

## Structural Analysis of Rocks and Regions 2017

### Maps and cross-sections

The practicals in SARR will introduce you to (or remind you of) the tools and skills that are typically used to reconstruct and quantify the deformation of rocks and to identify the signature of different deformation types in rocks and in landscapes. The analysis will be carried out at a range of scales, from the thin section to whole mountain ranges. These skills and tools include: geological cross-sections on real geological maps (weeks 1 and 3), topographic analysis using Geographical Information Systems (weeks 2 and 5), stereoplots and kinematic analysis (week 4), strain analysis (weeks 6 and 7), 3D seismic (week 8) and critical assessment of published literature (week 9). Please note that this is a new course so this schedule may be subjected to changes.

We begin with cross-sections: most of you are familiar with the basics but have not had much chance of practicing on real geological maps. This handout aims to provide all the information you need to be able to produce a professional cross-section in complex terrain – please bring back this handout in week 3 too.

We will start with a cross-section on the **Devil's Fence** map (Montana) which exhibits folded strata and magmatic intrusions. In week 3 we will produce a cross-section on the **Bristol** geological map which has folded strata, faulting and unconformities. Additional maps will be available in the JCMB lab for you to practice in your own time; online tutorials (on Learn) will help you with the following maps: **Grand Canyon**, Arizona (monoclinical structure + unconformities), **Williamsville**, Virginia (Folding + faulting + relief inversion) and **Canmore**, Canada (fold and thrust belt + unconformities). Feedback on the cross-sections you produce will be provided during the tutorials.

You are now going to analyse the geological map and build your cross-section, following a few steps that you will repeat for each map.

#### **I. Reading the map**

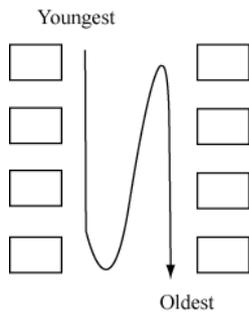
You have been given a geological map. Before starting anything, spend at least 10 minutes looking at the map and the caption.

*What is the scale of the map? What kind of landscape are you looking at: rolling hills? mountains? What is the topographic contour interval? What are the units used: meters? feet? furlongs? What do the different lines and symbols represent? What do the colours represent?*

The colours represent “geological units” which refer to a given rock type of a given age. These units are separated from each other by contacts which can be sedimentary, igneous, tectonic (faults), etc. Each unit has a symbol to help identification (e.g. “Qls”, “PPs”; please refer to the caption for more information).

Colour schemes and symbols are usually normalised within a given country: in French geological maps for example, Latin lowercase letters are used for sedimentary rocks, Latin uppercase letters for “drift” (Quaternary) units, Greek letters for igneous and metamorphic rocks; Jurassic rocks are blue, Cretaceous green, Tertiary orange-yellow, etc. Some rules seem to apply worldwide: the trace of faults is usually thicker than the trace of other types of contact (in some countries, fault traces are red). Igneous rocks are usually bright coloured. Symbols for geological units usually begin with a letter referring to their age: Permian units will be “P...”, Miocene rocks will be “M...”.

In the caption, the younger units will always be at the top left and the oldest ones at the bottom right:



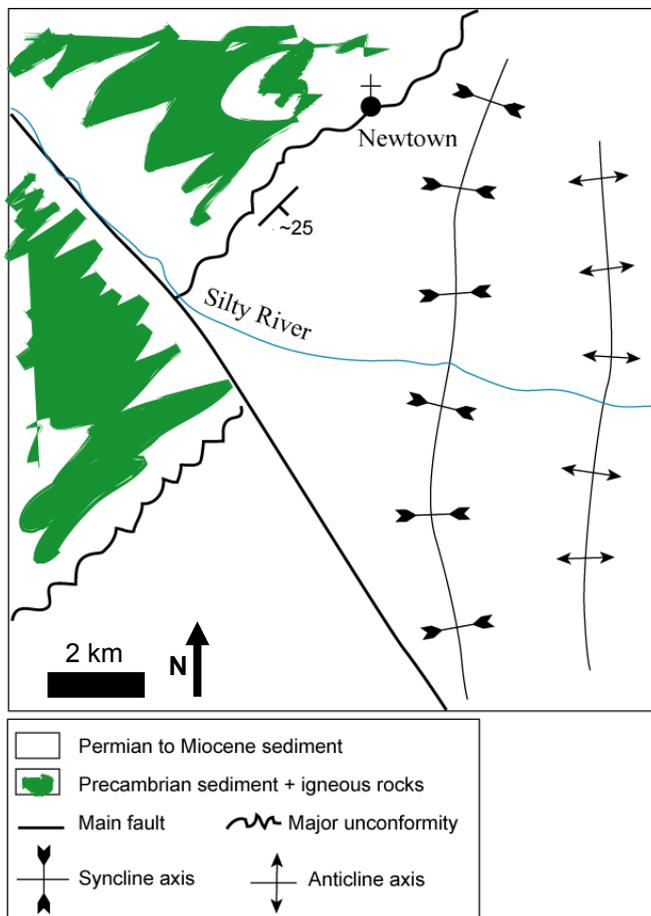
Additional useful information on the map may include the trace of fold axis and symbols giving the dip and dip direction of beds. In metamorphic rocks, different symbols may also give the dip and dip direction of foliation (see caption). Note that dip/dip direction symbols can differ between countries: a bed dipping 24 degrees in the direction N120 will be represented as follow:

USA, France: <sup>24</sup>

UK: <sup>24</sup>

## II. Drawing a structural diagram

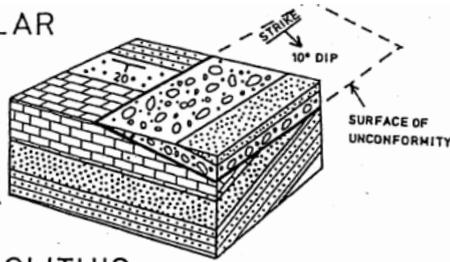
Now, you are going to spend ~30 minutes drawing a structural diagram: take an A4 page which will represent the extent of the map and draw on this page the main features that you recognize in the landscape: main geological units, main faults, unconformities, fold axis, etc. To do so, you will have to explore the map and look for such features: what are the rock types exposed? In which direction do they dip? Is this direction uniform across the map? Is the stratigraphic succession the same across the map? This is an important step because it means that you will already have an idea of the structures that you will cross when you will do your cross-section! On the structural diagram, you will draw these structures schematically. Below is an example of a hypothetical structural diagram:



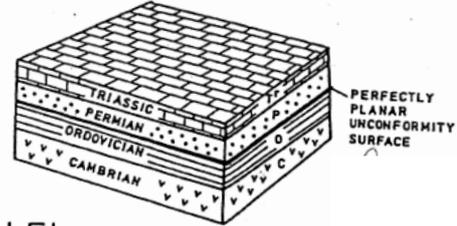
## ➔ How to identify unconformities?

There are different types of unconformities (see diagram below):

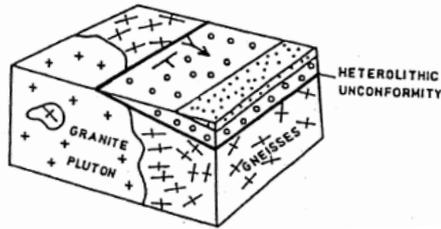
a. ANGULAR



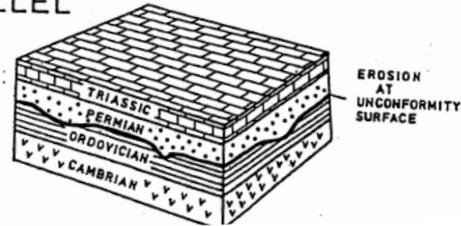
c. NON-DEPOSITIONAL



b. HETEROLITHIC



d. PARALLEL

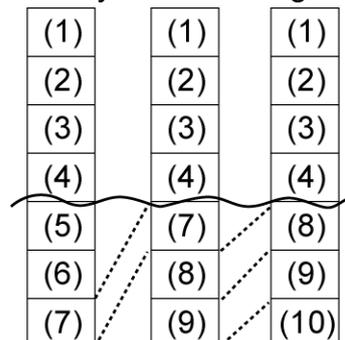


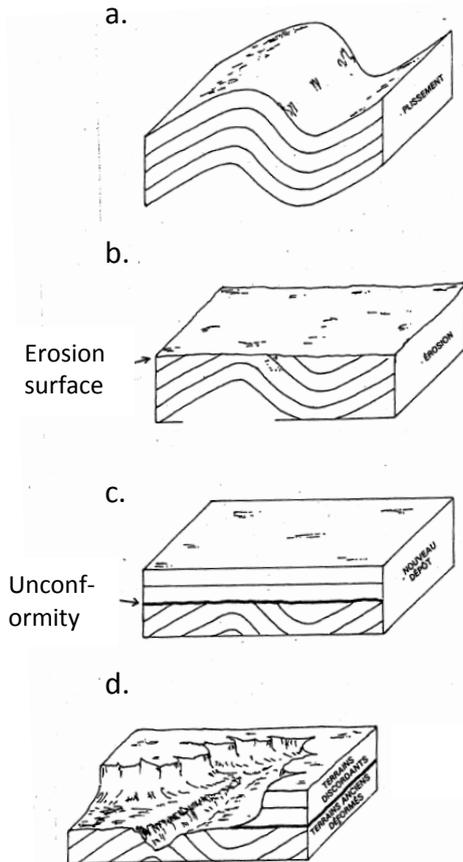
Non-depositional and parallel unconformities (c and d) are the most difficult to find because they just represent a gap in the record (some time is “missing”, in this case Silurian + Devonian + Carboniferous). Changes in the thickness of the Ordovician may help evidence the presence of a parallel unconformity in case d. Angular and heterolithic unconformities are much easier to identify on a geological map: “triple points” are what you will be looking for, that is, points where non-tectonic contacts intersect other non-tectonic contacts. In the case of the heterolithic unconformity, there will be a difference in rock type above and below the unconformity in addition to the presence of triple points (e.g. igneous and/or metamorphic below, sedimentary above). The diagrams in the following pages illustrate how angular unconformities can form and how they will appear on the map and in cross-section.

An additional way of identifying angular unconformities is to analyse the succession of rocks on the map: if the succession is a layer cake with layers 1, 2, 3, 4, 5, 6, and 7 without unconformity, then this succession should be found everywhere on the map (except where there are faults). If the succession changes, it means that there is an angular unconformity somewhere. For example, below are 3 successions observed at 3 different places on the map:

(1)	(1)	(1)
(2)	(2)	(2)
(3)	(3)	(3)
(4)	(4)	(4)
(5)	(7)	(8)
(6)	(8)	(9)
(7)	(9)	(10)

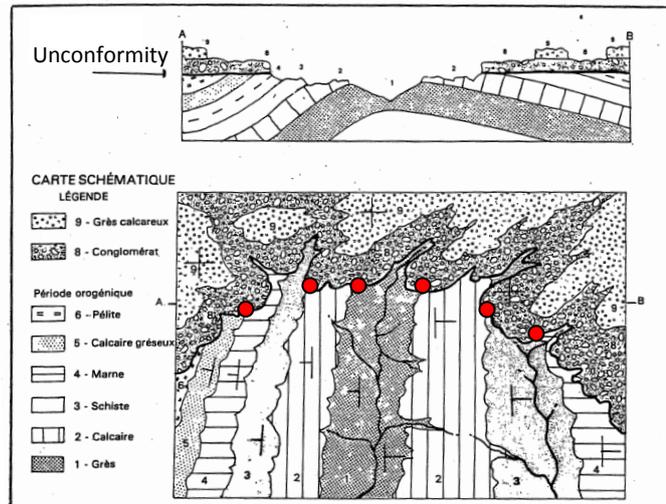
The succession 1, 2, 3, 4 is the same everywhere; the succession under 4 changes (layers 5 and 6 are missing in the 2<sup>nd</sup> location, layers 5, 6 and 7 are missing in the 3<sup>rd</sup> location) → the base of layer 4 is an angular unconformity:



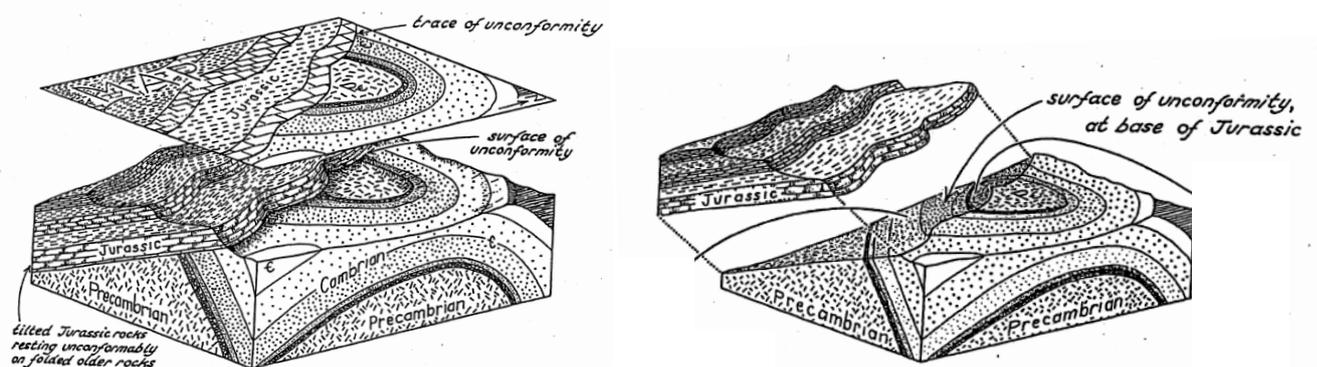


Left: example of formation of an angular unconformity. a: folding of an existing layered succession. b: erosion. c: deposition of sediment horizontally above the erosion surface. d: example of resulting landscape.

Below: cross-section and geological map showing a geological structure with unconformity. Triple points in red.



Below: map view and 3D view of an angular unconformity.



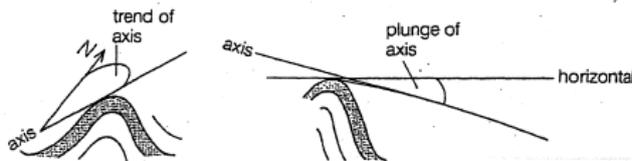
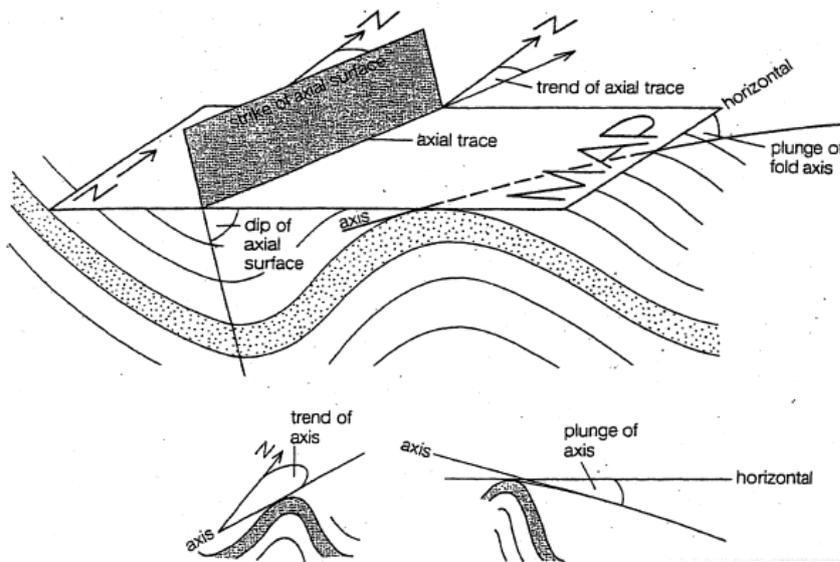
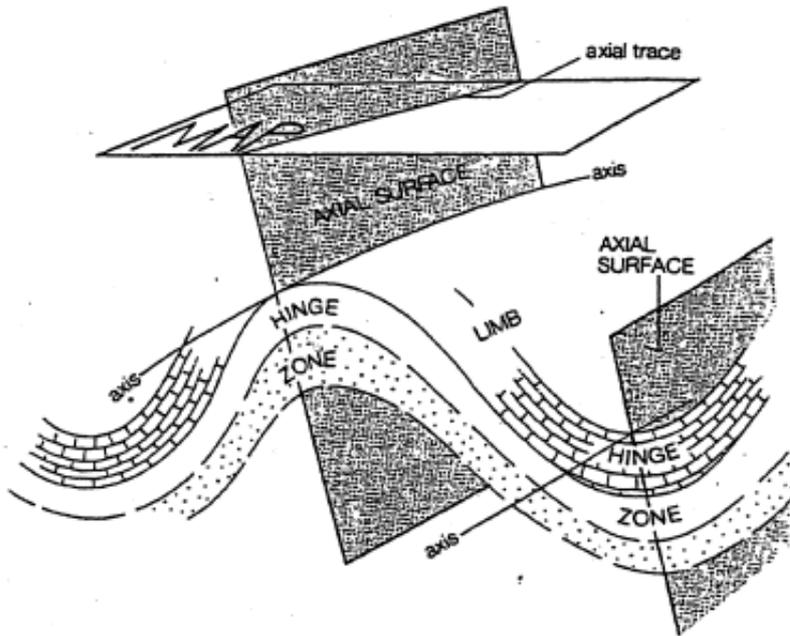
## ➔ How to identify folds?

Folds (anticlines and synclines) can be identified on the map in 2 ways:

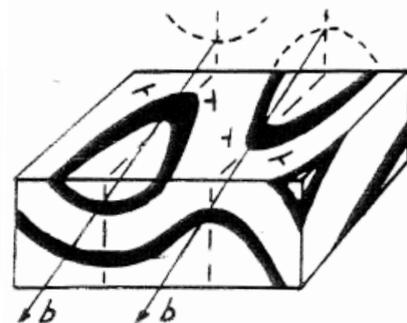
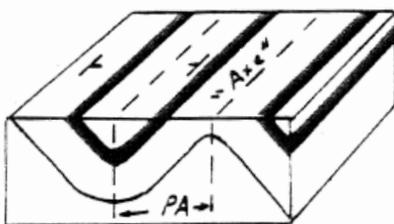
- symmetrical repetition of beds (e.g. 4, 3, 2, 1, 2, 3, 4),
- general change in dip direction by  $> 90^\circ$  ( $\sim 180^\circ$  in case of folds with horizontal axis).

The figures below illustrate these points.

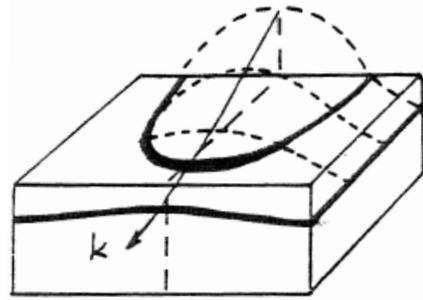
The different parts of a fold (top) and orientation of folded structures (bottom)



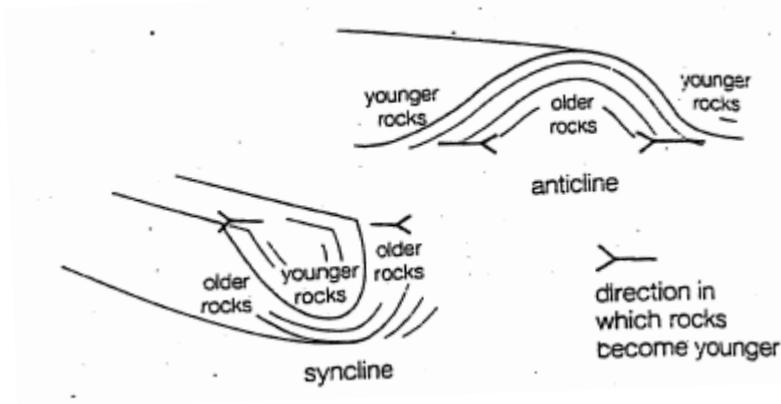
Below: folds and their traces on a map: symmetrical (left, "PA" for "axial surface"), asymmetrical (middle), plunging axis (right).



Note: symmetrical folds don't carry on forever. Their termination will produce a trace similar to those of a fold with plunging axis (see diagram to the right).

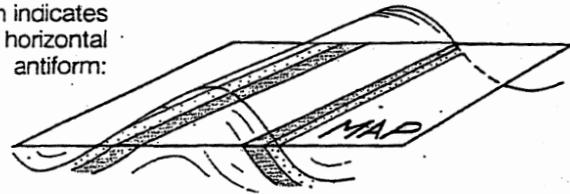
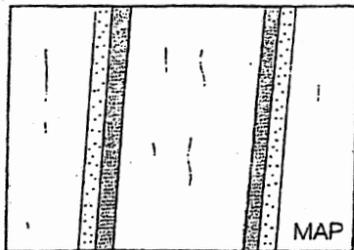


Below: syncline and anticline

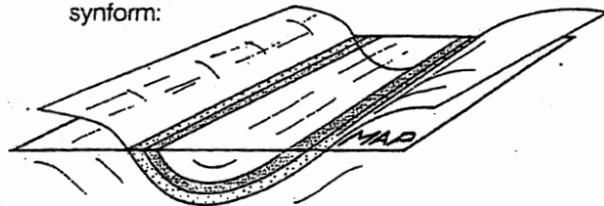


Below: folds and their trace on a map

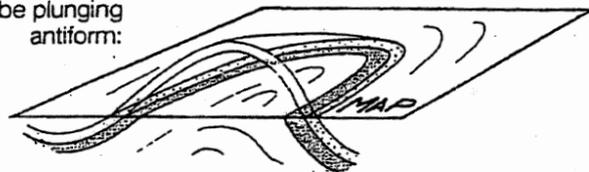
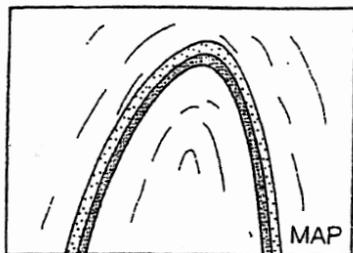
symmetrical repetition indicates folded beds; could be horizontal antiform:



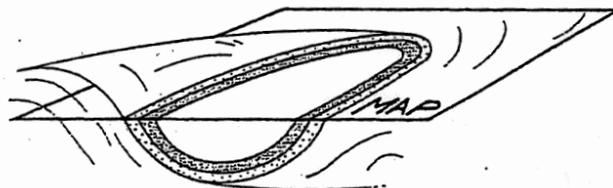
or horizontal synform:

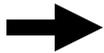


converging pattern indicates plunging fold; could be plunging antiform:

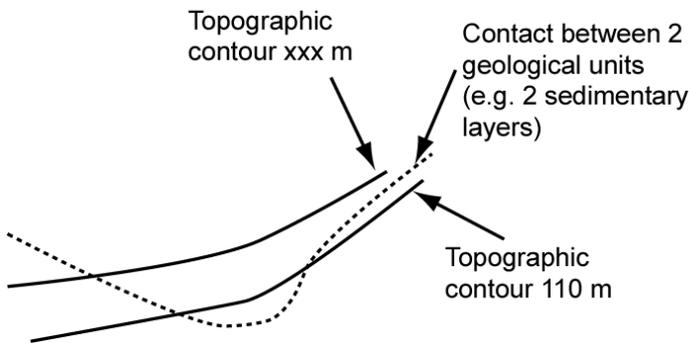


or plunging synform:

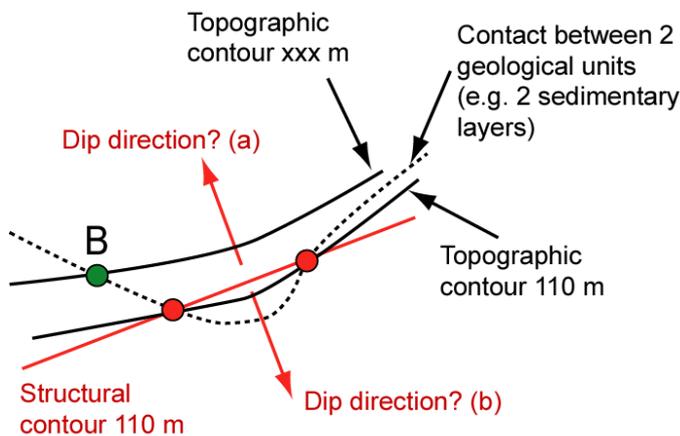




**Reminder:** dip and dip direction of layers are usually given by widespread symbols on the map. The dip direction can also be inferred quickly using the shape of the contacts in valleys and on ridges (see 3D model in the classroom: “v” in valleys point towards the dip direction) and/or using structural contours:



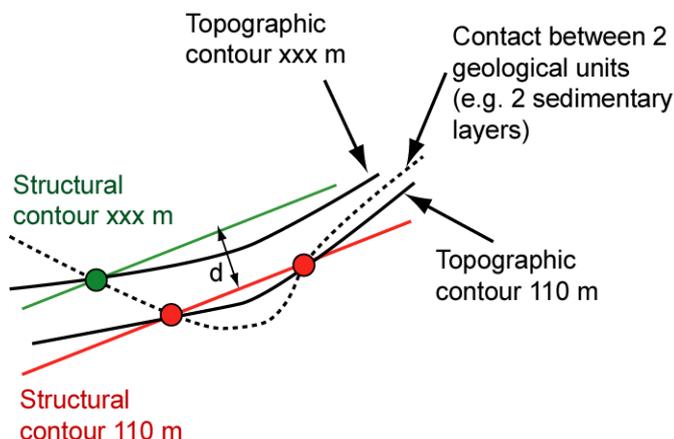
(1) Find a place where the contact intercepts twice the same topographic contour: the 2 intersection points are at the same elevation on the contact, so the line connecting these 2 points is a structural contour (at an elevation 110 m in this case). **The dip direction is perpendicular to this line (in direction (a) or (b), see diagram below left).** Note: if the two points are too close (i.e. less than ~5 mm away), the orientation of the structural contour will not be very accurate. If the two points are too far away (i.e. more than ~10 cm away), the accuracy may be compromised by changes in the orientation of the contact (e.g. folding).



(2) Find a place where the contact intersects another topographic contour, for example point B (see diagram to the left). This point is on the contact at an elevation xxx m. If

$xxx < 110\text{ m}$ , then the contact goes down in the (a) direction → dip direction is given by arrow (a). If  $xxx > 110\text{ m}$ , then the contact goes up in the (a) direction → dip direction is given by arrow (b).

**This test can be performed very quickly in many places on the map without having to trace anything!** If you want to calculate the dip value, I remind you below how to do it in such a situation:

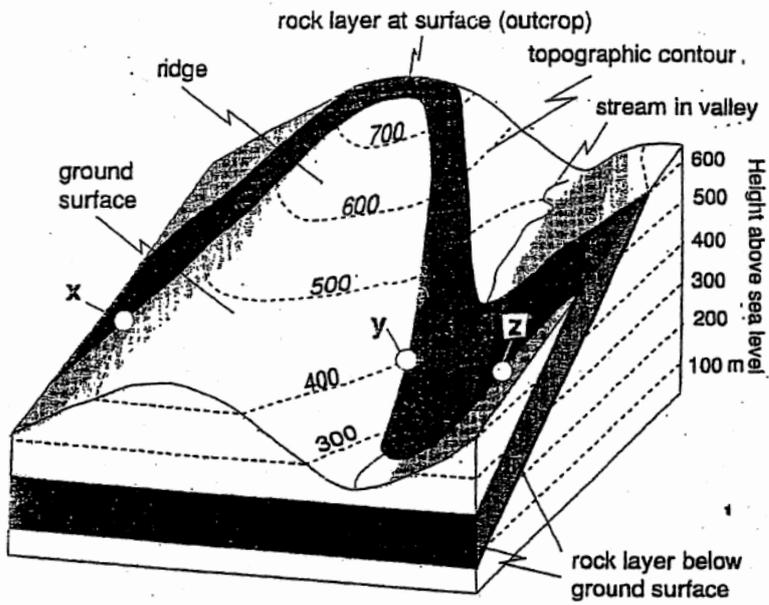


If  $d$  is the orthogonal distance (in meters) between the structural contours 110 and xxx m, then we have:

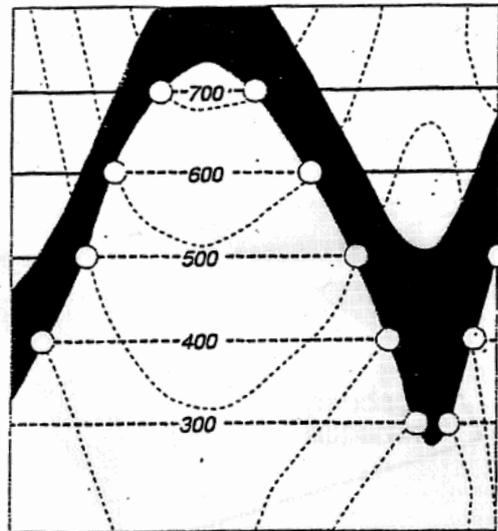
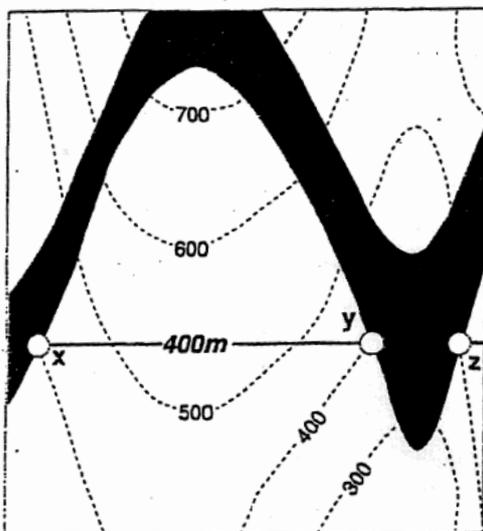
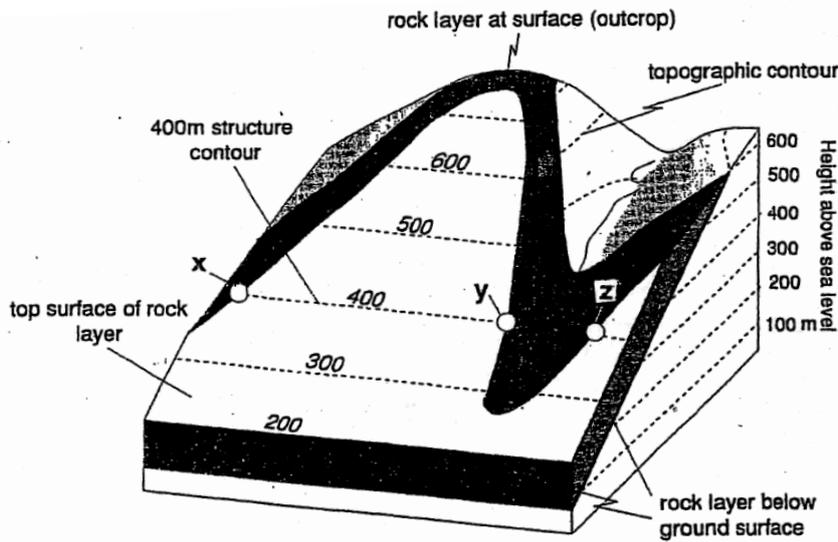
$$\tan \alpha = \Delta z / d$$

where  $\alpha$  is the dip of the contact and  $\Delta z$  is the difference in elevation between the two topographic contours,  $|110 - xxx|$ .

You will find on the next page some diagrams which will remind you what structural contours are and how to build them; you should know that pretty well by now.



Top: example of a layer intercepting the topography. Middle: the topography above the layer has been removed to show the structural contours. Bottom: building the structural contours on the map.



**Note: when you draw your geological cross-section, make as much use as possible of the dip and dip direction symbols on the map. Use the structural contour method to determine dip values only if necessary (e.g. no symbols near the cross-section line, dip and dip direction changing rapidly across the landscape).**

### III. Building the topographic profile

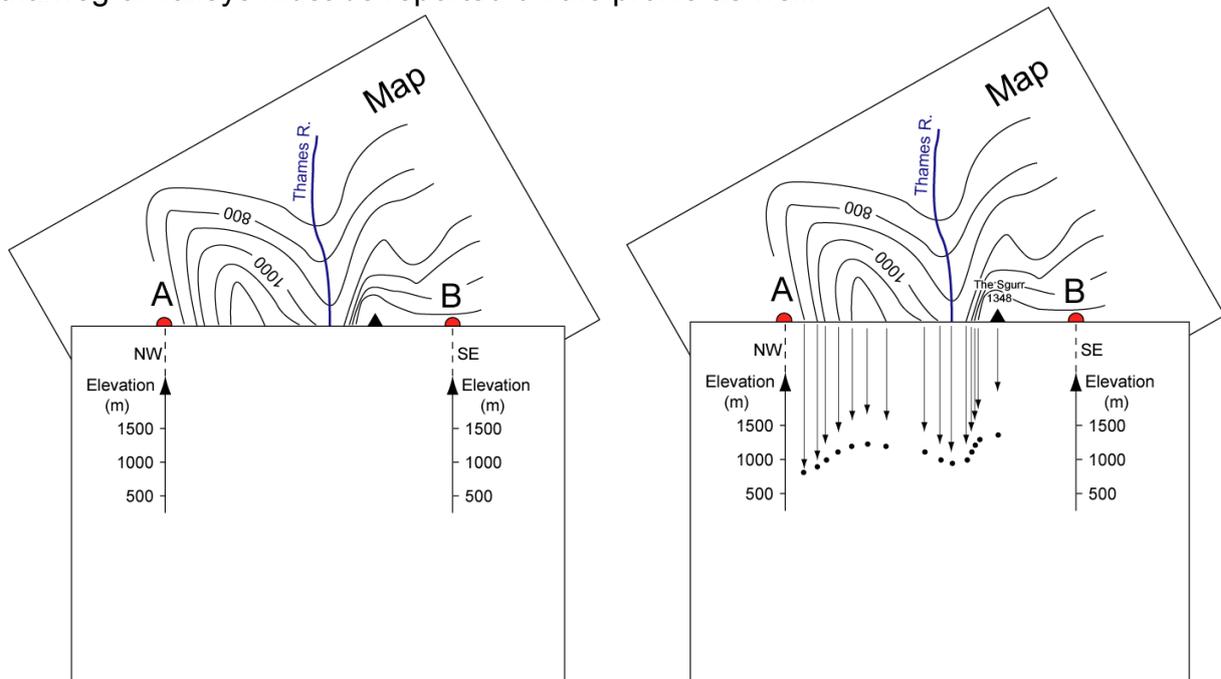
The line of cross-section will be specified to you. The first step involves building the topographic profile, that is, the shape of the landscape along this line. You will draw your profile **WITHOUT VERTICAL EXAGGERATION**. If the scale of the map is 1/50000, then you will use the same scale for the vertical heights: 1 mm represents 50000 mm, that is, 50 m (so 1 cm represents 500 m). Be careful: some maps have units in feet, others in meters, and you will fully appreciate the beauty of the imperial unit system with this exercise.

(1) Locate the beginning and end of your cross-section on the map.

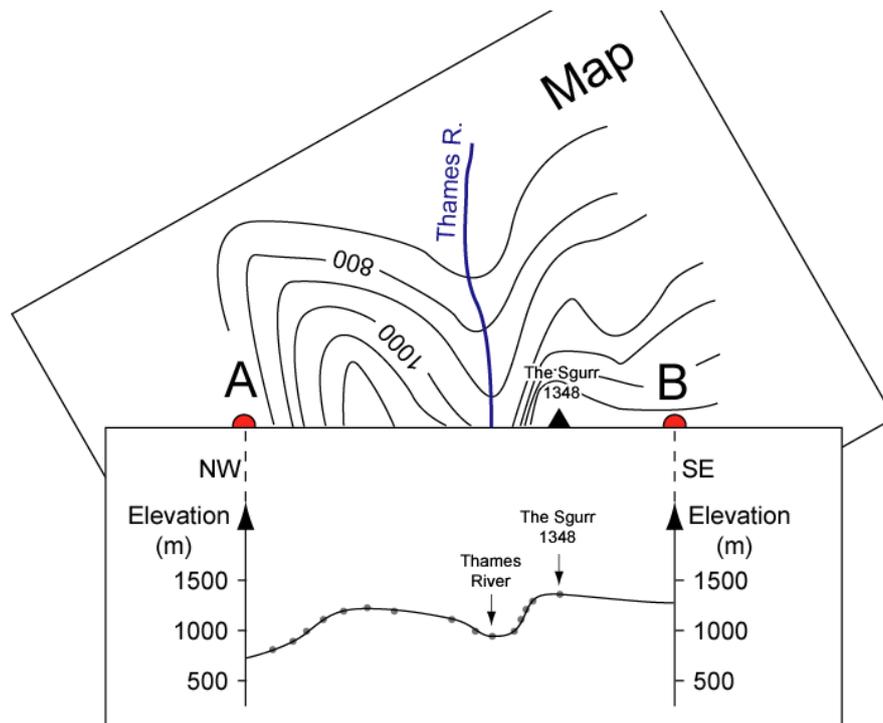
(2) Along the profile, find the lowest and highest elevations.

(3) On a A4 graph paper page, place the elevation axis at the extremity of your profile and the orientation of the profile. **Leave room below the profile to fill in the geology and put the caption** (see diagram below left; in this example, lowest elevation ~700 m and highest elevation is 1348 m → elevation on axis ranges between 500 and 1500 m).

(4) Report the points at their corresponding elevation (see diagram below right). Make small dots using a sharp pencil, avoid big blobs (if the scale is 1/50000, a 1-mm-thick dot will be 50-m thick!). You don't need to report the elevation of ALL contours: if the spacing between contours is uniform in an area, it means that slope is constant so a few points will do the job. However, it is important to report elevation where slope changes (i.e. spacing between contour changes); top of hills and thalweg of valleys must be reported on the profile as well.



(5) Connect the points (see figure next page). Note: you may want to annotate the key geographic locations (e.g. summits, valleys, cities) only when you are finished with your geological cross-section.

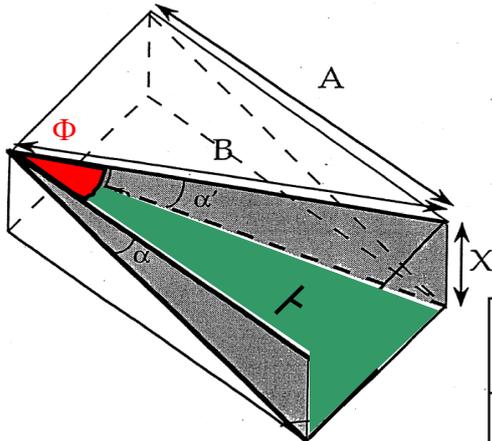


#### IV. Building the geological cross-section

Basic rules:

- **use a sharp pencil** (thin lead). Don't push too hard on the pencil until you are 100% sure of your drawing. Don't hesitate to draw, erase and correct your contacts until the relationship between your different units looks realistic. Use construction lines to help your drawing (e.g. lines with various dip values, see further).
- **don't use a ruler to draw your contacts or faults**, it doesn't look natural! However, you can use a ruler to guide your line (this can be useful in unfolded terrane): draw a very light line with the ruler and draw your "final" line free hand on top.
- **thickness of sedimentary units should be kept constant** except if stated otherwise (or if there is strong evidence on the map that thickness is changing). Most of the time, the thickness of the units will emerge naturally while you are constructing your cross-section (see further). Thickness is sometimes indicated in the caption or in the map booklet (when there is one). Thickness can also be calculated using structural contours.
- **draw from youngest to oldest**. If faults are the youngest features on the map, start with them (if not, draw the units which are younger than them first). Fill the cross-section with layers/units from youngest to oldest.
- **consider blocks delimited by faults independently**. If a contact has a given dip/dip direction on one side of a fault, it does not necessarily have the same on the other side.
- **don't draw contacts with the same dip down to the centre of the Earth!** The dip and dip direction information given on the map has been measured AT THE SURFACE. Draw your contacts as they appear near the surface, then look at how they behave as you move away from your cross-section before drawing them underground (e.g. a contact will be drawn horizontal if it follows topographic contours). Don't hesitate to look away from the cross-section line (it is the only way to see unconformities for example).

- **make use of the information available on the map.** Don't calculate dip and dip direction for each layer using structural contours if symbols provide this information. If dip and dip direction are fairly uniform within a given area, it justifies using these dip and dip direction to build your cross-section in this area.
- **calculate apparent dip:** depending on the angle between the line of section and the dip direction, contacts will have different "apparent" dips. If the line of section is parallel to the dip direction, apparent dip = true dip. If the line of section is perpendicular to the dip direction, apparent dip = 0 (the layer will appear horizontal). This is illustrated below.



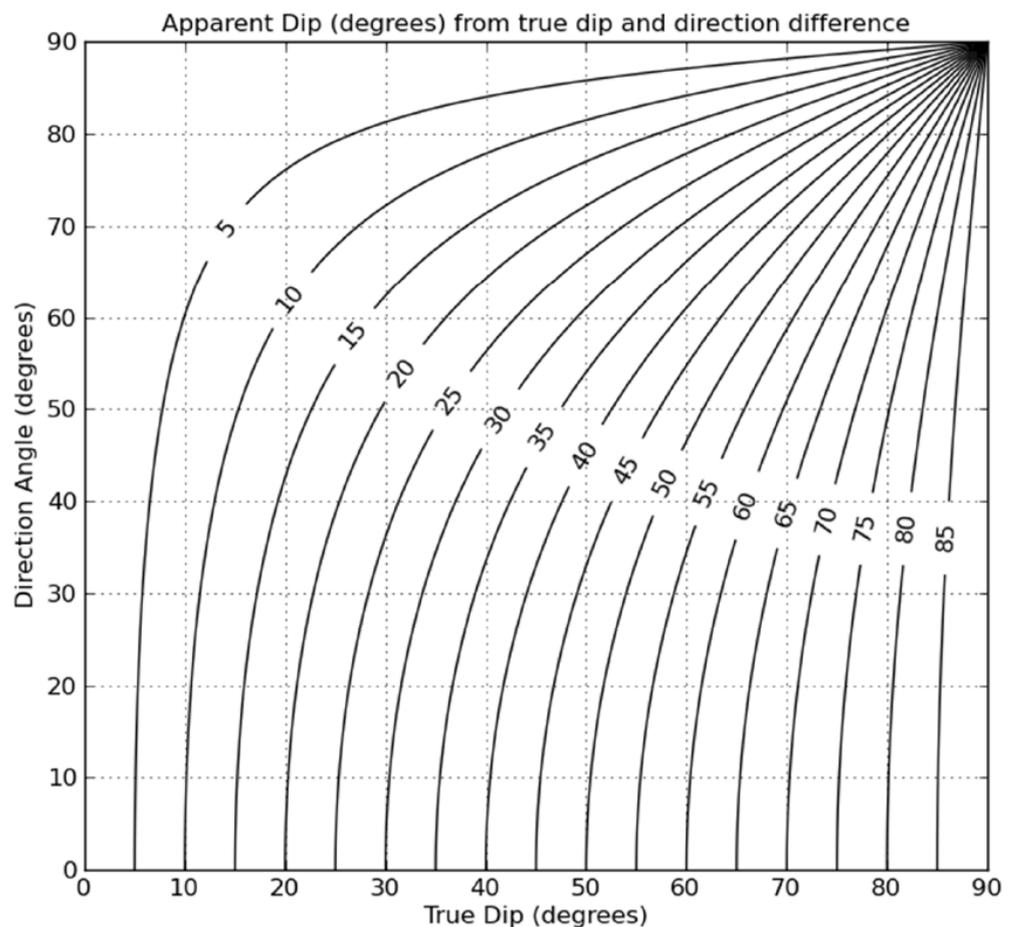
$\alpha$  = true dip,  
 $\alpha'$  = apparent dip along line of section (B),  
 $\Phi$  = direction angle = angle between line of section and dip direction.

$$\tan \alpha' = X/B = X/A * A/B = \tan \alpha * \cos \Phi$$

True Dip $\alpha$ :	If angle between line of section and dip direction $\Phi$ is:				
	10°	30°	50°	70°	90°
0	0	0	0	0	0
10	10	9	6	3	0
30	30	27	20	11	0
50	50	46	37	22	0
70	70	67	60	43	0
90	90	90	90	90	-

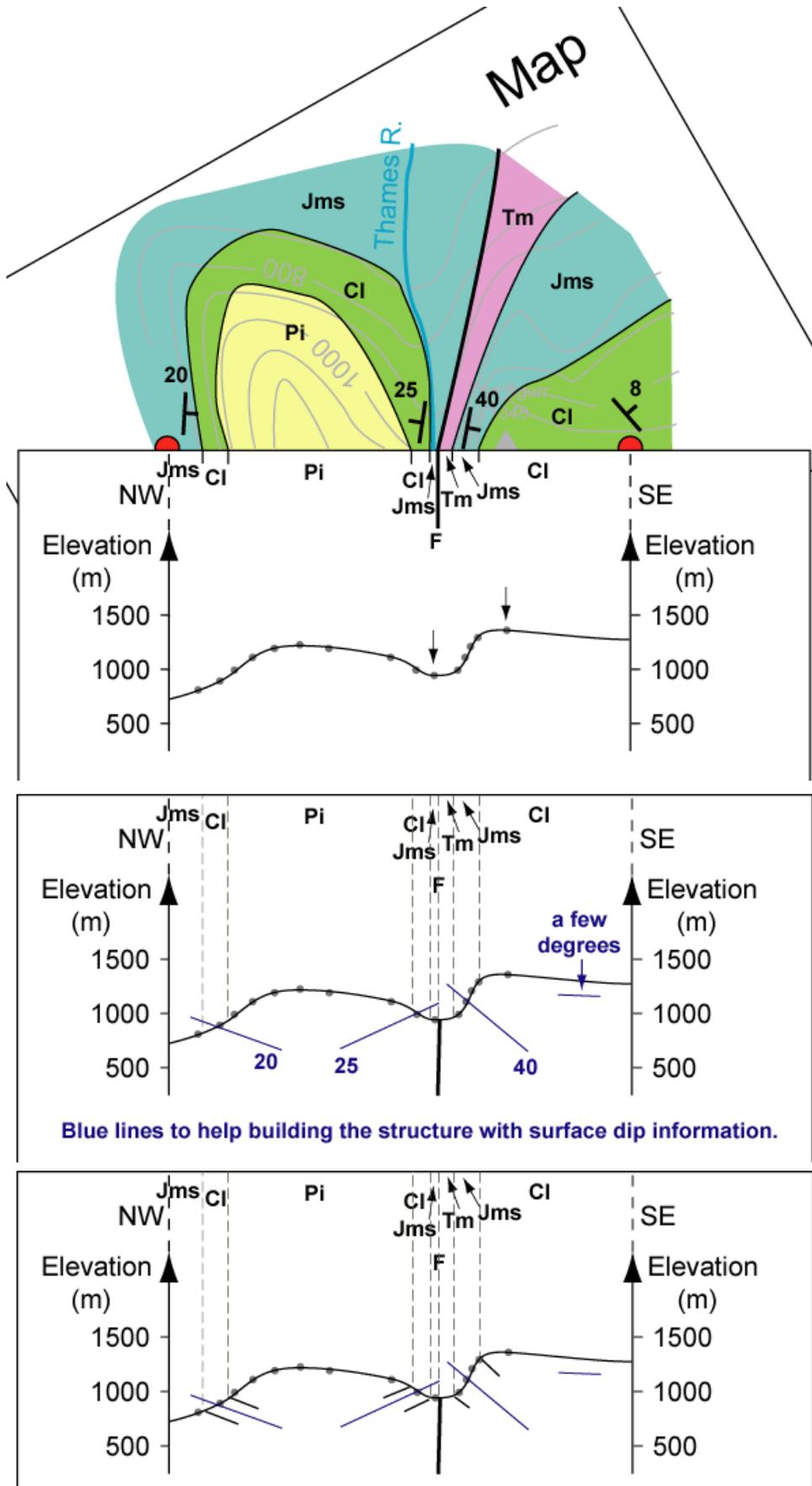
The table to the right gives results of calculation for a set of given values; diagram below (courtesy M. Hurst)

gives apparent dip (values on curves) for all possible combinations of true dip / direction angle.

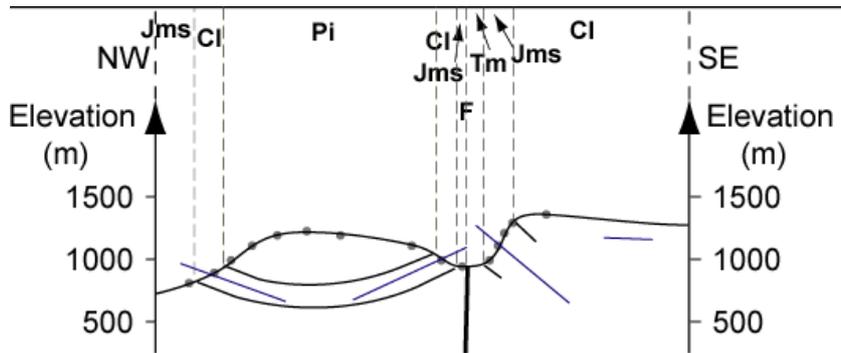


**With these rules in mind, you can begin building your cross-section:**

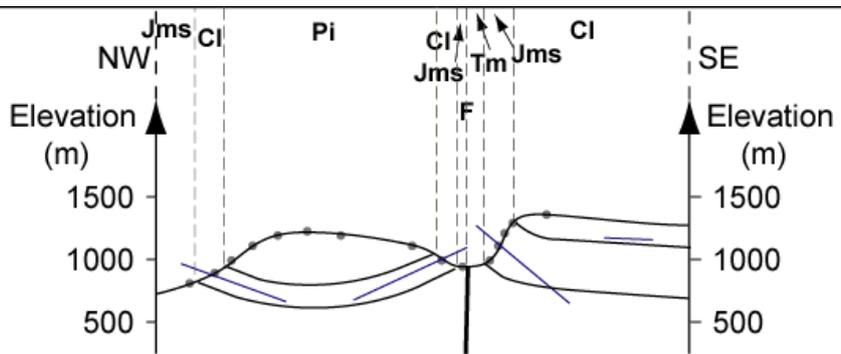
(1) Place faults and report your contacts on the cross-section. Trace the contacts a few millimetres under the cross-section.



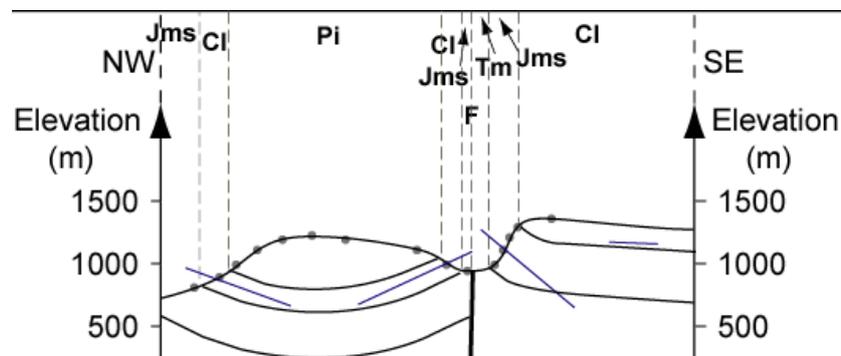
(2) Fill the landscape with the different units from youngest to oldest. Trace the contacts underground and try to keep the thickness of the units constant.



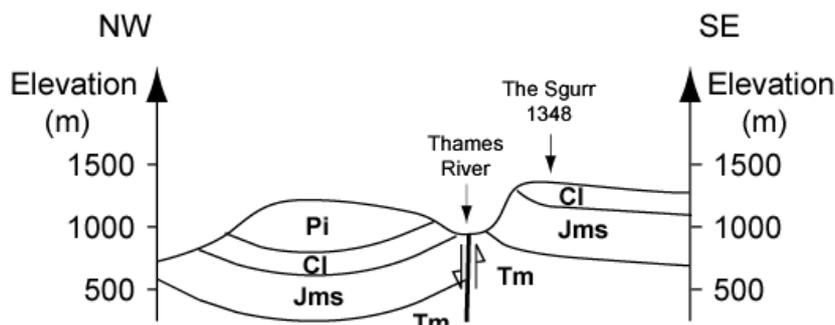
On the left hand side of the fault, you can easily constrain the shape of the syncline seen on the map. You can also determine the thickness of unit *Cl*: ~200 m. This will help building the contacts on the right hand side of the fault: *Cl* can't be thicker than 200m



A tight fold is required to have *Cl*'s thickness not exceeding 200 m on the right hand side of the fault. The contact between *Jms* and *Tm* can then be drawn → *Jms* is ~400 m thick. Knowing that, you can draw the contact between *Jms* and *Ts* on the left hand side of the fault. If you know the thickness of *Tm* (e.g. calculated somewhere else on the map or given in caption), you can draw the base of the *Tm* unit. Otherwise, your structure is complete.

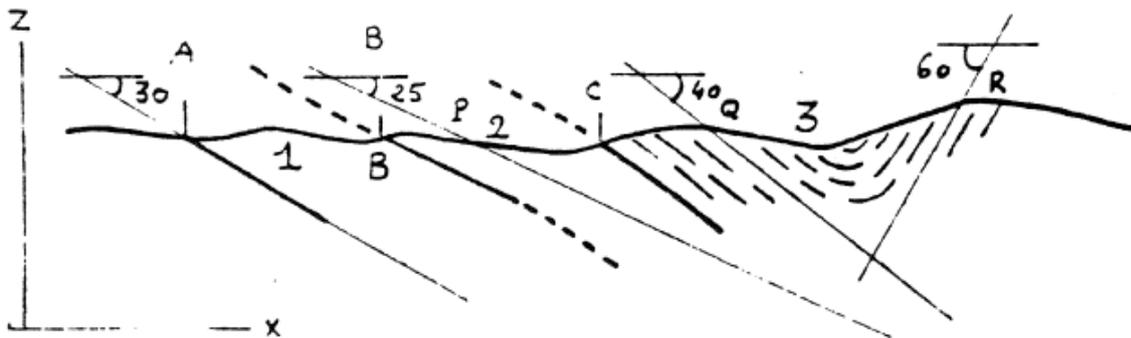


Remove the construction lines, add the direction of throw on the fault if possible (note: it could be a strike-slip fault; you need to look for evidence of horizontal or vertical motion on the map), annotate the key geographic locations (e.g. summits, valleys, cities). On the diagram below, I have put the name of each unit for illustration purpose only. On your cross-section, you will use geological patterns (see further).

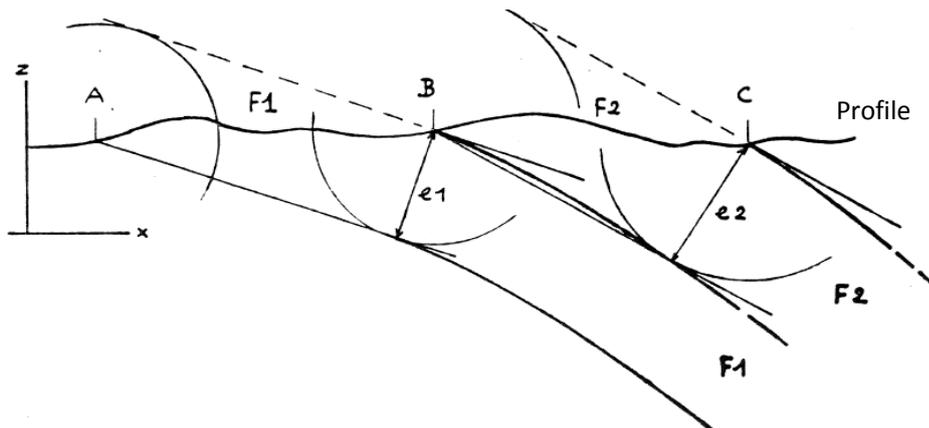


Remarks:

- if a fault is sub-vertical (linear trace barely affected by topography), you can still try to use structural contours on the fault trace to infer whether the fault is dipping steeply in a given direction (see page 7 for reminder of method). I assume that you all know what normal, reverse, thrust and strike-slip faults are and that you know how to identify them on the map. If you are unsure about that, ask a demonstrator.
- some geological units may be too thin to be drawn, e.g. a 20-m-thick sandstone bed in a cross-section at 1/50000 scale (1 mm represents 50 m). If the unit is a very important unit, you can still represent it with a thick line for example. Otherwise, you can group it with another unit. For example, this 20-m-thick sandstone layer from the lower Triassic (named *Tl*) could be overlain by a 200-m-thick sandstone layer from the middle Triassic (named *Tm*). In your cross-section, you can draw a 220-m-thick sandstone layer from the lower-middle Triassic (*Tl-m*).
- In the cross-section example shown in the previous pages, you built the structure using dip values (below is another example using this method).



If you know the thickness of the different units, you can use this information to build the structure instead:



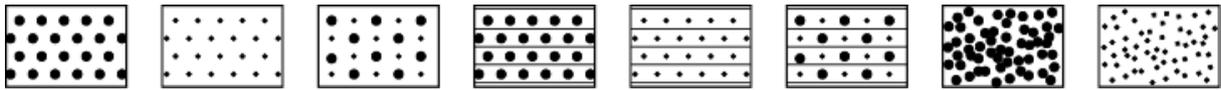
If you don't know the dip of the contacts, you can use a calliper to build the layers  $F_1$  and  $F_2$  of thickness  $e_1$  and  $e_2$ , respectively. The contacts will be tangent to the circles traced.

Alternatively, if you know the dip of the contact AND the thickness of the units, you can just use a ruler to measure the thickness of the units perpendicularly to the contacts along the profile (e.g. in A, B and C)

**TO FINISH THE GEOLOGICAL CROSS-SECTION:**

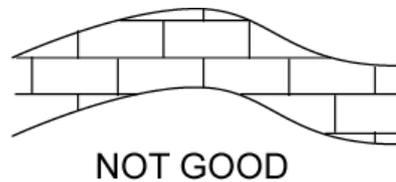
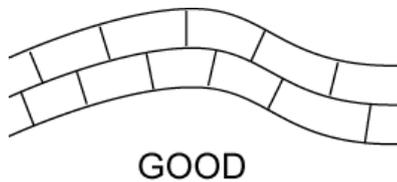
(1) Fill in the different units with the corresponding patterns. There are some general guidelines which are followed worldwide, e.g. “bricks” for limestone, dots for sandstone, “+” symbols for granite. The patterns shouldn’t be the fruit of your imagination (avoid little hearts or stars). However, you may have to be a bit imaginative if you have for example:

- 8 different sandstones in your cross-section; you need to be able to distinguish between them so you may have to create different patterns with dots, e.g.:



- some “composite” types of rocks”, e.g. sandy limestone. In this case, you could use bricks with dots in them.

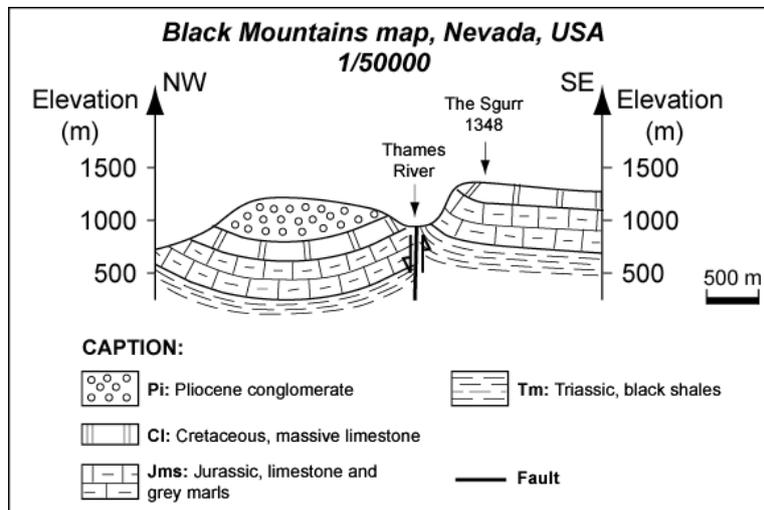
A list of the patterns commonly used is given at the end of this handout. Patterns must follow the curvature of the beds:



(2) Add a title at the top of your cross-section, a horizontal scale (which should be the same that the vertical one), and a caption below your section or on the side of it. In the caption, you will present each geological unit with its symbol (e.g. “Jms”), its age (e.g. “Jurassic”), a brief description of what it is made of (e.g. “limestone and grey marls”) and the corresponding pattern. The youngest must be at the top left and the oldest at the bottom right. You may separate sedimentary, igneous and/or metamorphic rocks in your caption.

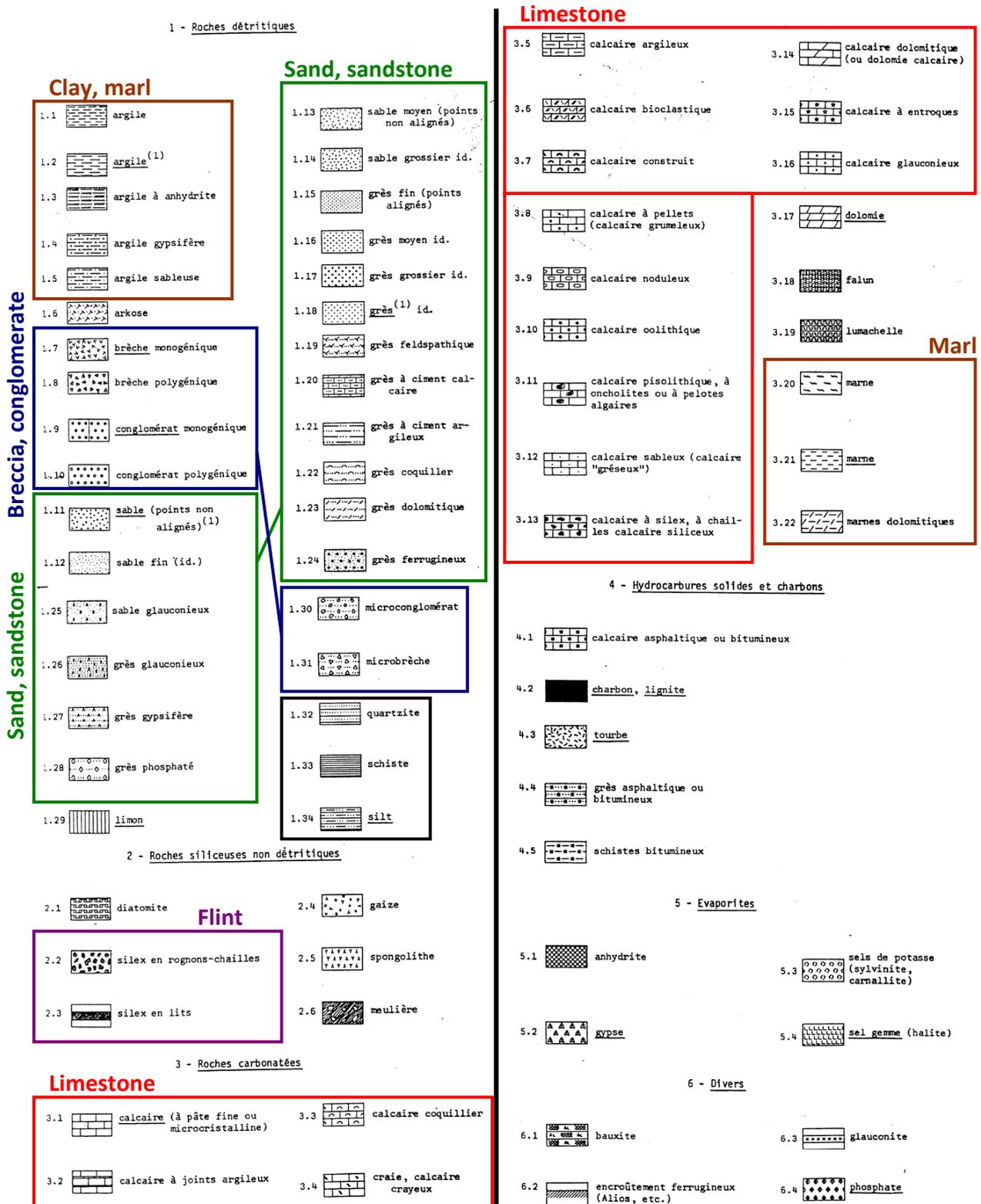
You will also explain what the different symbols you used mean: faults, unconformities (wavy contacts are usually used to show unconformities), and any other information that you may have displayed.

Below is the previous example finished. There are some other examples from French undergrads on Learn. They are not perfect (and some of them have the caption missing), but they give you an idea of the kind of work you will produce.



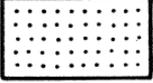
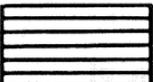
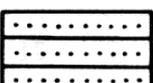
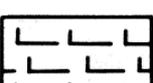
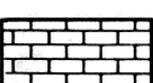
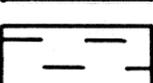
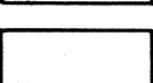
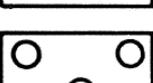
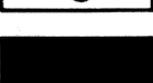
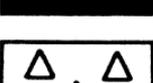
# APPENDIX 1: chart of patterns for rocks

1) Chart of patterns for sedimentary rocks (in French, sorry). 1. Clastic rocks. 2. Non-clastic siliceous rocks. 3. Carbonates. 4. Solid hydrocarbon and coal. 5. Evaporites. 6. Others. The most frequent rock types are highlighted and grouped in categories (boxes).

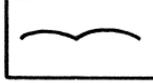
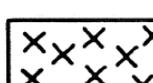
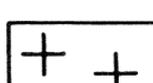


2) Chart of patterns for various types of rocks, from Bennison, G. M., "An introduction to geological structures and maps".

### SEDIMENTARY ROCKS

	} Sandstone
	
	} Shale
	
	Sandy Shale
	} Limestone
	
	Sandy Limestone
	Clay or Mudstone
	Marl
	Conglomerate
	Coal
	Breccia

### SUPERFICIAL DEPOSITS

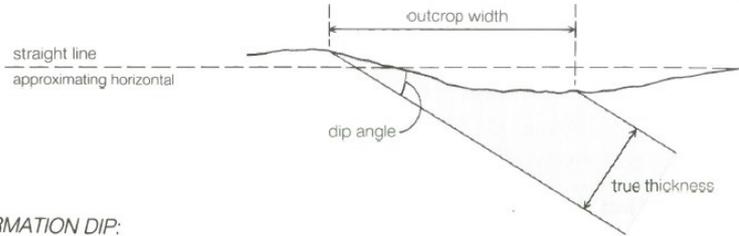
	Alluvium
	Terraces
	Boulder clay
<b>IGNEOUS ROCKS</b>	
	Volcanics (Basalt, andesite, etc.)
	Ashy Sediments
	Dolerite, porphyry, etc.
	Granite
<b>METAMORPHIC ROCKS</b>	
	Quartzite
	Slate
	Schist, Gneiss, etc.

**APPENDIX 2: calculation of true bed thickness.**

This diagram (and many others in this handout) are from the excellent “Geological maps - an introduction” by Alex Maltman, ISBN 0-471-93240-X (Print, can be found for relatively cheap), 978-1-4684-6664-5 (Print, another version that seems identical to the previous one but is much more expensive (?!)) or 978-1-4684-6662-1 (Online).

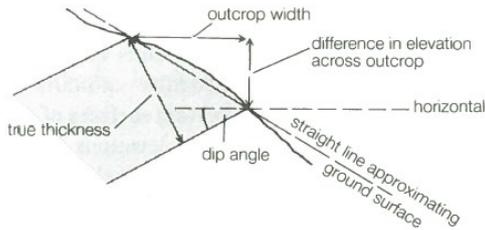
LEVEL GROUND:

$$\text{true thickness} = \text{outcrop width} \times \sin \text{dip angle}$$



SLOPING GROUND:

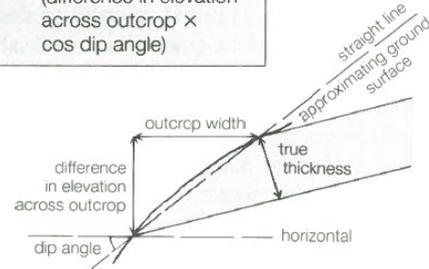
(a) SLOPE IN OPPOSITE DIRECTION TO FORMATION DIP:



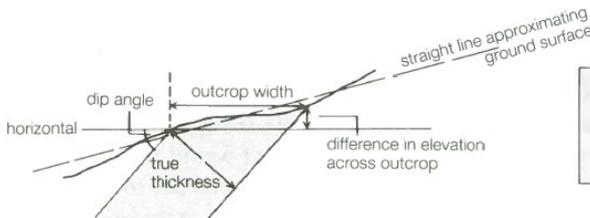
$$\text{true thickness} = (\text{outcrop width} \times \sin \text{dip angle}) + (\text{difference in elevation across outcrop} \times \cos \text{dip angle})$$

(b) SLOPE IN SAME DIRECTION AS FORMATION DIP, BUT STEEPER:

$$\text{true thickness} = \frac{(\text{difference in elevation across outcrop} \times \cos \text{dip angle})}{(\text{outcrop width} \times \sin \text{dip angle})}$$

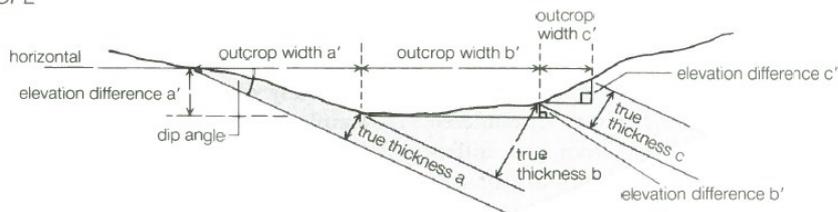


(c) SLOPE IN SAME DIRECTION AS FORMATION DIP, BUT LESS STEEP



$$\text{true thickness} = (\text{outcrop width} \times \sin \text{dip angle}) - (\text{difference in elevation across outcrop} \times \cos \text{dip angle})$$

(d) COMPLEX SLOPE



$$\text{true thickness of formation} = a + b + c$$