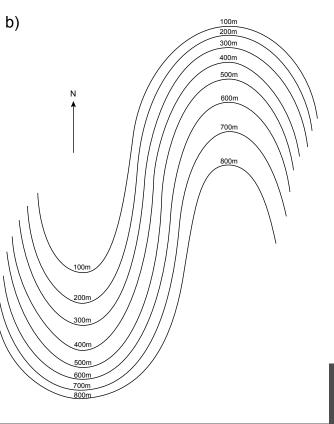

Map 5: Structure contours on a faulted surface.

Structure contours on a folded surface

So far we have dealt with structure contours on a planar surface, that is one with a constant strike and dip. For surfaces which vary in strike and/or dip structure contours can still be constructed.

Figure 15 shows a fold pair with structure contours.   As the strike of the beds varies around the fold so do the structure contours. Figure 15b shows the map view of the fold. Note how where the dip of the beds are steeper the structure contours are closer together and where the dip of the beds is shallower the structure contours are more widely spaced.
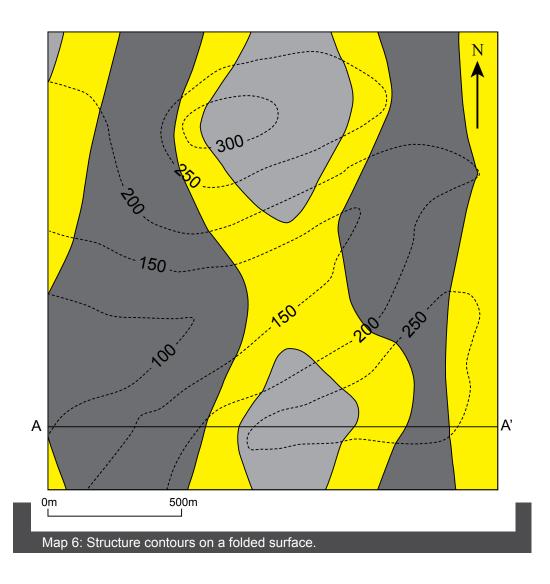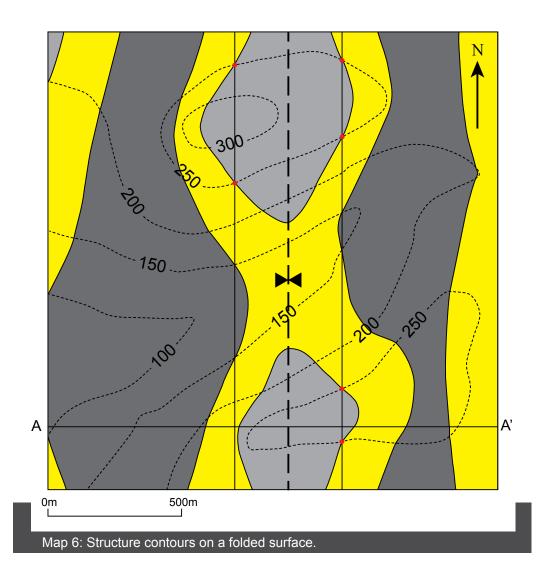
a)

b)

Figure 15: a) Block model of a fold pair. b) Map view of the same fold pair.

Structure contours on a folded surface

Structure contours on a folded surface are constructed in the same way as for a dipping surface. This first example is for a simple, non-plunging upright fold, where the limbs have consistent strikes and dips, making the process of drawing the structure contours and cross section the same as for a dipping bedding planes.

Map 6: Structure contours on a folded surface.
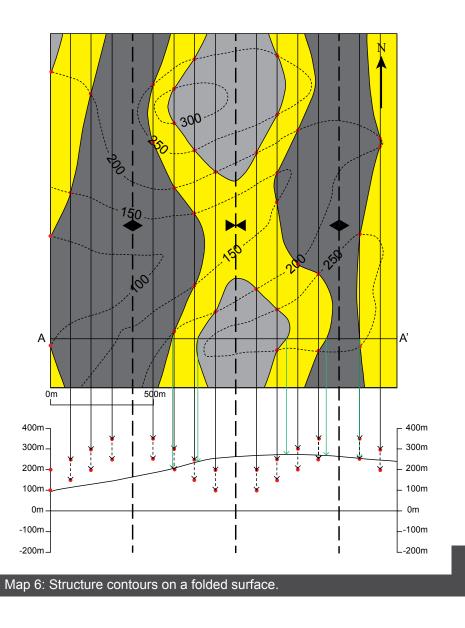
Structure contours on a folded surface

The beds map 6 show the repeating outcrop pattern of folded beds. The red dots show where the yellow/light grey boundary crosses the 250m topographic contour. There are two ways the dots could be joined to form structure contours - either east-west or north-south. However, from the way the beds vee in the valley it can be deduced the axial planes of the folds run roughly north-south and so the structure contours for the limbs must also be north-south.

Map 6: Structure contours on a folded surface.

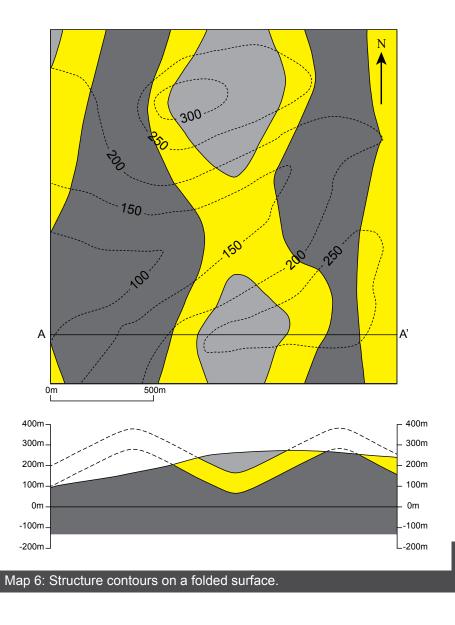# Structure contours on a folded surface

The structure contours for the rest of the boundary and the yellow/dark grey boundary can be drawn in in the usual way and projected on to the cross section as before.

Map 6: Structure contours on a folded surface.

Structure contours on a folded surface

Completed cross section.

Map 6: Structure contours on a folded surface.

Contents

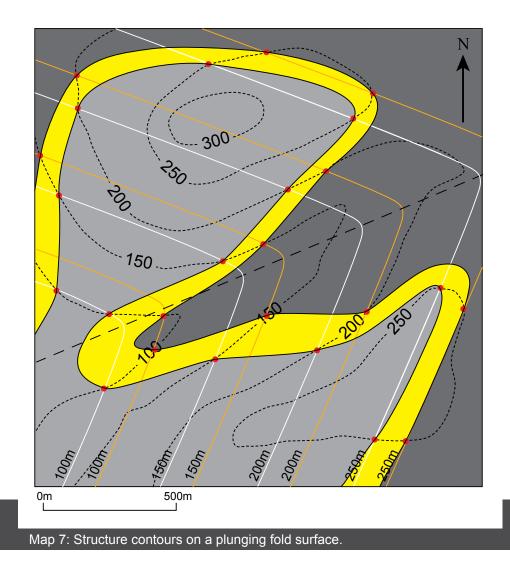# Structure contours on a folded surface

Map 7 shows a plunging syncline with structure contours. The white structure contours are for the yellow/pale grey boundary and the orange structure contours are for the yellow/dark grey boundary. The dashed line is the axial trace. The plunge of the syncline can be calculated from the structure contours in the same way as dip is calculated using:

plunge = tan^{-1}(vertical/horizontal)

where the vertical is the difference in the value of the structure contours and the horizontal is measured from the map.

Azimuth is measured clockwise from north.

Map 7: Structure contours on a plunging fold surface.

Acknowledgments and references

Map sources:

Geological maps are all copyright of NERC and BGS and have been made available via GeoScholar.

Bibliography:

Bennison, G.M. and Moseley, K.A., 2011. An introduction to geological structures and maps: a practical guide. Eighth edition, Hodder education.

This module is based on the maps component of the first year stratigraphic principles and maps course of the Geological Sciences degree programme at the School of Earth and Environment, the University of Leeds.

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