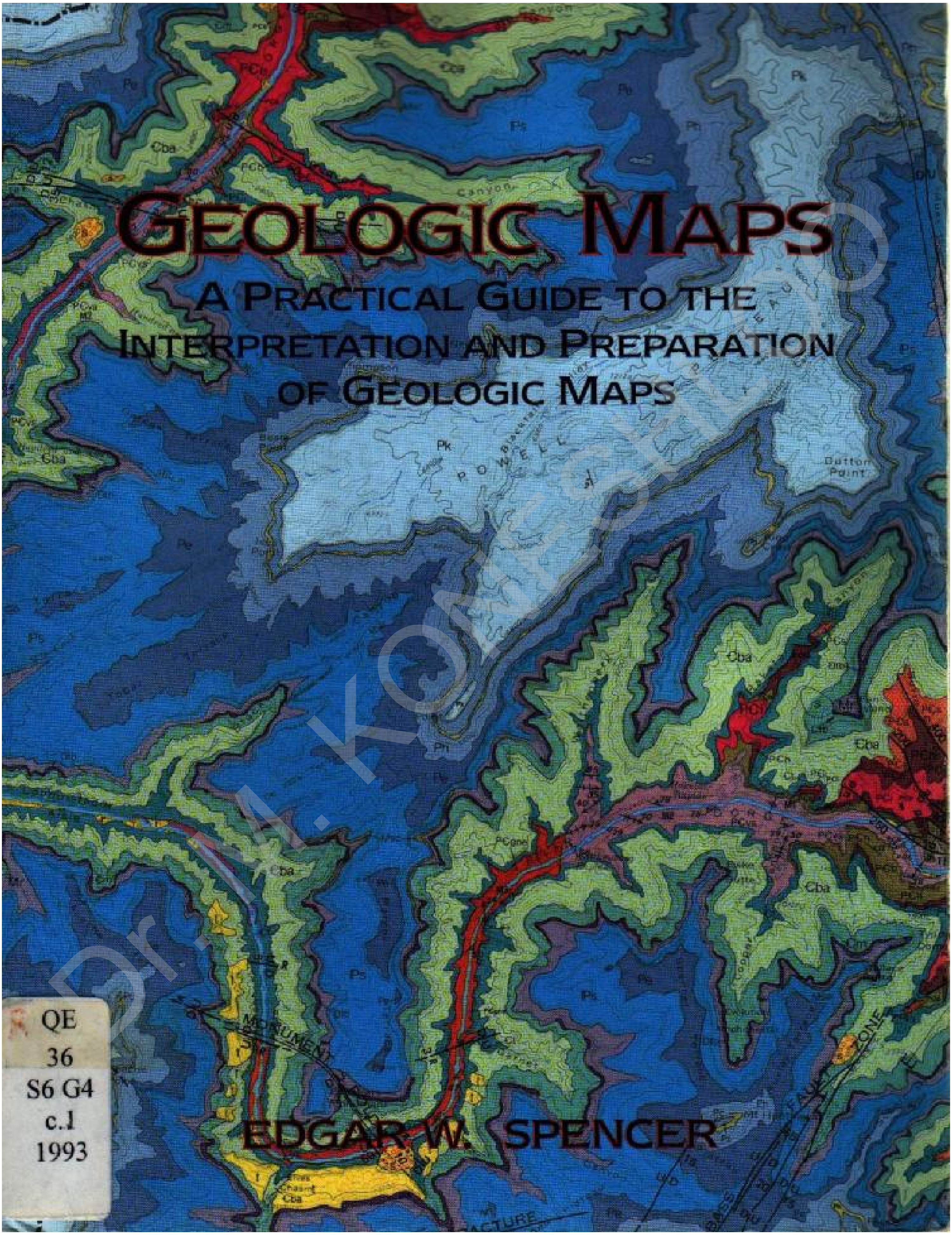
GEOLOGIC MAPS
A PRACTICAL GUIDE TO THE
INTERPRETATION AND PREPARATION
OF GEOLOGIC MAPS
EDGAR W. SPENCER
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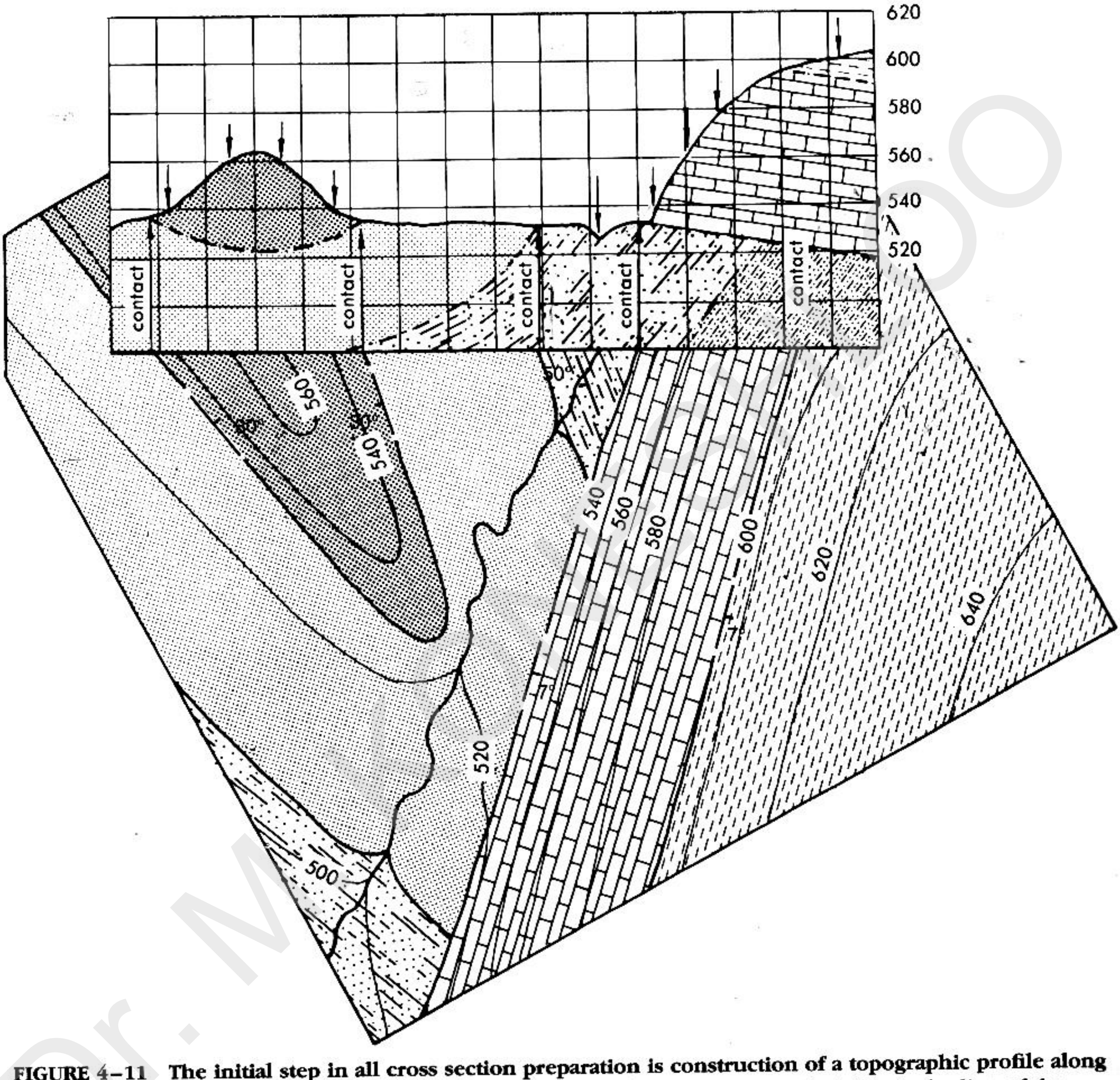
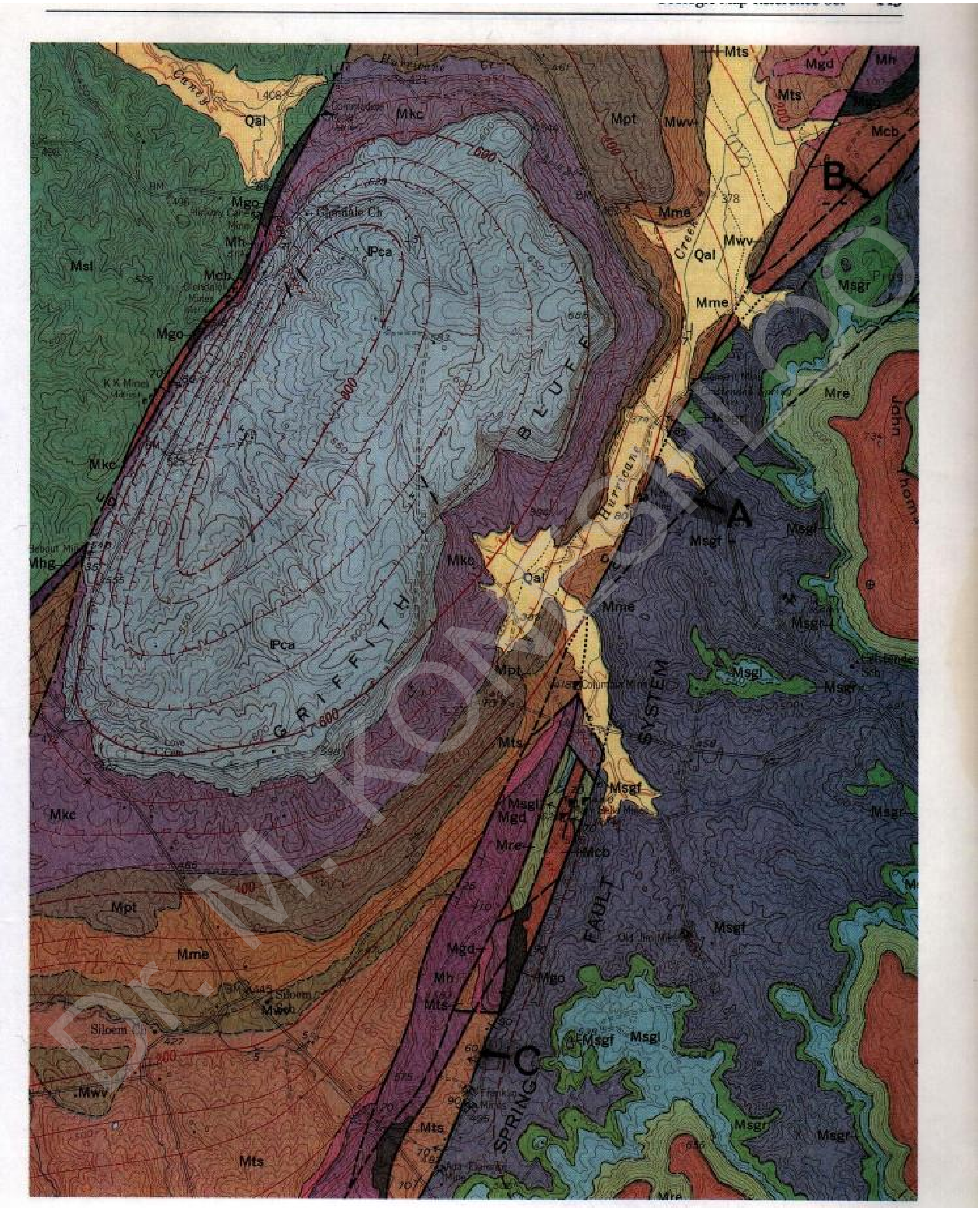


FIGURE 4–11 The initial step in all cross section preparation is construction of a topographic profile along the line of the section. Next strike and dip data from the geologic map are projected into the line of the section. If the dips are very low or if the angle between the line of the cross section and the strike of the beds is great, true dips should be converted to apparent dips in the cross section. Third, the dips of contacts are drawn on the topographic profile. Finally, if the cross section is to be drawn freehand, contacts are projected, and connected if desirable, in the subsurface, as shown in this figure. Unless other information is available, the thickness of the rock units is maintained constant across the section.



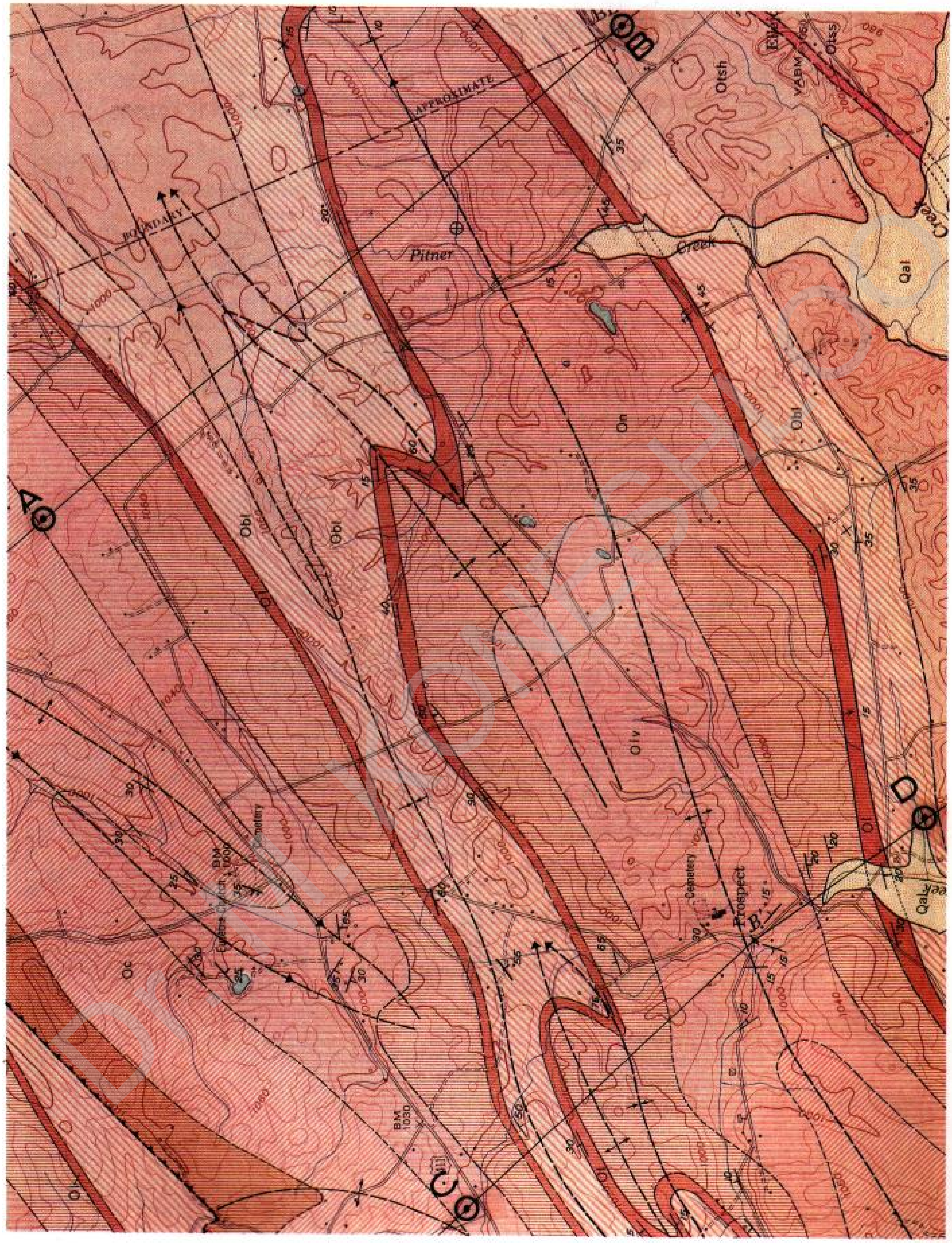
Salem Quadrangle, Kentucky
1:24,000

10. SALEM QUADRANGLE, KENTUCKY

Scale: 1:24,000
Geology by R. D. Trace
U.S.G.S. G.Q.-206, 1962

Map Units:

Qal	Quaternary	Alluvium
IPca	Pennsylvanian	Caseyville Formation
Mkc	Mississippian	Kinkaid Limestone—Clore Limestone
Mpt	"	Palestine Sandstone
Mme	"	Menard Limestone
Mwv	"	Waltersburg Sandstone
Mts	"	Tar Springs Sandstone
Mgd	"	Glen Dean Limestone
Mh	"	Hardinsburg Sandstone
Mgo	"	Golconda Formation
Mhg	"	Hardinsburg Sandstone and Golconda Formations combined
Mcb	"	Cypress Sandstone
Mre	"	Renault Formation
Msg	"	Ste. Genevieve Limestone
Msl	"	St. Louis Limestone



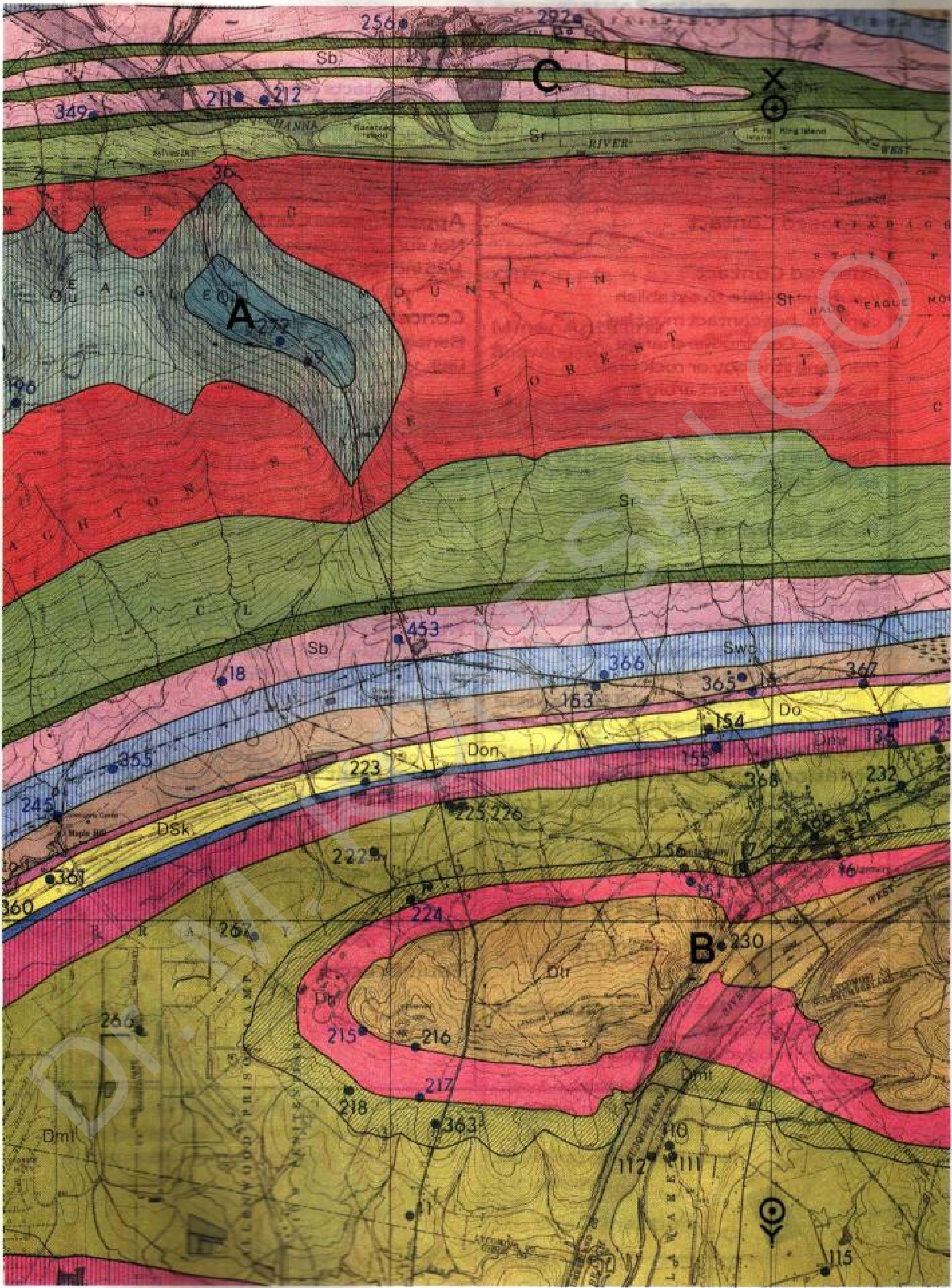
Wildwood Quadrangle, Tennessee
1:24,000

11. WILDWOOD QUADRANGLE, TENNESSEE

Scale: 1:24,000
Geology by R. B. Neuman
U.S.G.S. G.Q.-130, 1960

Map Units:

Otsh/Otss	Ordovician	Tellico Formation (shale/sandstone)
Obl	"	Blackhouse Shale
Ol	"	Lenoir Limestone
On	"	Newale Formation
Olv	"	Longview Dolomite
Oc	"	Chepultepec Dolomite



Williamsport Quadrangle, Pennsylvania
1:50,000

12. WILLIAMSPORT QUADRANGLE, PENNSYLVANIA

Scale: 1:50,000
Geology by O. B. Lloyd, Jr. and L. D. Canswell
Pennsylvania Department Environmental Resources, 1981

Map Units:

Dtr	Devonian	Trimmers Rock Formation
Dh	"	Harrell Formation
Dmt	"	Mahantango Formation
Dmr	"	Marcellus Formation
Don	"	Onondaga Formation
Do	"	Old Port Formation (incl. Ridgeley Member)
DSk	"	Keyser Formation
Sto	"	Tonoloway Formation
Swc	"	Wills Creek Formation
Sb	"	Bloomsburg Formation
Sm	"	Mifflintown Formation
Sr	"	Rose Hill Formation
St	"	Tuscarora Formation
Oju/Ojl	"	Juanita Formation

MAP SYMBOLS

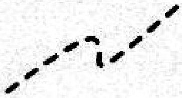
LINES ON MAPS

Contact line symbols signify accuracy of location or character of exposure on maps at scales of 1:24,000, 1:62,500, and 1:50,000; only solid line contacts are used for maps at scales smaller than 1:125,000. Lines are solid where contacts are exposed; long-dashed where they are approximately located; short-dashed where they are inferred; dotted where they are concealed; queried where they are doubtful.

CONTACTS

Exposed Contact

Inferred Contact
Insufficient data to establish contact, but contact must be present. Continuous change from one lithology or rock type to another. Contact arbitrary.



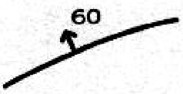
Approximate Contact
Not surely located within 1/25 inch at scale of map.

Concealed Contact
Beneath mapped geologic unit, water, or ice.

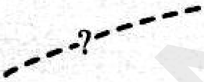
FAULTS

Same line conventions are used for faults as for contacts.

Fault, Showing Dip



Probable or Doubtful Fault
Queries, spaced three or more dashes apart, indicate uncertainty of existence, not location.



Fault Showing Bearing and Plunge of Grooves, Striations, or Slickensides

High-Angle Fault
Showing dip; U, upthrown side; D, downthrown side.

High-Angle Fault
Bar and ball are on the downthrown side.

Strike Slip Fault
Fault showing relative horizontal movement.

Normal Fault
Hachures are on apparently downthrown side.

Reverse Fault
R, upthrown side; angle of dip originally greater than 45 degrees.

Thrust Fault
Sawteeth are on the upper plate.

Fault (Shear or Mylonite) Zone
Showing dip.

Fault Breccia

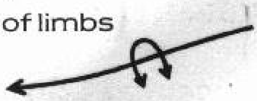
FOLDS

Same line conventions used as for contacts.

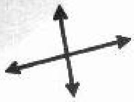
Anticline
Showing crestline and direction of plunge.

Assymetric Anticline
Showing dip of limbs and plunge.

Overturned Anticline
Showing direction of dip of limbs and plunge.



Dome
Generally used on small scale, tectonic maps only.

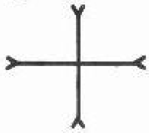


Syncline
Showing troughline and direction of plunge.

Asymmetric Syncline
Showing dip of limbs and direction of plunge.

Overturned Syncline
Showing direction of dip of limbs and plunge.

Basin



MINOR FOLD AXES

Minor Anticline
Showing plunge.

Minor Syncline
Showing plunge.

Minor Folds
Showing plunge of axes.
Used where beds are too tightly folded to show axes of individual folds separately.

PLANAR FEATURES

Planar symbols (strike and dip of beds, foliation or schistosity, and cleavage).

BEDDING

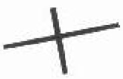
Strike and Dip of Beds

Strike and Dip of Beds
Top of beds known from sedimentary features.

Strike and Dip of Overturned Beds
Horizontal beds.

Strike and Dip of Overturned Beds
Top of beds known.

Strike of Vertical Beds
Crumpled, plicated, crenulated, or undulatory beds and beds of average dip.

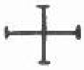


CLEAVAGE

Strike and Dip of Cleavage

Strike of Vertical Cleavage

Horizontal Cleavage

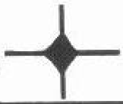


FOLIATION OR SCHISTOSITY

Strike and Dip of Foliation

Strike of Vertical Foliation

Horizontal Foliation



LINEAR FEATURES

May be combined with the above planar symbols as shown.

Bearing and Plunge of Lineation

Vertical Lineation

Chapter 4: Geological Cross-Sections

THE THREE-DIMENSIONAL structure of an area may be effectively illustrated by the combination of a geological map and one or more cross-sections. Cross-sections serve to clarify the subsurface structure, usually as seen in a vertical plane. The construction of cross-sections across any geological structure involves the risk of several geometric distortions. This chapter outlines the nature of these distortions, and provides guidelines for selecting section lines that show the most appropriate view of the subsurface. A technique related to cross-section construction, representing the subsurface structure in block diagrams, is addressed in chapter ten. The vertical sides of such block diagrams effectively show cross-sectional views of the subsurface.

Contents: Criteria for the selection of section lines are discussed in section 4-1. Further instructions for profile construction are given in section 4-2. Visual distortions occurring in differentially scaled cross-sections are outlined in section 4-3. The effects of apparent thickness and dip are resumed in section 4-4.

4-1 Location of sections

Geological maps are commonly accompanied by cross-sections, illustrating the geological structure of the region. Cross-sections intend to show the form and orientation of geological structures in the subsurface. However, various kinds of distortion of the form and orientation of rock structures may arise in such cross-sections. These distortions depend on: (1) the relative scaling of the horizontal and vertical axes in the section, and (2) the way in which the section cuts the actual structure. These two sources of distortions are discussed in some detail in sections 4-3 and 4-4, respectively.

The previous chapter explained that cross-sections should, preferably, be constructed, as close as possible, normal to the regional trend of structures. If the surface trace of the profile is oblique to the structural trend, an apparent thickness of layers would be seen rather than the true thickness. Likewise, dips of layers in such oblique sections are apparent rather than true.

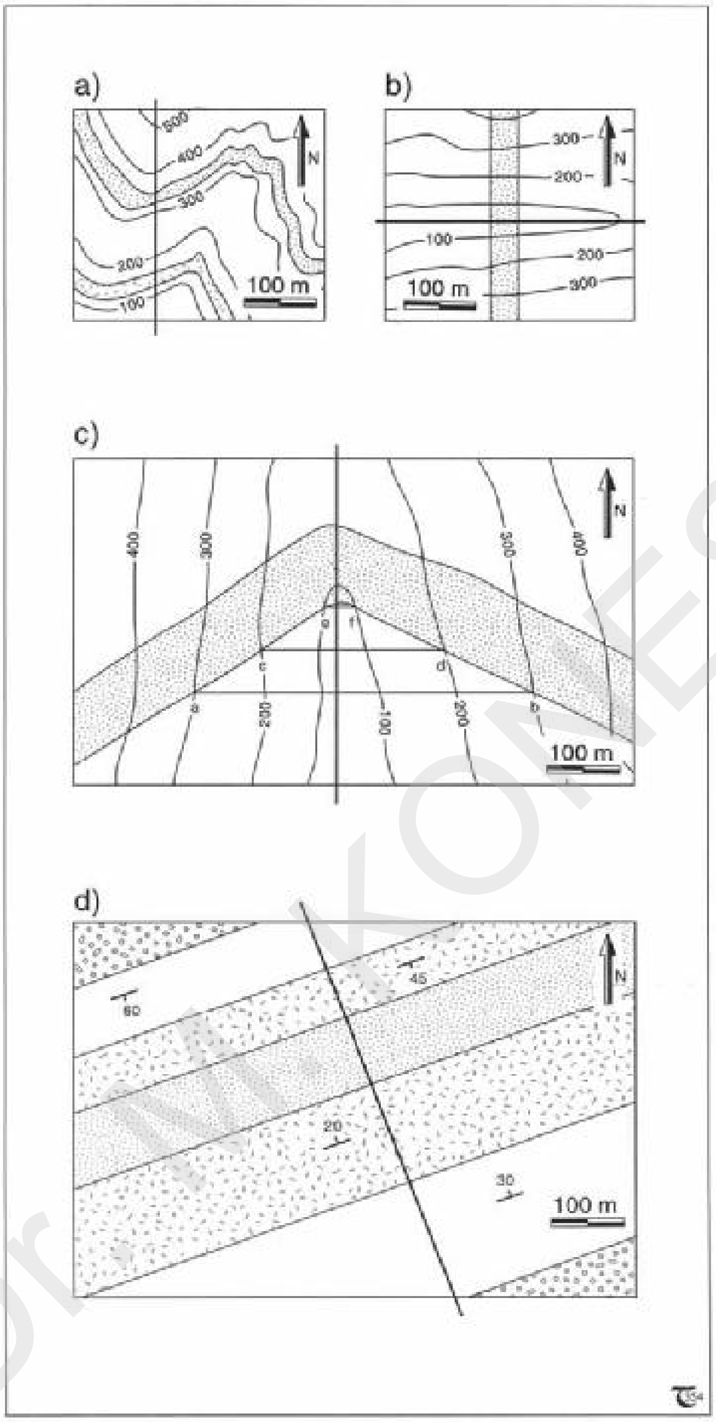


Figure 4-1: a) to d) Four geological maps, each representing a different structure, but the best section line is consistently normal to the strike of the strata.

Figure 4-1 illustrates four geological maps of terrains with stratified rocks. When constructing cross-sections across these terrains, the criteria to keep in mind are as follows: The line of section should be perpendicular to the strike of the beds and close to any field measurements of strike and dip indicated on the maps. But the layers in the map of Figure 4-1a are subhorizontal, and, in that case, the only criterion used is that the section should show the most complete view of the stratigraphy. This is achieved by choosing the line of section so that it crosses the points of lowest and highest elevation within the area.

If a layer is vertical, its outcrop pattern will not be distorted by the topography, and the section is chosen conveniently normal to its strike so that the true thickness will be preserved in the section (Fig. 4-1b). If a layer is dipping moderately, the outcrop pattern in rugged terrains may be complex (Fig. 4-1c). The direction of dip is indicated by the V-pattern in the valley intersection. The cross-section should be selected normal to the strike of the layers as indicated by structure contours labeled a-b and c-d (for details on structure contours, see chapter five). Folded sequences are, also, sectioned perpendicular to strike (Fig. 4-1d).

4-2 General procedure

If the strike and location of a cross-section have been chosen carefully, the construction of the section itself starts with the transferral of the topography of the terrain to the section (Fig. 4-2a & b). First, mark the topographic elevation along the line of section on a strip of paper. Second,

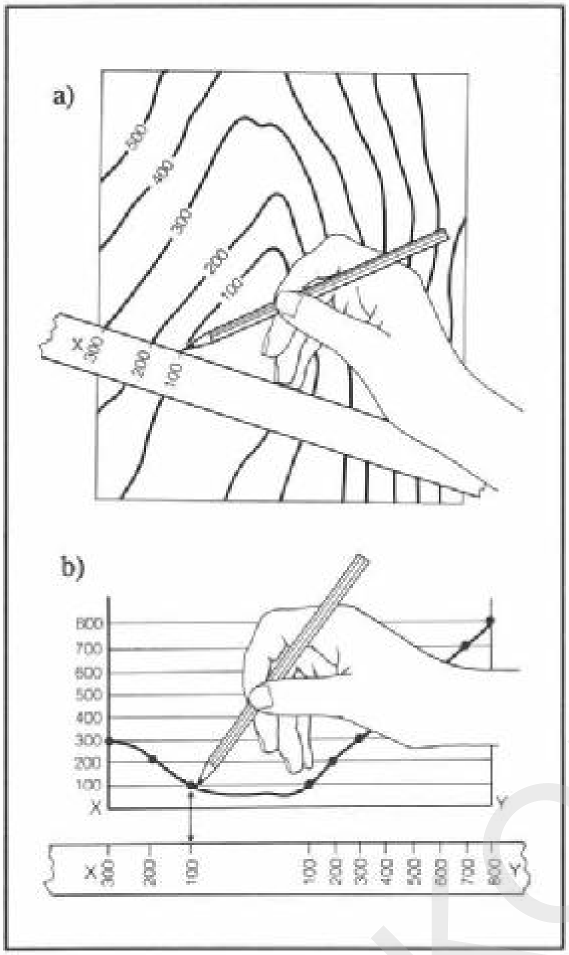


Figure 4-2: *a) & b) Steps involved in construction of a topographic cross-section.*

transfer the elevations from the paper-strip to a cross-section, showing the topography of the ground surface. The scaling of the depth axis of the section preferably should be equal to that of the horizontal scale; otherwise, the slope of the terrain appears different from that in reality. An increased vertical length scale exaggerates the slope of the terrain, whereas a decreased vertical length scale suppresses topography (Fig. 4-3a to c). For convenience of construction, use only a few of the topographic contours if many intersect the line of section, but always take sufficient points to define accurately the distinctive parts of the profile, such as ridge crests and valley floors.

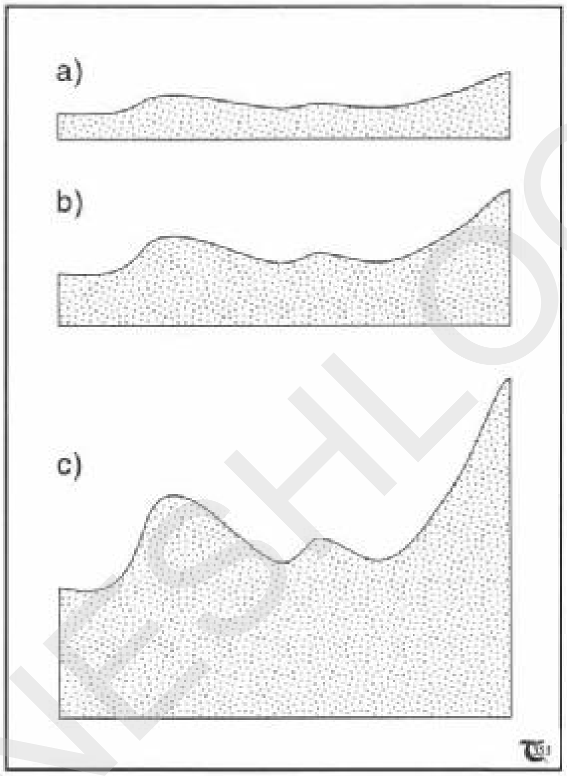


Figure 4-3: *Visual effects of variable horizontal and vertical scaling. a) Vertical scale is half the length of the horizontal scale. b) Isometrically scaled. c) Vertical scale is extended 2.5 times.*

Finally, geographical orientations should always be indicated near the vertical scale bars at either side of the section. It is, also, common and useful to write explicitly under the section "horizontal and vertical scales equal" or "horizontal:vertical=1:1" or "no vertical exaggeration."

Once the topographic section is completed (Fig. 4-4a), the geological contacts are transferred to the surface of the section (Fig. 4-4b). This can be achieved by marking contacts on a slip of paper placed along the line of section on the geological map. Use colors to distinguish the rock units separated by the contact markings. If available, data from drill cores and seismic reflection profiles could be included in the section. Remember that dip angles may need correction for apparent dip, if necessary. Indicate the

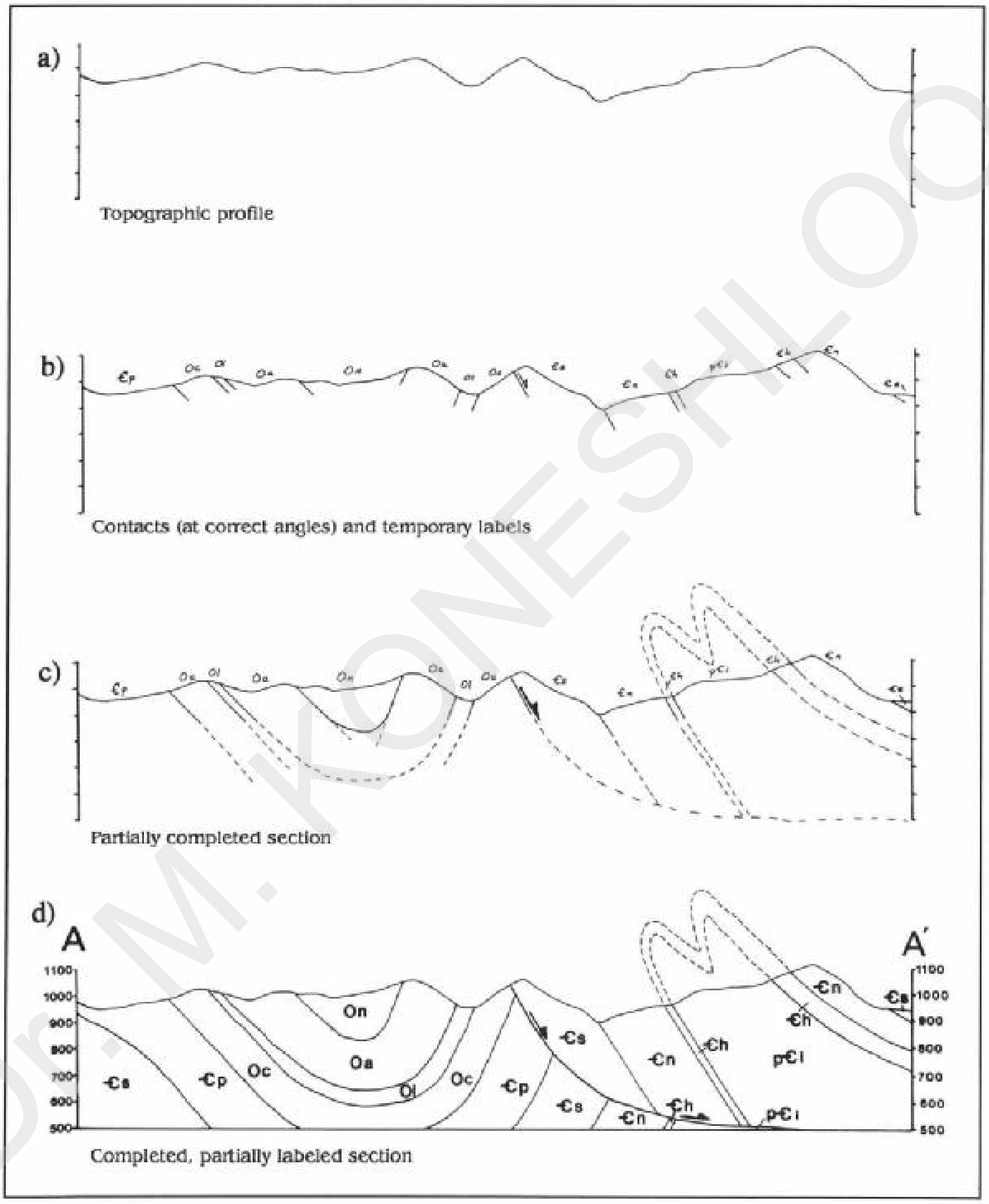


Figure 4-4: a) to d) The construction of geological cross-sections: a) Topographic profile, b) Transferral of surface dips from map to section, c) Extrapolation of surface data to depth, d) Completed section.

direction and amount of dip for all the geological contacts involved (Fig. 4-4b).

The next step, completion of the section, involves a great deal of interpretation. Attempt to be as realistic as possible, and, therefore, use the surface observations close to the line of section as a starting point. The scarcer the subsurface data, the larger the interpretation factor will be. The reliability of the extrapolation of the surface data downwards in the section decreases with depth. It is, therefore, important to consider to what depth the cross-section can be extended with some certainty. The depth of the section should be no more than two to three kilometers in the absence of drill or seismic data. Guidelines for subsurface interpretation are poor, and the extrapolation is largely a matter of personal style and experience. In folded terrains it is common to assume that the stratigraphic thickness of the layers will remain constant within the plane of the cross-section (Fig. 4-4c). Fold limbs may be connected in the section by dashed curves above the ground surface to clarify the geological structure.

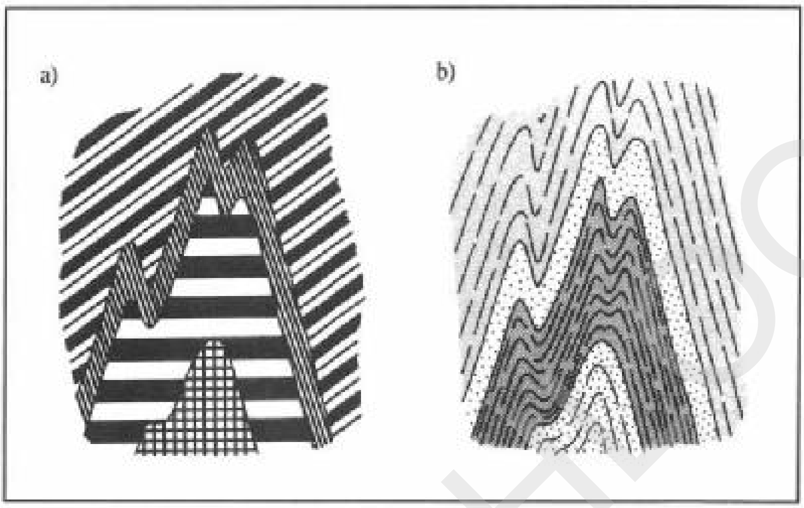


Figure 4-5: a) & b) Symbols in cross-sections: a) Inappropriate use of symbols. b) Properly used symbols follow form lines of the bedding.

Finally, the cross-section will be complete only if the units are clearly labeled and their symbols are explained in a legend of the units. The legend lists the layers with the oldest units below and the youngest units above, maintaining their proper sequence. The labeling of the section may be done either by lettering (Fig. 4-4d) or by using lithological symbols. The symbols used in cross-sections are classically bound to a particular lithology (Fig. 2-16). Limestone, dolomite, and sandstone all have their characteristic symbols. The form surface of the structures (e.g., lines that parallel bedding within formations) should be expressed as clearly as possible when making use of these symbols. Figure 4-5a shows how *not* to use the symbols and Figure 4-5b shows a more appropriate use. The visual image of cross-sections allows us to appreciate the shape and orientation of geological structures. Such sections are complementary to geological maps, and their preparation and proper interpretation deserves careful attention.

☐ **Exercise 4-1: Complete the cross-section of Figure 4-4c using arbitrary symbols, and draw up a legend.**

☐ **Exercise 4-2: Construct cross-sections along each of the section lines outlined on the maps of Figure 4-1a to d.**

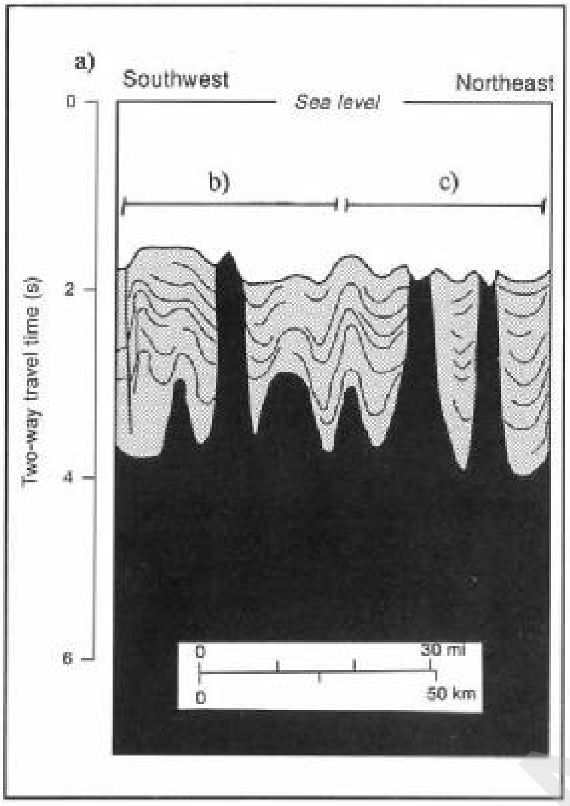


***Figure 4-6a:** Seismic section through salt domes (black), piercing a sedimentary sequence (gray shade). The steepness of the domes is entirely artificial, due to exaggeration of the depth scale.*

4-3 Scaling of sections

It is vital to understand the detailed geometric implications of vertical exaggerations in structural profiles. There is a growing trend in the industry to remove such exaggerations where possible, because they introduce problems to structural interpretations. But, in some circumstances, depth scales of cross-sections are deliberately exaggerated with respect to the horizontal scale. Such unequal length scales are sometimes adopted when base lines are extremely long, and this is particularly common for cross-sections based on the interpretation of seismic reflection profiles. Figure 4-6a illustrates a common migrated seismic section through salt domes, piercing a sedimentary sequence. The exaggeration of the layer thickness and their dips is large, as becomes apparent from a representation of the same section with the vertical exaggeration removed (Figs. 4-6b & c). Obviously, the form and orientation of structures is distorted in vertically exaggerated sections, thereby obscuring the very information the structural section seeks to illustrate. It is, therefore, extremely important always to include in any cross-section clear information, concerning the vertical exaggeration factor.

Four visual effects, associated with an increased vertical scale, are: a) any structural planes appear to dip more steeply than their

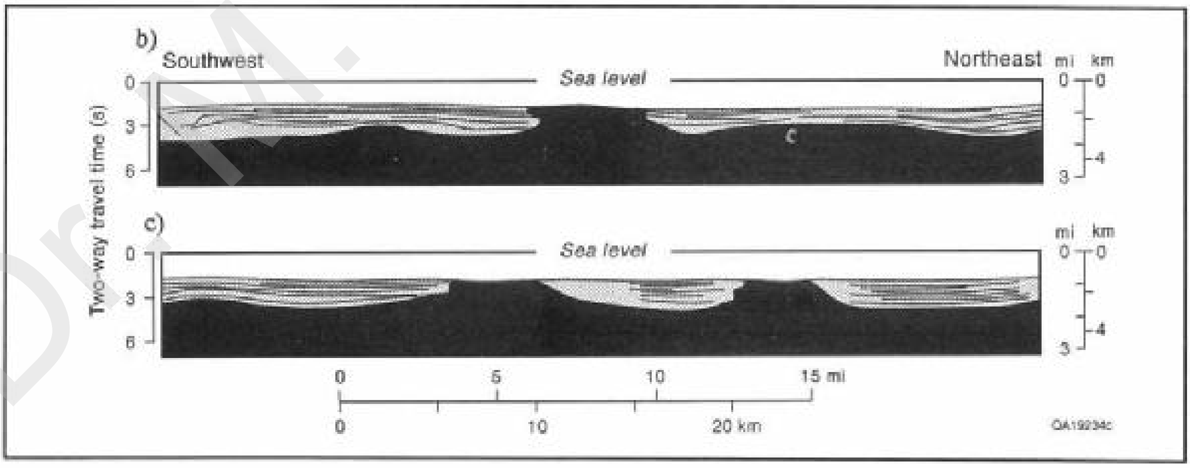


***Figure 4-6:** b) & c) Restoration of the same seismic section to equidimensional or isometric scales.*

actual dip in that section plane (remember that the section is not necessarily normal to the strike), (b) the angles between cross-cutting structures are distorted in a complex fashion, (c) the thickness of geological units appears generally much greater than their true thickness, and (d) layer thicknesses may falsely appear to change laterally. Each of these effects will be discussed in detail below as they are particularly common features of seismic profiles used by the oil and gas industry.

a) Exaggerated dip

The dip of any non-horizontal layers will be exaggerated if the vertical scale is increased. The exaggeration factor, V, can be defined as the ratio of the vertical and horizontal length scales. It is easy to see that the true dip, α, will be exaggerated into the apparent dip, α^*, by the exaggeration factor, V:

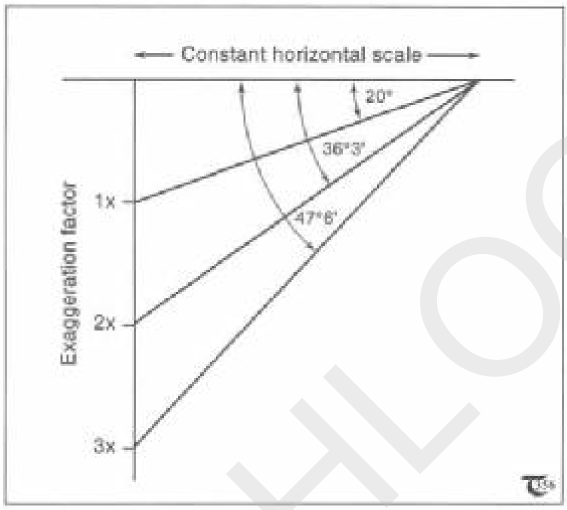


***Figure 4-7:** The angle of dip increases if the vertical scale of seismic and other cross-sections is exaggerated. See eq. (4-1).*

$\tan \alpha^* = V \tan \alpha$ (4-1)

The dip exaggeration principle is illustrated in Figure 4-7 for a planar surface whose true dip is 20° due west. If the vertical length scale is twice the horizontal length, the exaggeration factor, V, equals 2 and the exaggerated dip will be 36°. If the exaggeration factor, V, equals 3, the exaggerated dip is 48°.

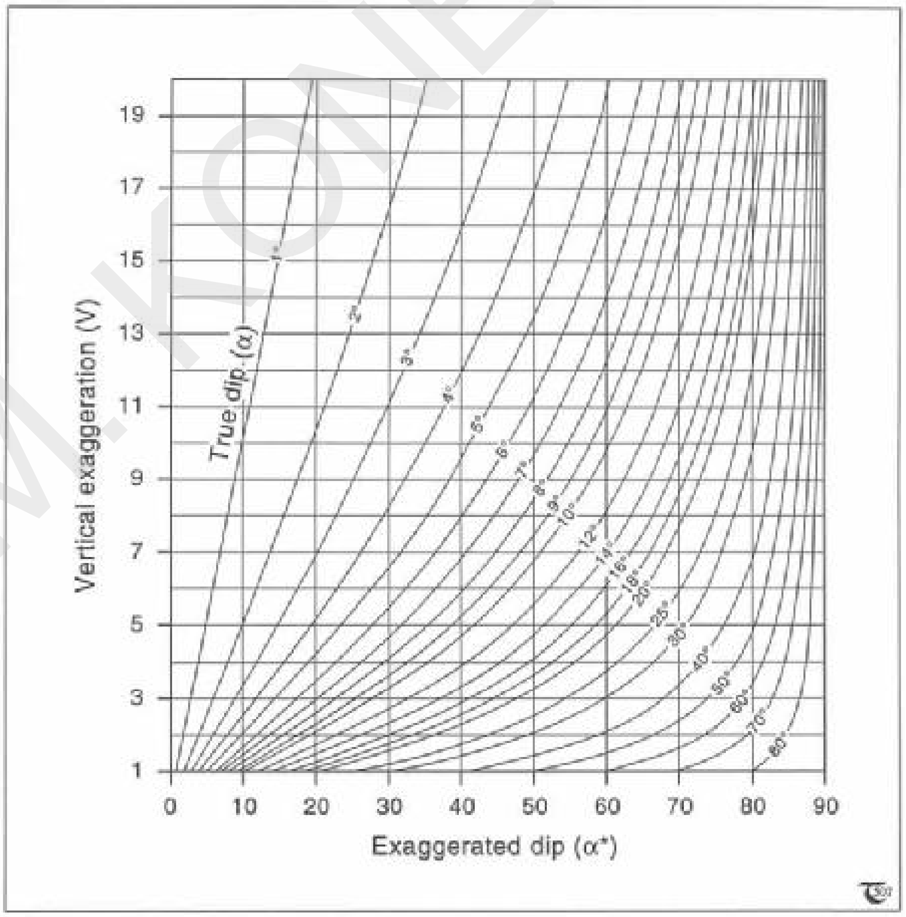


Figure 4-8: Nomogram relating the true dip, α, to the exaggerated dip, α^*, for a range of vertical exaggeration factors [eq. (4-1)].

Instead of calculating equation (4-1), it may be faster to use a nomogram to obtain one of the unknown angles from the vertical exaggeration factor. Figure 4-8 shows an example of a nomogram, used to transform exaggerated dip to true dip and vice versa. Note that the effect of dip exaggeration becomes less profound for layers which have already large true dips. The extreme case is a vertical layer; its dip will not change by vertical exaggeration.

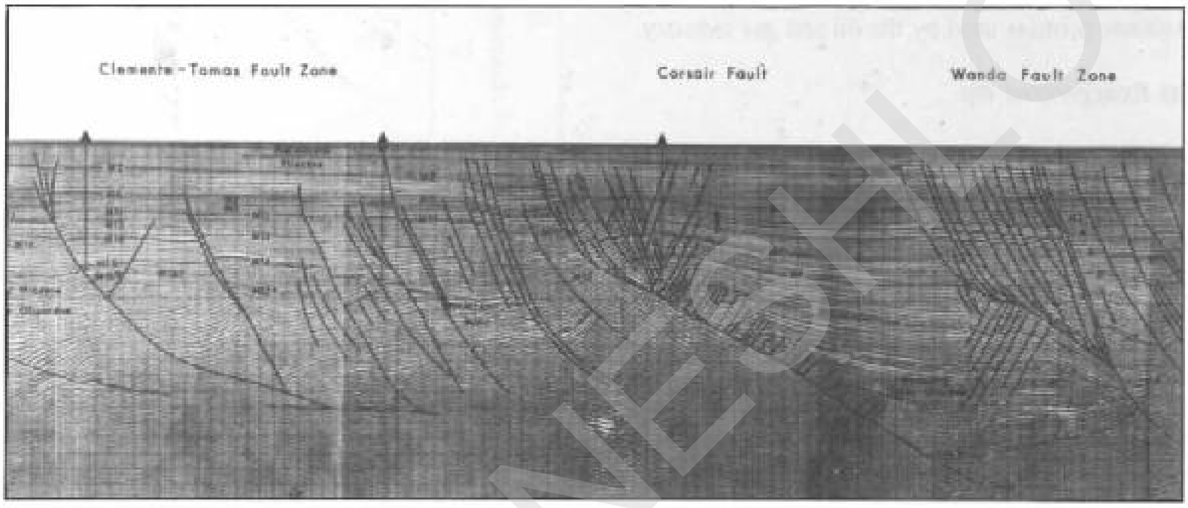


Figure 4-9a: *Original seismogram across the Clemente-Tomas, Corsair, and Wanda fault systems in the Gulf of Mexico, off-shore Texas.*

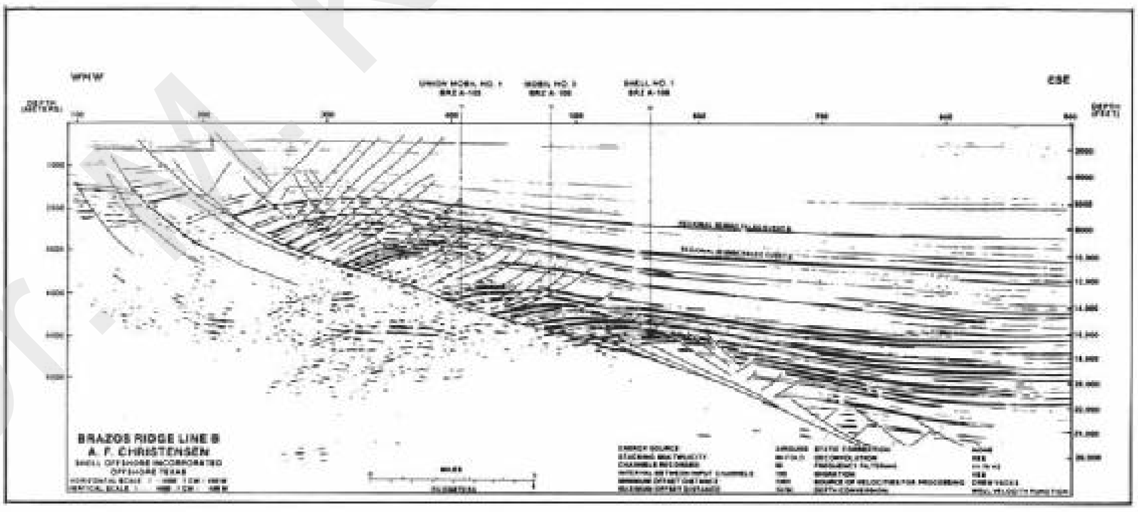


Figure 4-9b: *Restored section of the Corsair fault system with the horizontal and vertical scales equal.*

☐**Exercise 4-3: The Clemente-Tomas and Corsair fault systems are prominent structural features beneath the submerged floor of the Gulf of Mexico. Figure 4-9a illustrates the seismic section with the vertical scale exaggerated, and Figure 4-9b is scaled with no vertical exaggeration. The difference in dip of the main Corsair fault in the two figures can be used to determine the exaggeration factor for the seismic section in Figure 4-9a. Obtain the answer in two different (but similar) ways: (a) applying equation (4-1), and (b) using the nomogram of Figure 4-8. Your answers should converge.**

b) Distortion of angles

Figure 4-10a illustrates a cross-section, with horizontal and vertical scales equal, portraying a faulted sequence unconformably overlain by another, onlapping sequence of sedimentary rocks. Figure 4-10b shows the appearance of the same section with a vertical exaggeration factor, V=8. One important aspect is the apparent increase in the dip of both the faults and the layers. Angular differences between shallow dipping contacts are *increased*. For example, the true unconformity angle is 5°, but it appears as 27° in the exaggerated section. Angular differences between steeply dipping surfaces are *reduced*. For example, the acute angle between the two normal faults is 24° in reality but appears as only 5° in the exaggerated section.

c) Exaggerated thickness

Exaggerating the vertical length scale in cross-sections not only exaggerates the dip of geologi-

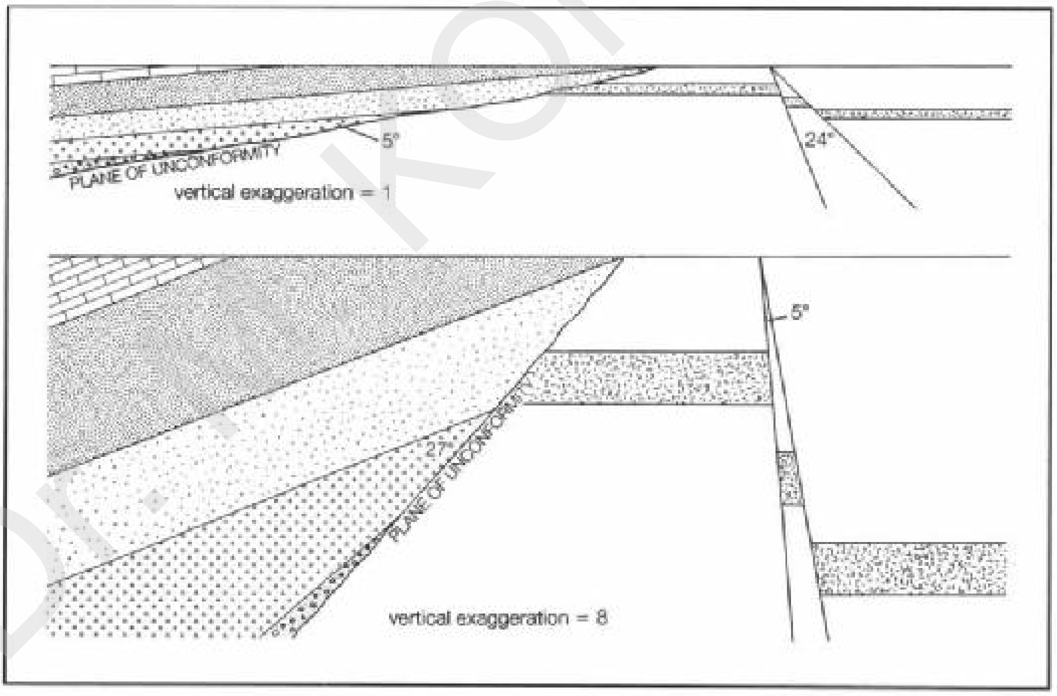


***Figure 4-10:** a) & b) Distortion of angles occurs in non-isometrically scaled sections. a) Original isometric section. b) Same section with vertical exaggeration factor of eight.*

cal contact surfaces, but, in addition, visually distorts the thickness of all layers, except for vertical beds. The length/thickness ratio of the central, horizontal sandstone layer, located between the fault plane and the unconformity in Figure 4-10b, is markedly decreased, as compared to that in the true-to-scale section in Figure 4-10a. The normalized exaggerated thickness, T^*/T, is dependent on the vertical exaggeration factor, V, and the original layer dip, α:

$$T^*/T=[V/\cos\alpha]\cos[\tan^{-1}(V\tan\alpha)] \qquad (4\text{-}2)$$

□Exercise 4-4: Figure 4-12a is a true-to-scale cross-section, illustrating two vertical igneous dikes separated by a sedimentary sequence tilted at 10°. The same section is redrawn in Figure 4-12b with a vertical exaggeration factor of 8. The sandstone - an important aquifer - has an exaggerated thickness of 100 meters. Estimate the true thickness of the aquifer, using: (a) equation (4-2), and (b) the nomogram of Figure 4-11.

Instead of using equation (4-2), it may be faster to use a nomogram to obtain the normalized exaggerated thickness from the vertical exaggeration factor, V, and the particular original dip of the strata. Figure 4-11 shows an example of a nomogram used to obtain the orthogonal thickness exaggeration from V and the original layer dip. The effect of thickness exaggeration becomes less profound for layers with steep dips. The effect is largest for horizontal layers (i.e., $T^*/T=V$) and is absent for vertical layers. The thickness of vertical layers will not change by vertical exaggeration.

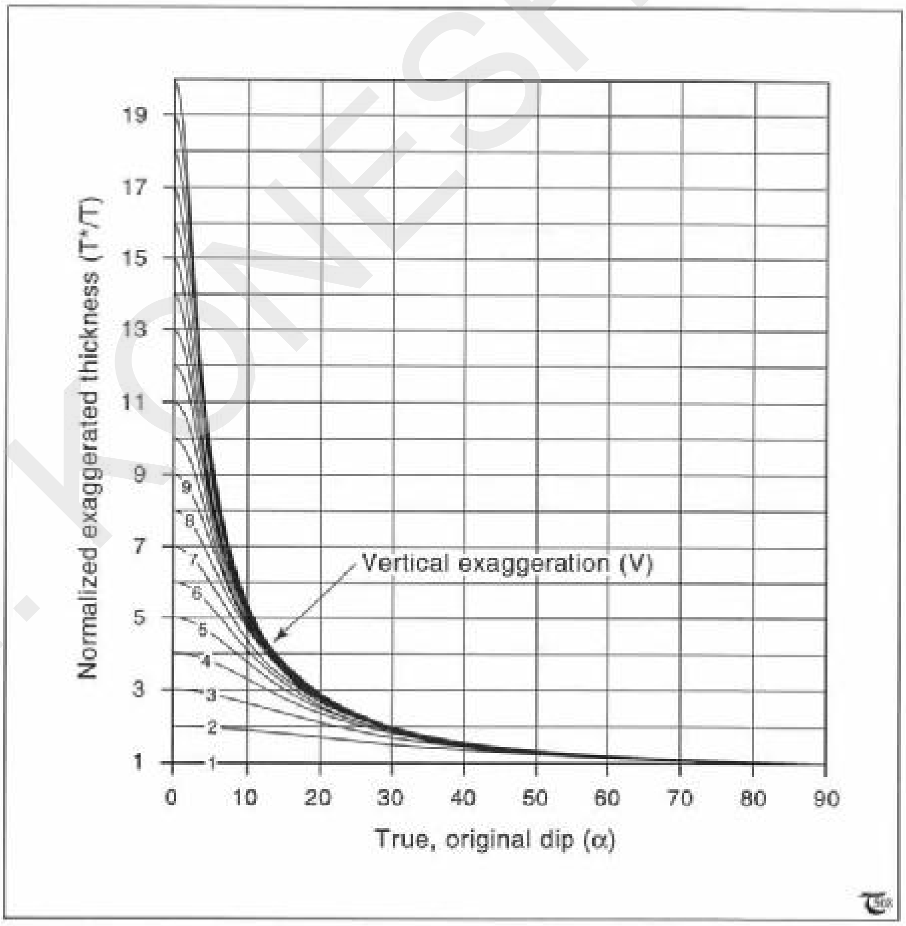


Figure 4-11: Nomogram relating the true dip, α, to the normalized exaggerated thickness of a layer, T/T, for a range of vertical exaggeration factors, V. See eq. (4-2).*

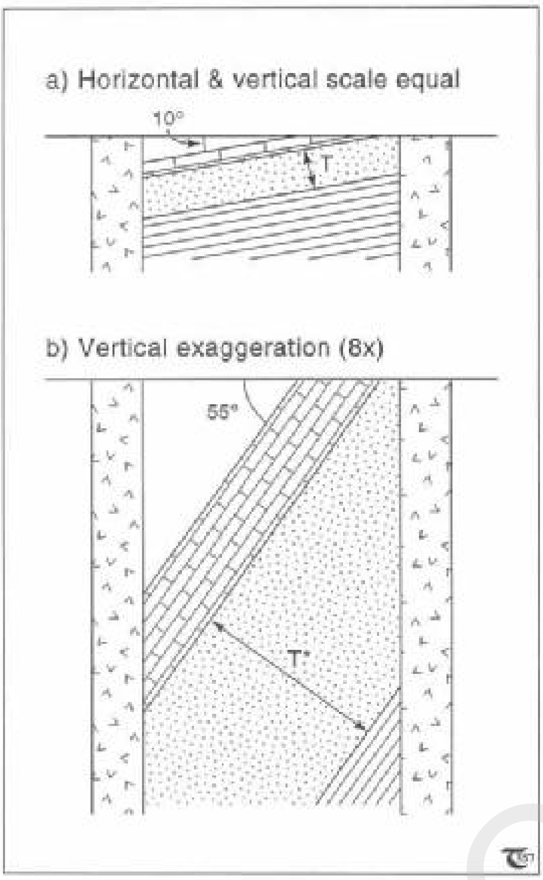


Figure 4-12: a) & b) Isometric and vertically exaggerated cross-sections (V=8). The layer thickness, T, is artificially enhanced in the exaggerated section to T. See exercise 4-4.*

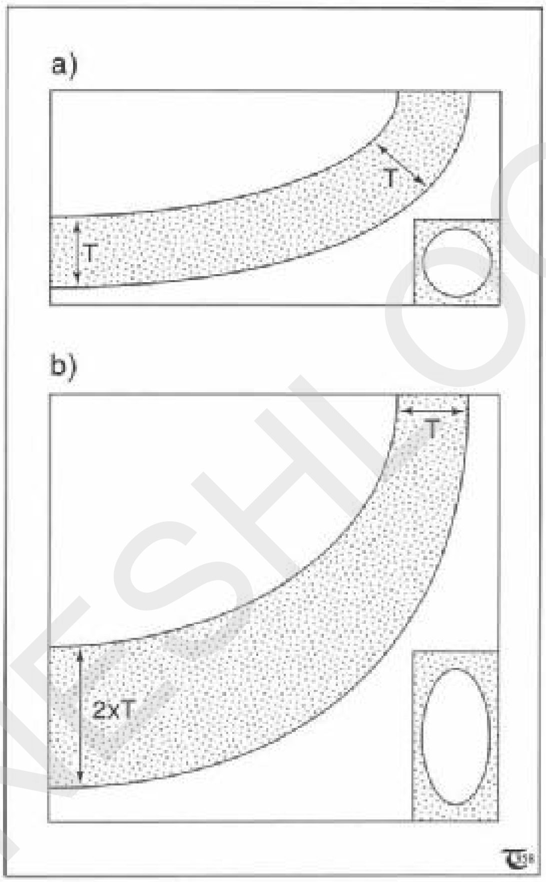


Figure 4-13: a) & b) Appearance of folded layer of constant thickness in: (a) isometrically scaled, and b) vertically exaggerated cross-section, two-fold (V=2). The strain ellipse scales the exaggeration.

d) Apparent thickness change

The thickness of dipping layers is affected, either more or less, by exaggerating the vertical length scale, depending upon the initial or true dip of the beds. A very informative example of this effect occurs on layers of *constant thickness*, but with gradual changes in the amount of dip (Fig. 4-13a), which appear on the exaggerated cross-section with *lateral changes in thickness* (Fig. 4-13b). Consequently, the thickness of a folded sequence will be attenuated in seismic sections on the hinge zones. Similarly, the central part of depocenters may appear thickened on vertically exaggerated seismic sections, purely as an apparent visual, rather than a real, feature. An expression linking the normalized exaggerated thickness of beds, T^*/T, directly to the vertical exaggeration factor, V, and the exaggerated dip, α^*, is:

$$T^*/T = [V \cos \alpha^*] / \cos[\tan^{-1}(\tan \alpha^*/V)] \qquad (4\text{-}3)$$

The function is plotted in the nomogram of Figure 4-14 for practical use.

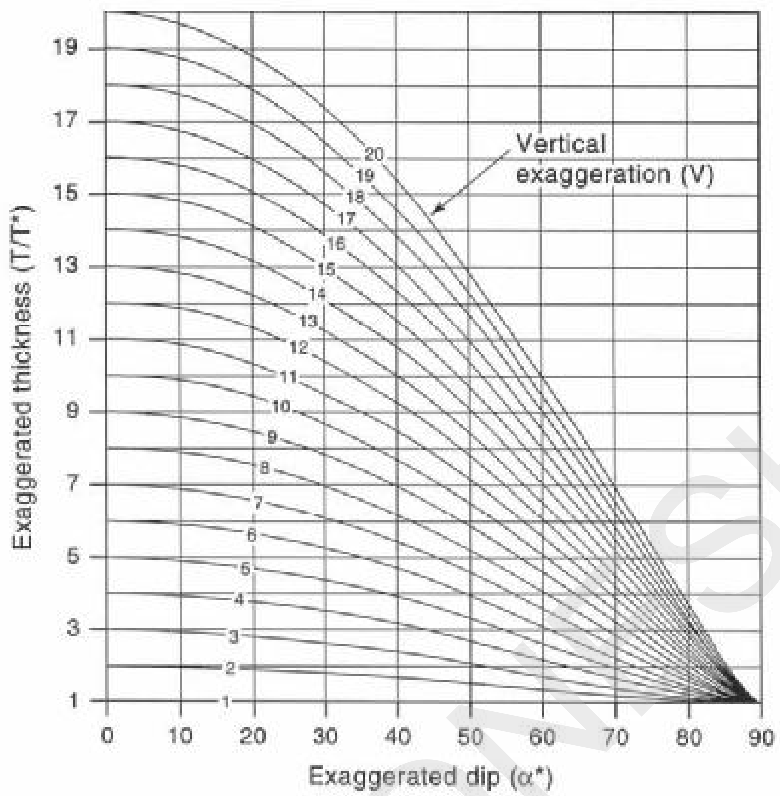
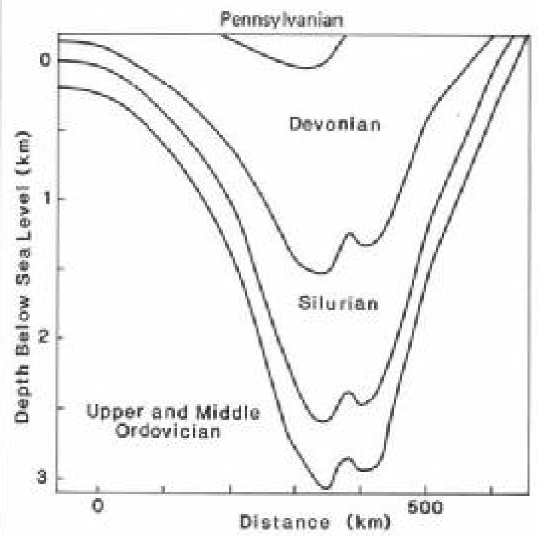


Figure 4-14: Nomogram relating the exaggerated dip, α, to the normalized exaggerated layer thickness, T*/T, for a range of vertical exaggeration factors, V. See eq. (4-3).*

Figure 4-15: Cross-section, two hundred times vertically exaggerated, of the Michigan Basin, North America.

☐Exercise 4-5: Study the cross-section through the Michigan Basin (Fig. 4-15). The true thickness of about one kilometer of the Silurian beds can be read from the vertical scale, where the layers are horizontal, i.e., in the center of the basin. The section suggests that the Silurian thins dramatically towards the margins of the basin. However, this is largely a visual artifact due to the extremely large vertical exaggeration. Although the Michigan basin is just a gentle depression, the section suggests it has the shape of a tight synform. Use equation (4-1) to specify the true dip of the base of the Silurian in the steepest part of the basin.



4-4 Apparent thickness and dip

The distortions outlined in section 4-3 are all artifacts of the difference in horizontal and vertical scales, sometimes used in the construction of cross-sections. Two other distortional effects, associated with the orientation of cross-sections, are (a) apparent dip and (b) apparent thickness of layers (see, also, chapter three). However, these distortions are of a different nature from the purely artificial distortions discussed in section 4-3. Natural surfaces cutting oblique to the strike of geological structures actually display apparent dips, and appear less steep than the true dip.

☐Exercise 4-6: The cross-section of Figure 4-16 shows the hydrocarbon-bearing cover sequence of the Arabian shield. The basement appears at the surface in the extreme left of the section, and the contact with the main fault of the Zagros Mountains is indicated in the right-hand part. The vertical exaggeration of the section is of factor V=80. a) Use equation (4-1), and specify the true dip of the base of the cover sequence in the steepest part of the basin. b) Discuss all the visual effects which are only apparent and thus distort the true geometry of the subsurface structure seen.

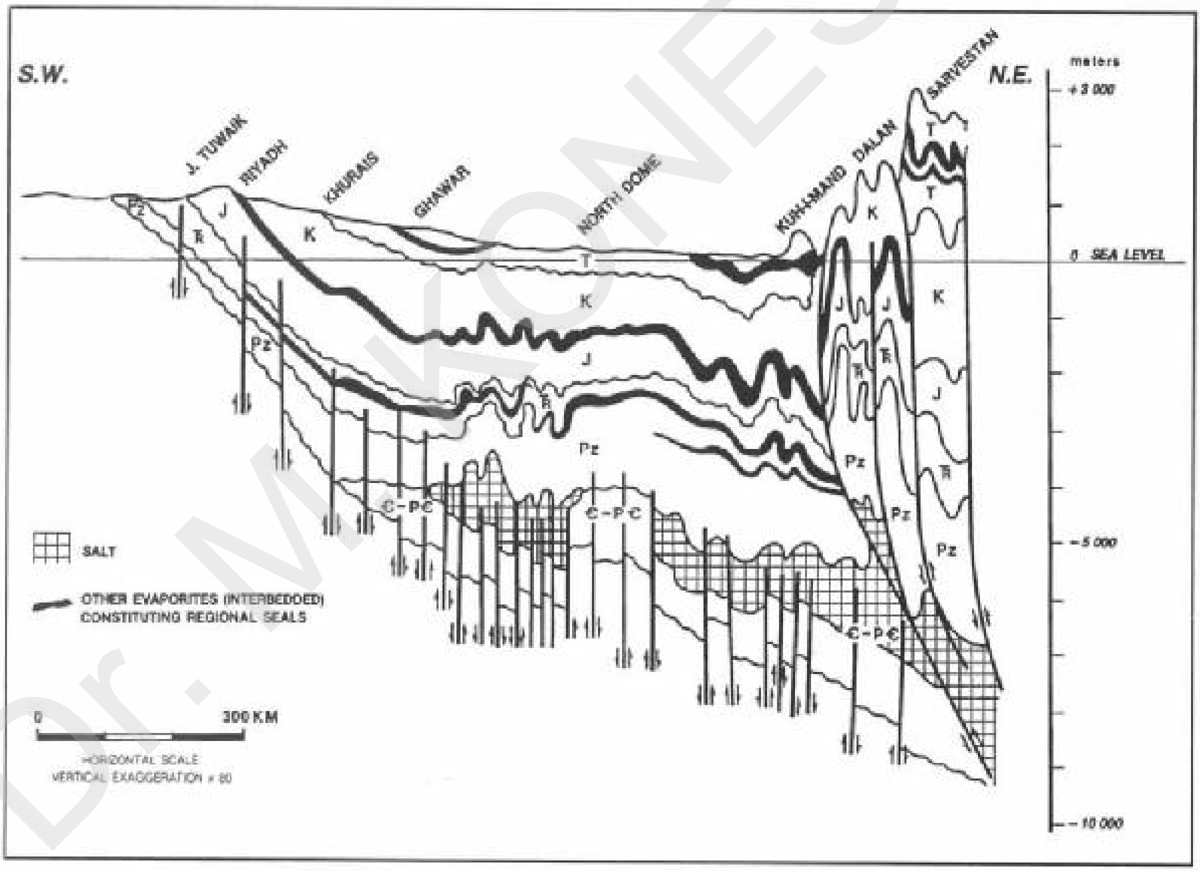


Figure 4-16: Cross-section, eighty times vertically exaggerated, of the Arabian platform sequence, adjacent to the Zagros Mountains in the northeast.

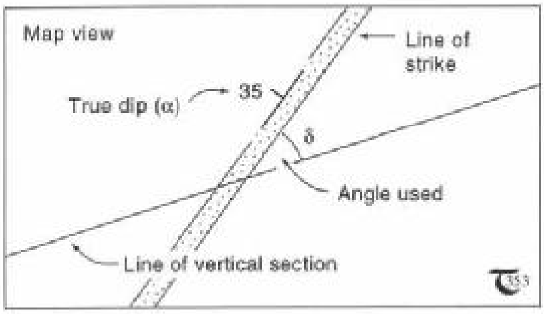


Figure 4-17: *The angle, δ, is measured in map views between the strike of a bed and the section line. Thickness exaggeration relates to the true dip, α, through the section angle, δ.*

This is because the dip of inclined layers may, in cross-sections without scale exaggeration, vary between zero and the true dip, depending upon whether the profile line is parallel or perpendicular to the strike of that plane. The apparent dips and thicknesses in oblique cross-sections may give misleading views of the structure of a region. Geologists must be aware of these kinds of visual distortions, especially when examining field exposures of rock structures. The walls of natural canyons and man-made road cuts are likely to be oblique to the structural strike. It is often hard to conceive that such sections of real rock surfaces may show misleading, distorted views. One danger associated with the interpretation and study of both constructed and natural cross-sections is that sectional distortions are overlooked. The true thickness and true dip of sedimentary beds are seen only if the cross-section is oriented perpendicular to the strike of the beds. If cross-sections are constructed with apparent thickness and dip of the layers, the transferral of the map data to such oblique sections is more elaborate than in profiles normal to the strike. In such oblique cross-sections, all true dips need to be transformed to apparent dips. For example, at least some beds in areas of gently plunging folds will strike oblique to any vertical plane of section (see chapter seven, exercise 7-10), and the effects of apparent dip and thickness may be different for limbs at either side of the axial plane.

The thickness of inclined layers in vertical cuts oblique to strike is exaggerated and appears with an apparent thickness, T_A. True and apparent thicknesses are partly controlled by the angle, δ, measured between the section line and the strike

Table 4-1: *Factors of thickness exaggeration for layers of true dip, α, cut oblique at angle δ.*

True dip, α	Acute angle between strike and line of section, δ: 0	5	10	15	20	25	30	40	50	60	70	80	90
0	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1
10	1.02	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1
15	1.04	1.03	1.04	1.03	1.03	1.03	1.03	1.02	1.01	1.01	1.00	1.00	1
20	1.06	1.06	1.06	1.06	1.06	1.05	1.05	1.04	1.03	1.02	1.01	1.00	1
25	1.10	1.10	1.10	1.10	1.09	1.08	1.08	1.06	1.04	1.02	1.01	1.00	1
30	1.16	1.15	1.15	1.14	1.13	1.12	1.11	1.08	1.06	1.03	1.02	1.00	1
35	1.22	1.22	1.22	1.20	1.19	1.17	1.15	1.11	1.08	1.04	1.02	1.00	1
40	1.31	1.30	1.29	1.28	1.26	1.23	1.20	1.15	1.10	1.06	1.03	1.01	1
45	1.41	1.41	1.39	1.37	1.34	1.30	1.27	1.19	1.12	1.07	1.03	1.01	1
50	1.56	1.55	1.53	1.49	1.44	1.39	1.34	1.24	1.15	1.08	1.04	1.01	1
55	1.74	1.73	1.69	1.64	1.57	1.49	1.42	1.28	1.18	1.10	1.04	1.01	1
60	2	1.98	1.92	1.83	1.72	1.61	1.51	1.34	1.20	1.11	1.05	1.01	1
65	2.37	2.33	2.22	2.07	1.91	1.75	1.61	1.39	1.23	1.12	1.05	1.01	1
70	2.92	2.84	2.64	2.38	2.13	1.91	1.72	1.44	1.26	1.13	1.06	1.01	1
75	3.86	3.64	3.24	2.78	2.38	2.07	1.83	1.49	1.28	1.14	1.06	1.01	1
80	5.76	5.14	4.10	3.24	2.64	2.22	1.92	1.52	1.29	1.15	1.06	1.02	1
85	11.47	8.13	5.16	3.67	2.84	2.33	1.98	1.55	1.30	1.15	1.06	1.02	1
90	∞	11.47	5.76	3.86	2.92	2.37	2	1.56	1.55	1.31	1.06	1.02	1

of the strata studied (Fig. 4-17). Layers of dip, α, and map width, W, have, in vertical cuts at angle δ to their strike, an apparent thickness, T_A:

$$T_A = W \sin[\tan^{-1}(\tan \alpha \sin \delta)]/\sin \delta \qquad (4\text{-}4)$$

The true thickness, T, relates to map width, W, and dip, α, by:

$$T = W \sin \alpha \qquad (4\text{-}5)$$

Consequently, the thickness exaggeration factor, T_A/T, is:

$$T_A/T = \sin[\tan^{-1}(\tan \alpha \sin \delta)]/(\sin \alpha \sin \delta) \qquad (4\text{-}6)$$

Equations (4-4) and (4-6) are invalid if δ equals zero. For such cases, the vertical thickness of layers is given by: $T_A = W/\sin(90°-\alpha)$. The corresponding thickness exaggeration factor then becomes: $T_A/T = 1/\sin(90°-\alpha)$. For α equal to 90°, the thickness exaggeration factor reduces to: $T_A/T = 1/\sin \delta$.

Table 4-1 lists exaggeration factors for the full range of angles possible for α and δ. The thickness of sedimentary beds, visually exaggerated in sections oblique to the strike of the beds, can, also, be inferred using the thickness exaggeration factors, included in the nomogram of Figure 4-18. This nomogram can, also, be used to trans-

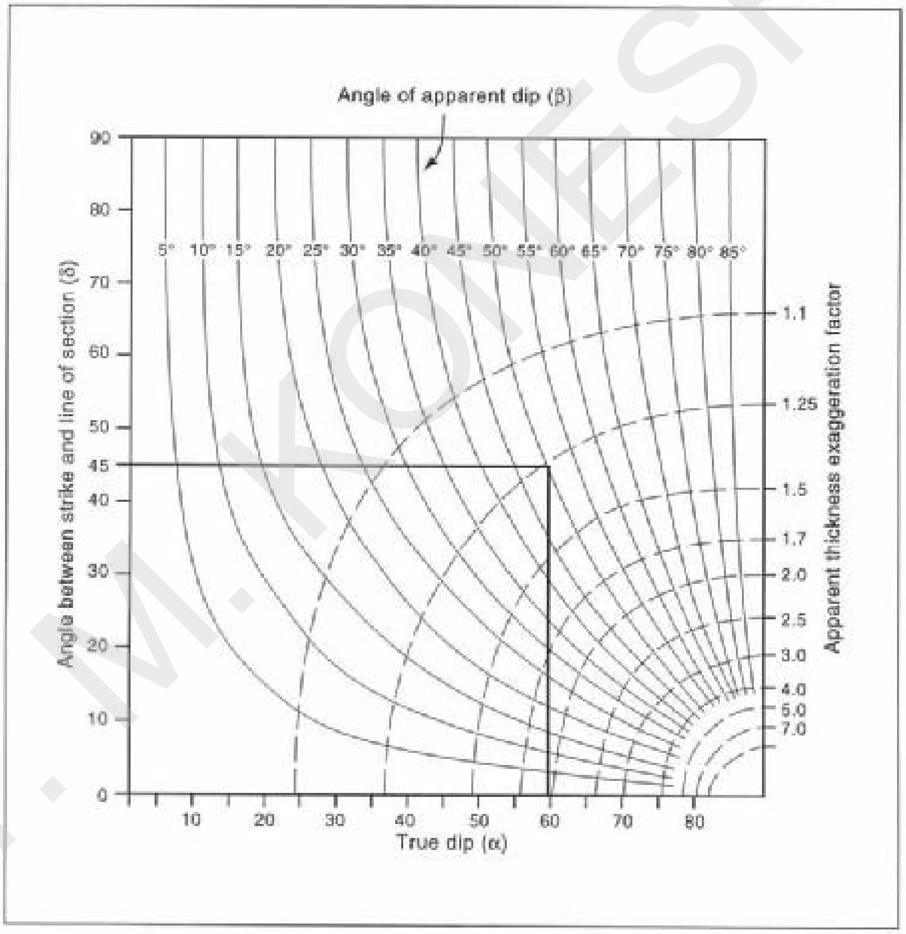


Figure 4-18: *Nomogram relating true and apparent dip, including the exaggeration factor for the apparent thickness of beds in sections oblique to the structural strike.*

form true dips from geological maps to apparent dips on cross-sections, and vice versa. Similarly, apparent dips, as seen in oblique cross-sections, may be converted to true dips measured in field outcrops. The mathematical expression used to obtain true dips from apparent dips of strata in sections oblique to strike was given in chapter three [eq. (3-1)].

Figure 4-19: *View of the Grand Canyon from Lipan Point, about fifty kilometers east from the visitors' center. See exercise 4-8.*

☐Exercise 4-7: A sandstone bed dips 60° due east. A canyon cuts the bed at 45° to its strike. a) Use the nomogram of Figure 4-18 to predict which dip you will see for the bed in the canyon walls. b) If the bed in the canyon walls appears with a thickness of 128 meters, how much is the true thickness according to the nomogram? c) What is the outcrop width of the bed as seen on the horizontal plateau next to the canyon? d) A limestone bed concordant with the sandstone bed is known to have a true thickness of 200 meters. What will be the thickness as seen in the canyon wall?

☐Exercise 4-8: A subhorizontal Paleozoic top sequence (1.5 kilometers thick) rests unconformably on the Precambrian Grand Canyon Series, which dip gently to the NW (Fig. 4-19). a) Explain why the contact between the Paleozoic and Precambrian beds seems concordant in the right part of the picture, whereas an angular unconformity appears in the left part. b) Explain why the thicknesses of the Precambrian beds in the left and right parts of the picture appear almost similar, despite the different orientations of the canyon slopes.

Geology and Landscapes 2010 – Maps and cross-sections

Practicals 2 to 6 will be dedicated to the study of geological maps and the production of geological cross-section. Below is a summary of the different tasks for each of the practicals:

- 18/01: practical 2 in geol. lab in JCMB (room 6307). Cross-section building in the Grand Canyon area (Arizona). *Monoclinal structure + unconformities.*
- 25/01: practical 3 in Joseph Black building, room LR40 (lecture theatre 44, room G092). Cross-section building in the Devils Fence area (Montana). *Folded structures + magmatic intrusions*. You will hand in the cross-section and 1-page summary describing the relationship between the geological structure and the morphology of the landscape in the Grand Canyon area.
- 01/02: practical 4 in geol. lab in JCMB (room 6307). Cross-section building in the Bristol area (UK). *Folded structures + faulting + unconformities*. You will hand in the cross-section and 1-page summary of the Devils Fence area. Feedback on the Grand Canyon work will be given to you.
- 08/02: practical 5 in Joseph Black building, room LR40 (lecture theatre 44, room G092). Cross-section building in the Canmore area (Canada). *Fold and thrust belt + unconformities*. You will hand in the cross-section and 1-page summary of the Bristol area. Feedback on the Devils Fence work will be given to you.
- 15/02: practical 6 in geol. lab in JCMB (room 6307). Cross-section building in the area that will be investigated during the Spain field trip. *Folded structures + faulting + unconformities*. You will hand in the cross-section and 1-page summary of the Canmore area. Feedback on the Bristol work will be given to you.
- 22/02: you will hand in the cross-section and 1-page summary of the Spain area at the teaching office, Drummond Street. Feedback on the Canmore work will be ready to be collected there.
- 01/03: feedback on the Spain work will be ready to be collected at the teaching office, Drummond Street.

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

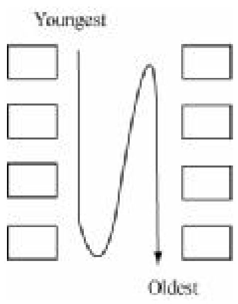
You have been given a geological map. Before starting anything, spend at least 10 minutes looking at the map and the caption.

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:

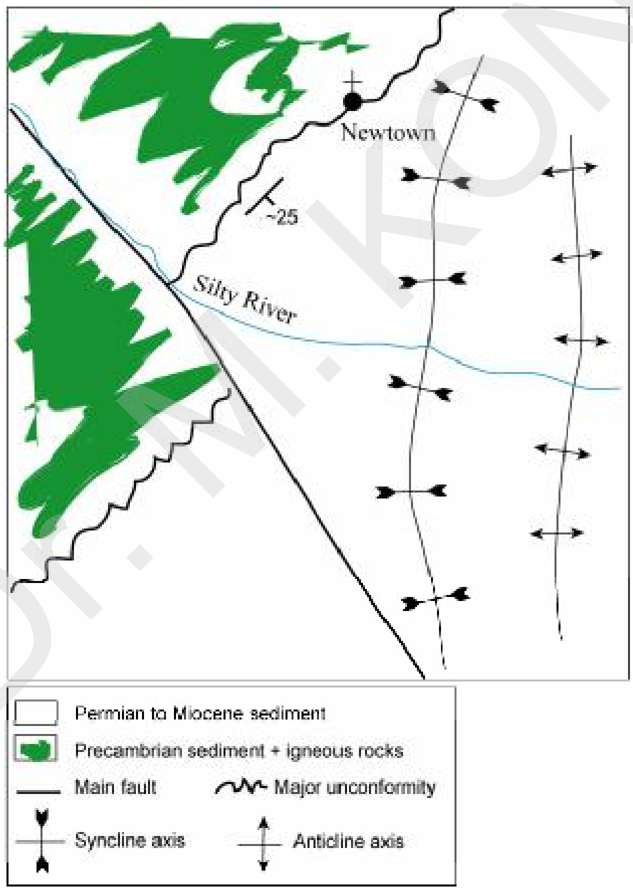


Additional useful information on the map may include the trace of fold axis and symbols giving the dip and dip direction of beds. In metamorphic rocks, different symbols may also give the dip and dip direction of foliation (see caption). Note that dip/dip direction symbols can differ between countries: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

USA, France: 24 UK: 24

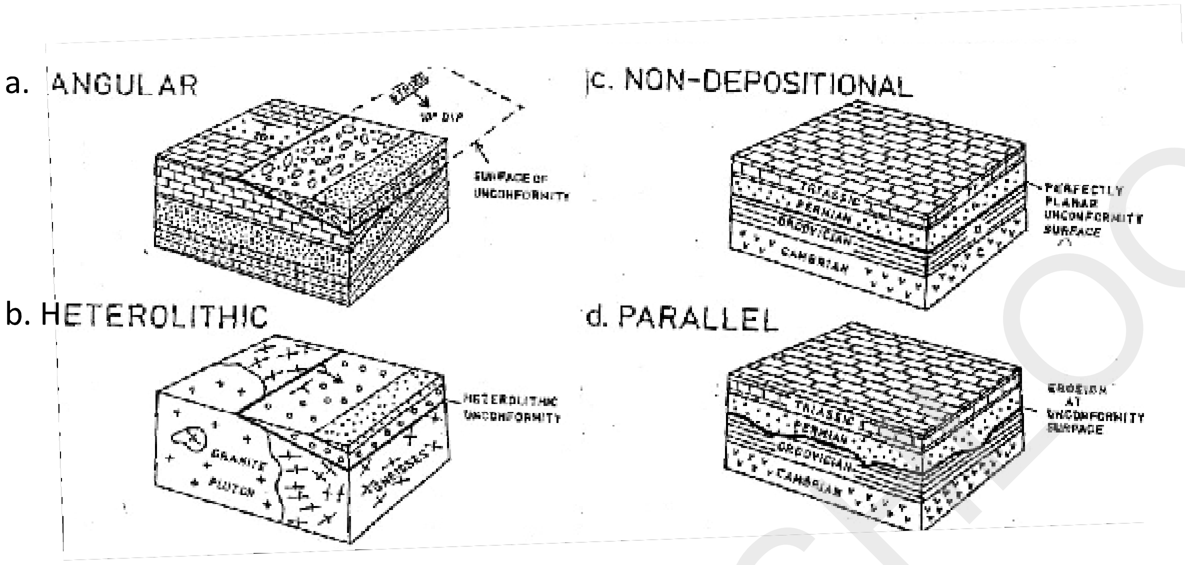
II. Drawing a structural diagram

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):

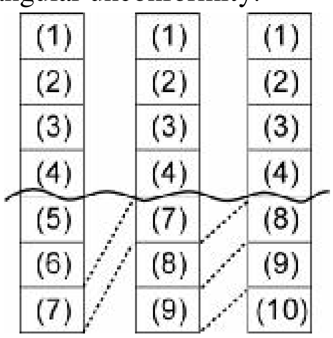


Non-depositional and parallel unconformities (*c* and *d*) are the most difficult to find because they just represent a gap in the record (some time is "missing", in this case Silurian + Devonian + Carboniferous). Changes in the thickness of the Ordovician may help evidence the presence of a parallel 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 2nd location, layers 5, 6 and 7 are missing in the 3rd location) → the base of layer 4 is an angular unconformity:



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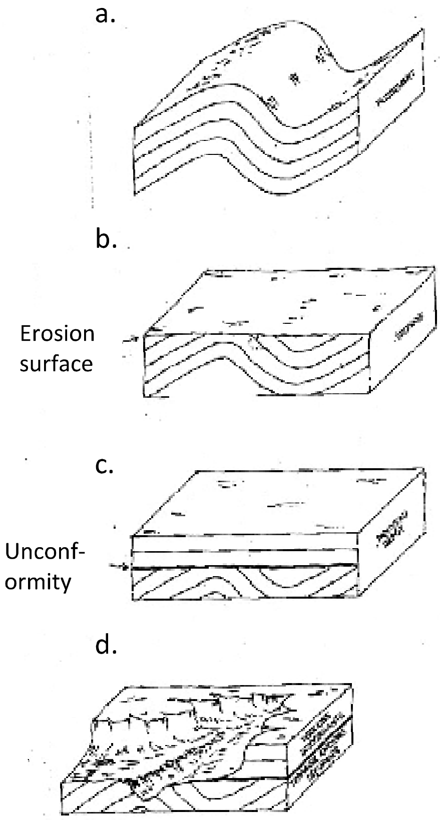
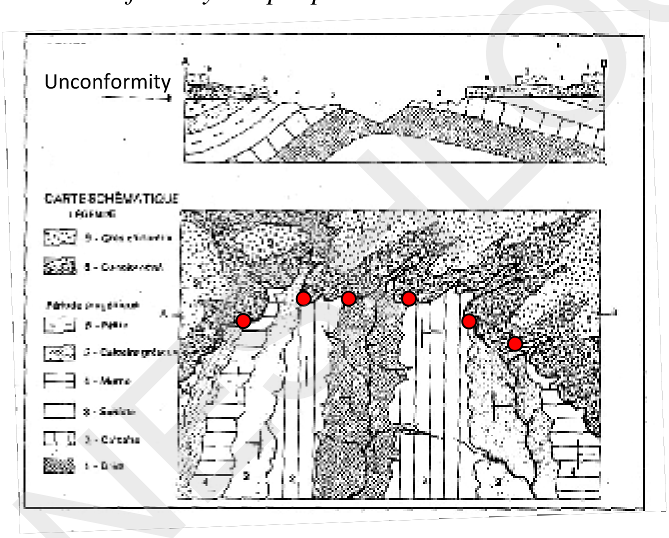
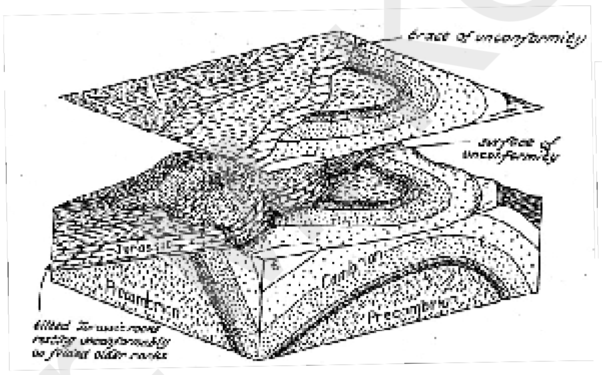


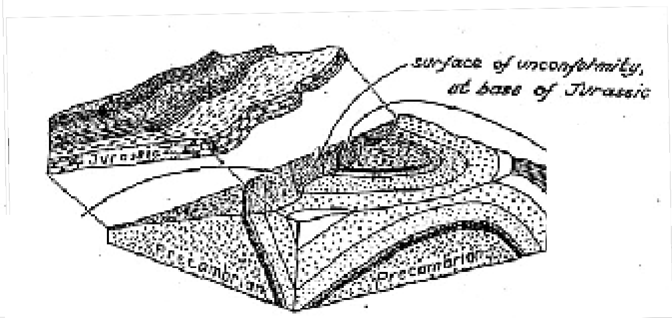
Left: example of formation of an angular unconformity. a: folding of an exiting layered succession. b: erosion. c: deposition of sediment horizontally above the erosion surface. d: example of resulting landscape.

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.





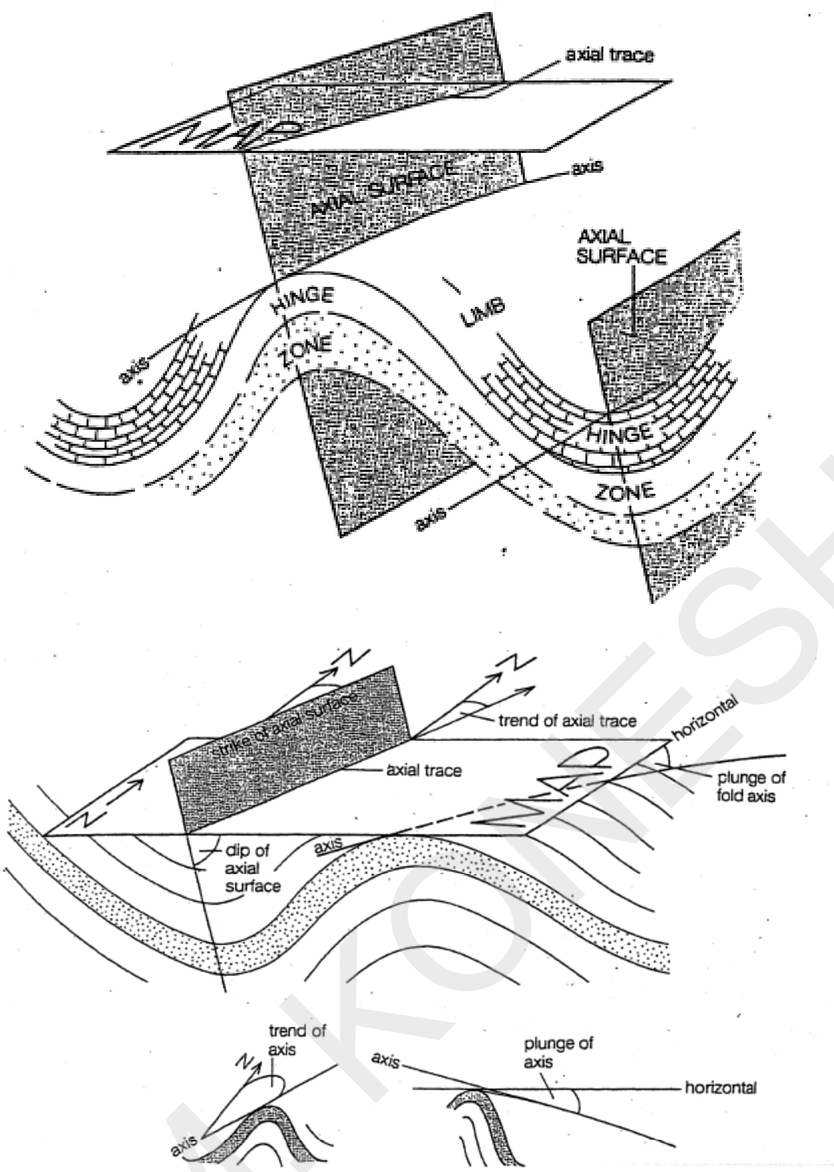
How to identify folds?

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° (~180° in case of folds with horizontal axis).

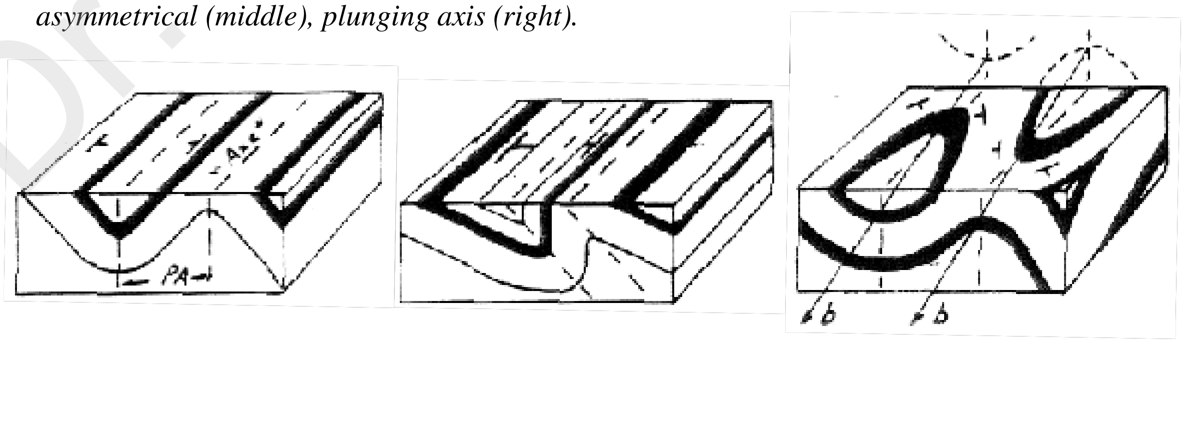
The figures below illustrate these points.

4



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).



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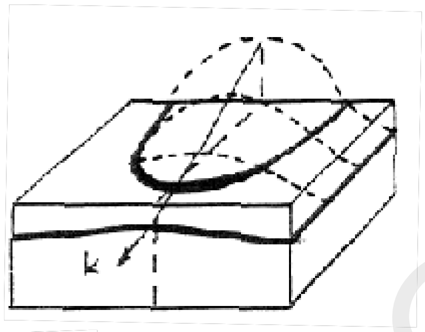
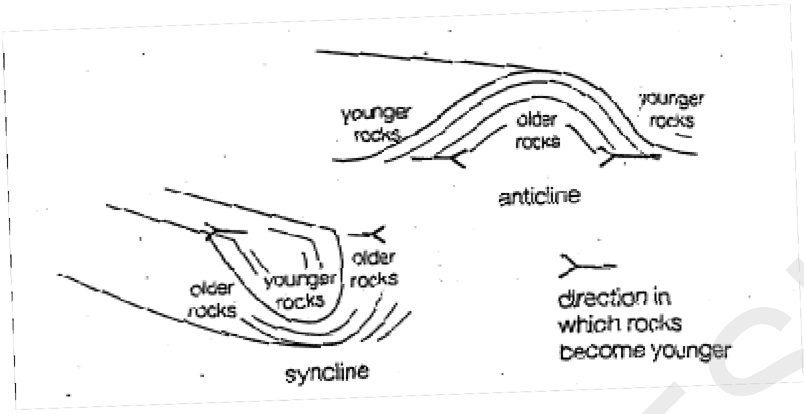
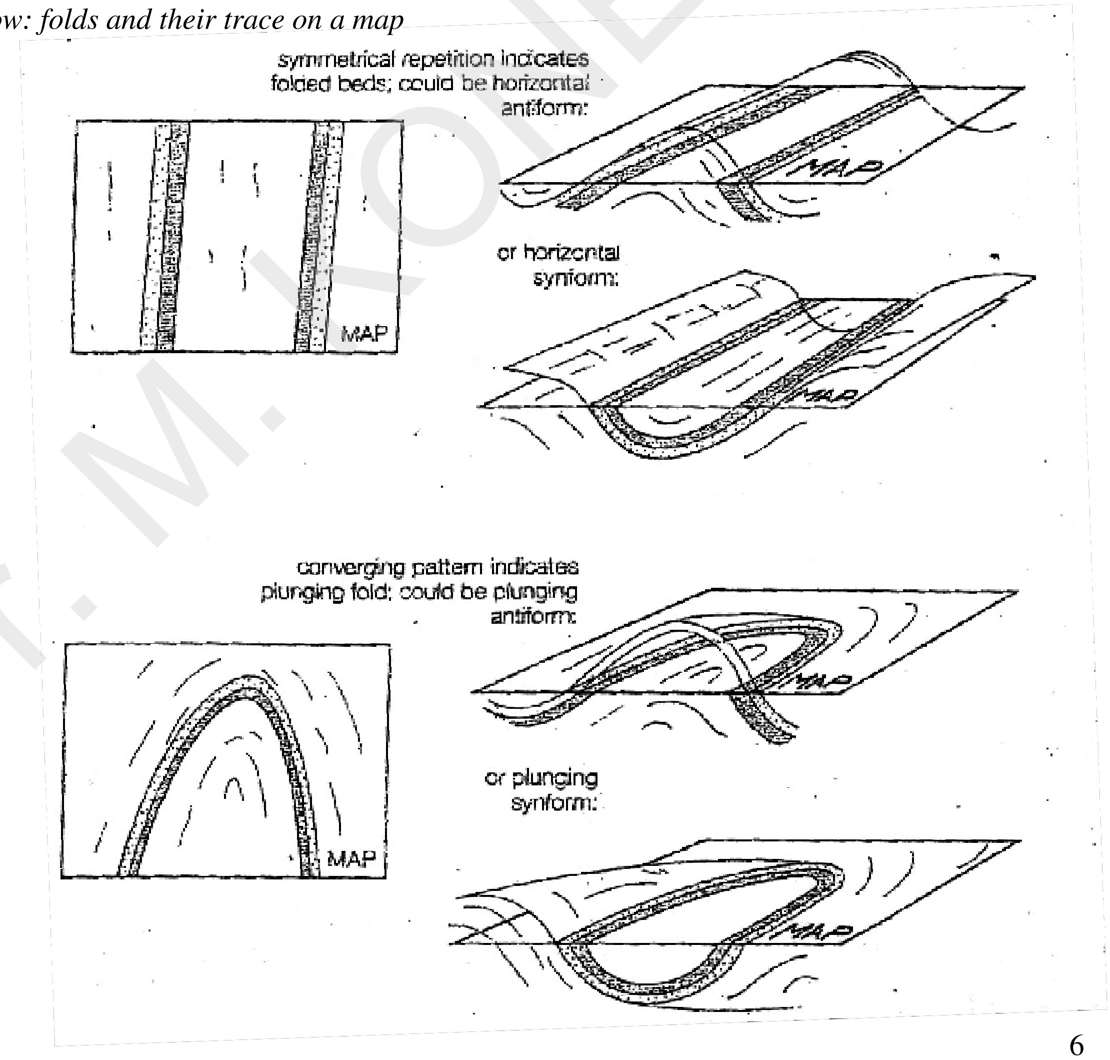
Note: symmetrical folds don't carry on forever. Their termination will produce a trace similar to those of a fold with plunging axis (see diagram to the right).



Below: syncline and anticline

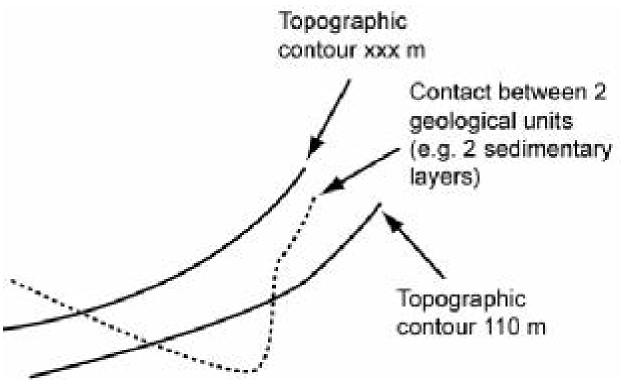


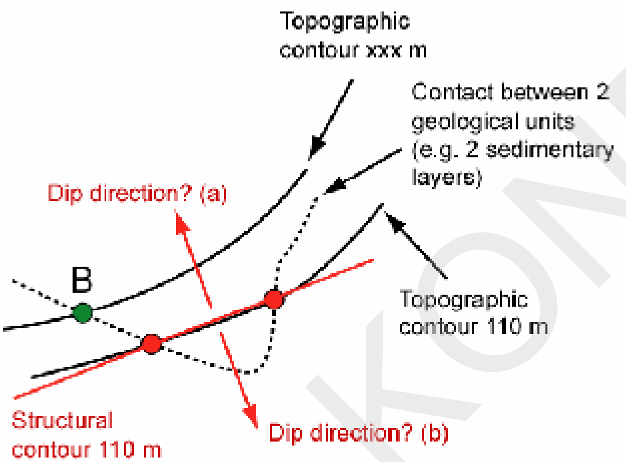
Below: folds and their trace on a map



6

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:

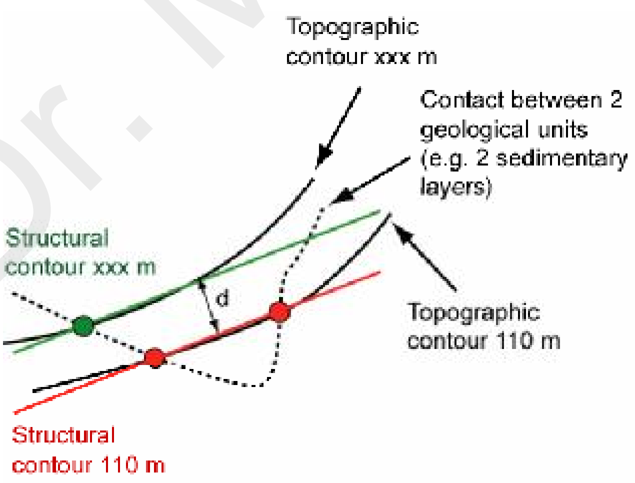




(1) Find a place where the contact intercepts twice the same topographic contour: the 2 intersection points are at the same elevation on the contact, so the line connecting these 2 points is a structural contour (at an elevation 110 m in this case). ***The dip direction is perpendicular to this line (in direction (a) or (b), see diagram below left).*** *Note: if the 2 points are too close (i.e. less than ~5 mm away), the orientation of the structural contour will not be very accurate. If the 2 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 m, then the contact goes down in the (a) direction → dip direction is given by arrow (a). If xxx > 110 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 α is the dip of the contact and Δz is the difference in elevation between the 2 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.

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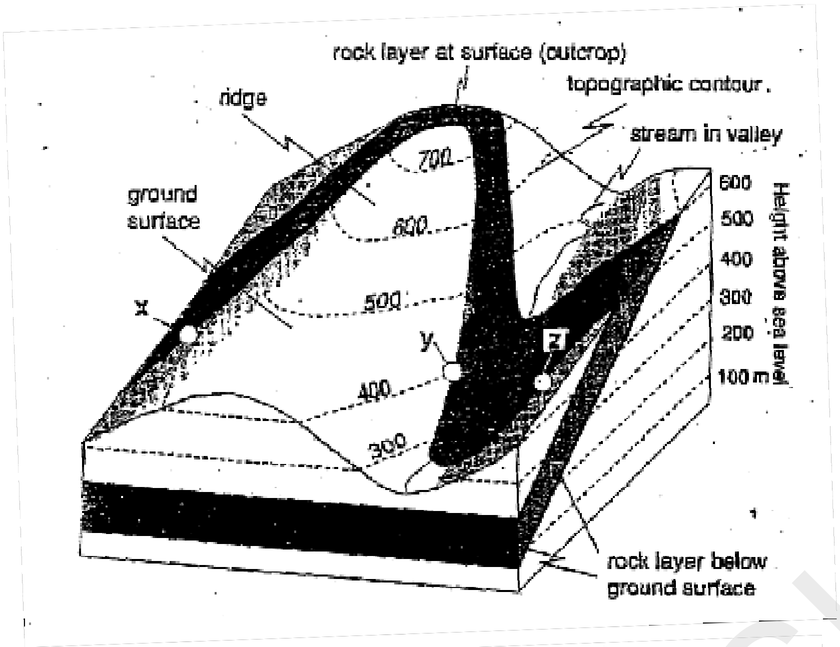
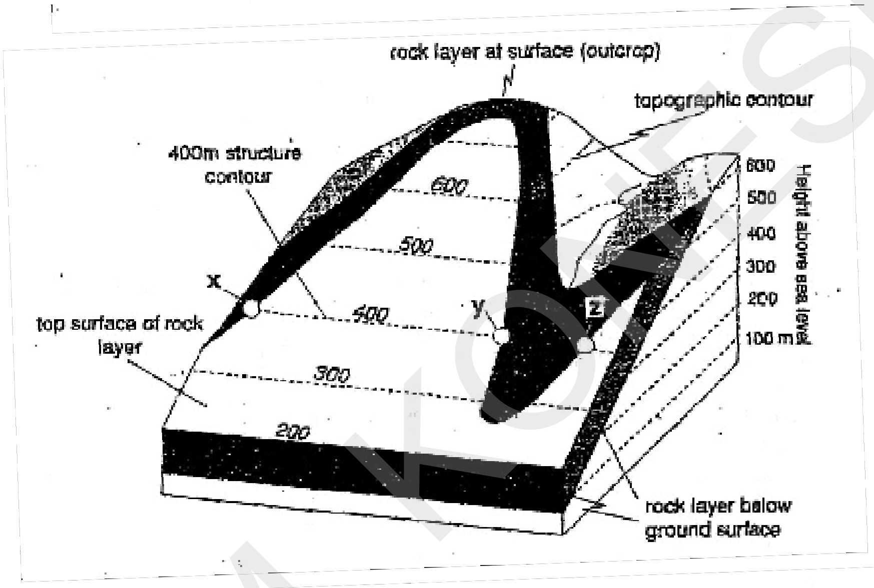
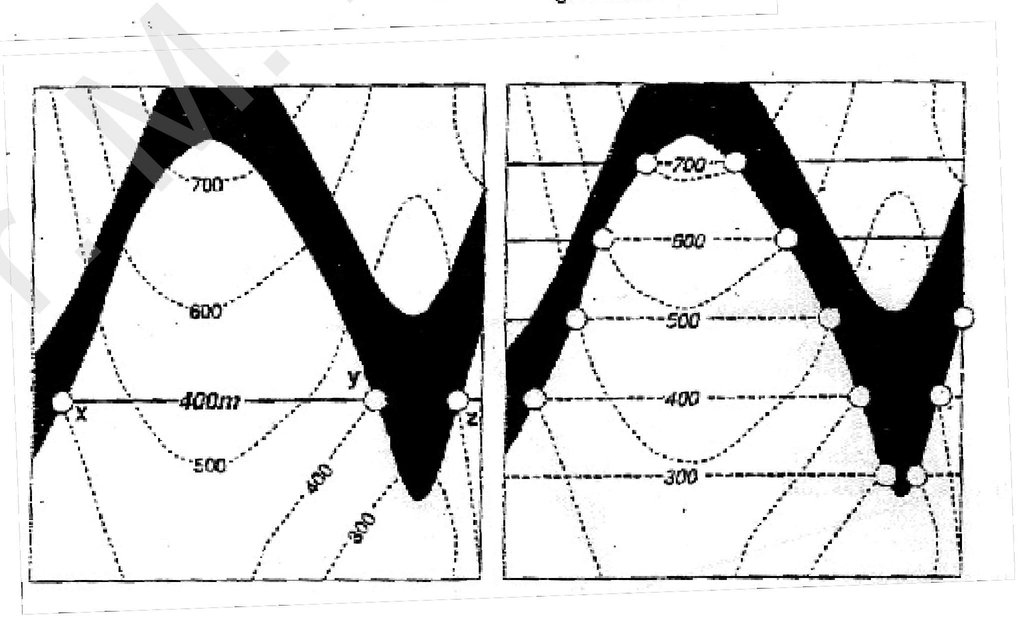


Top: example of a layer intercepting the topography. Middle: the topography above the layer has been removed to show the structural contours. Bottom: building the structural contours on the map.





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

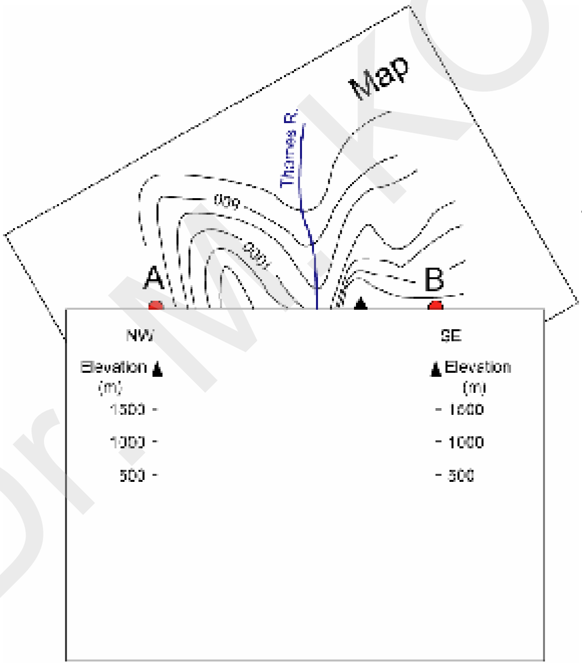
The line of cross-section will be specified to you. The first step involves building the topographic profile, that is, the shape of the landscape along this line. You will draw your profile WITHOUT VERTICAL EXAGGERATION. If the scale of the map is 1/50000, then you will use the same scale for the vertical 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.

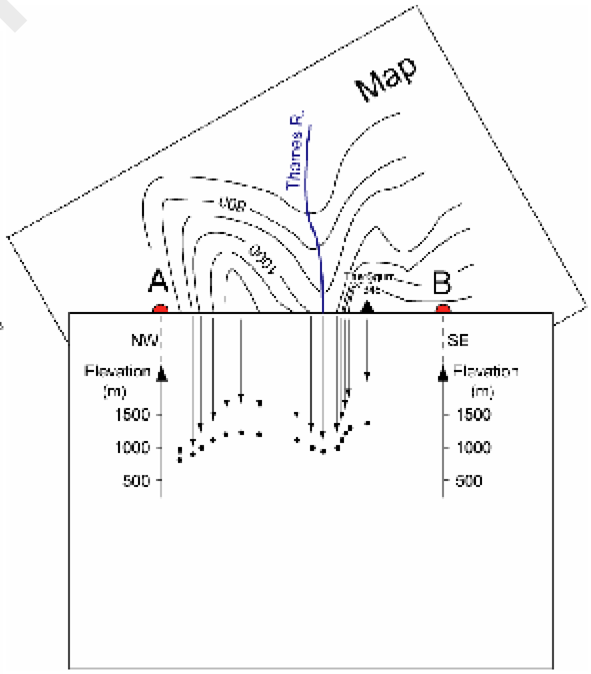
(1) Locate the beginning and end of your cross-section on the map.

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

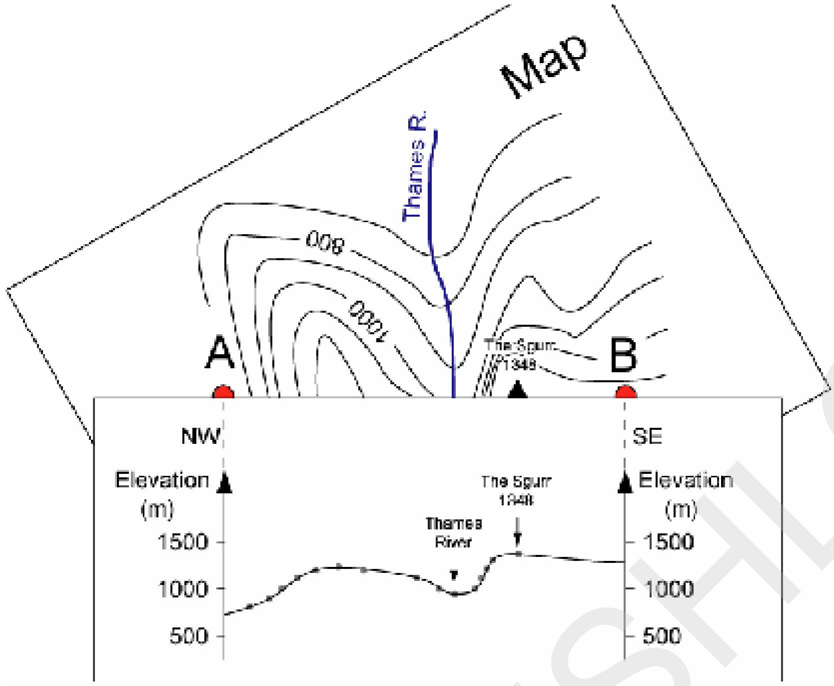
(3) On a A4 graph paper page, place the elevation axis at the extremity of your profile and the orientation of the profile. **Leave room below the profile to fill in the geology and put the caption** (see diagram below left; in this example, lowest elevation ~700 m and highest elevation is 1348 m → elevation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

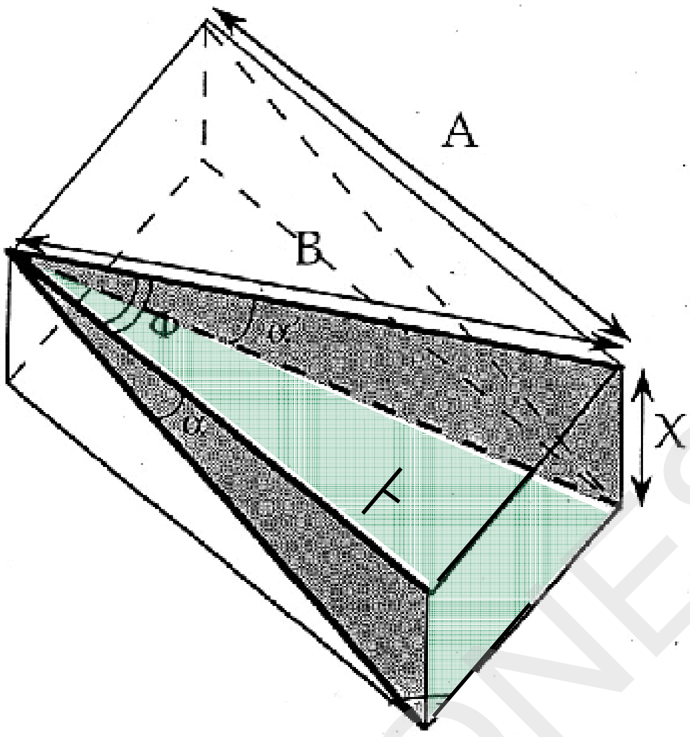


IV. Building the geological cross-section

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.

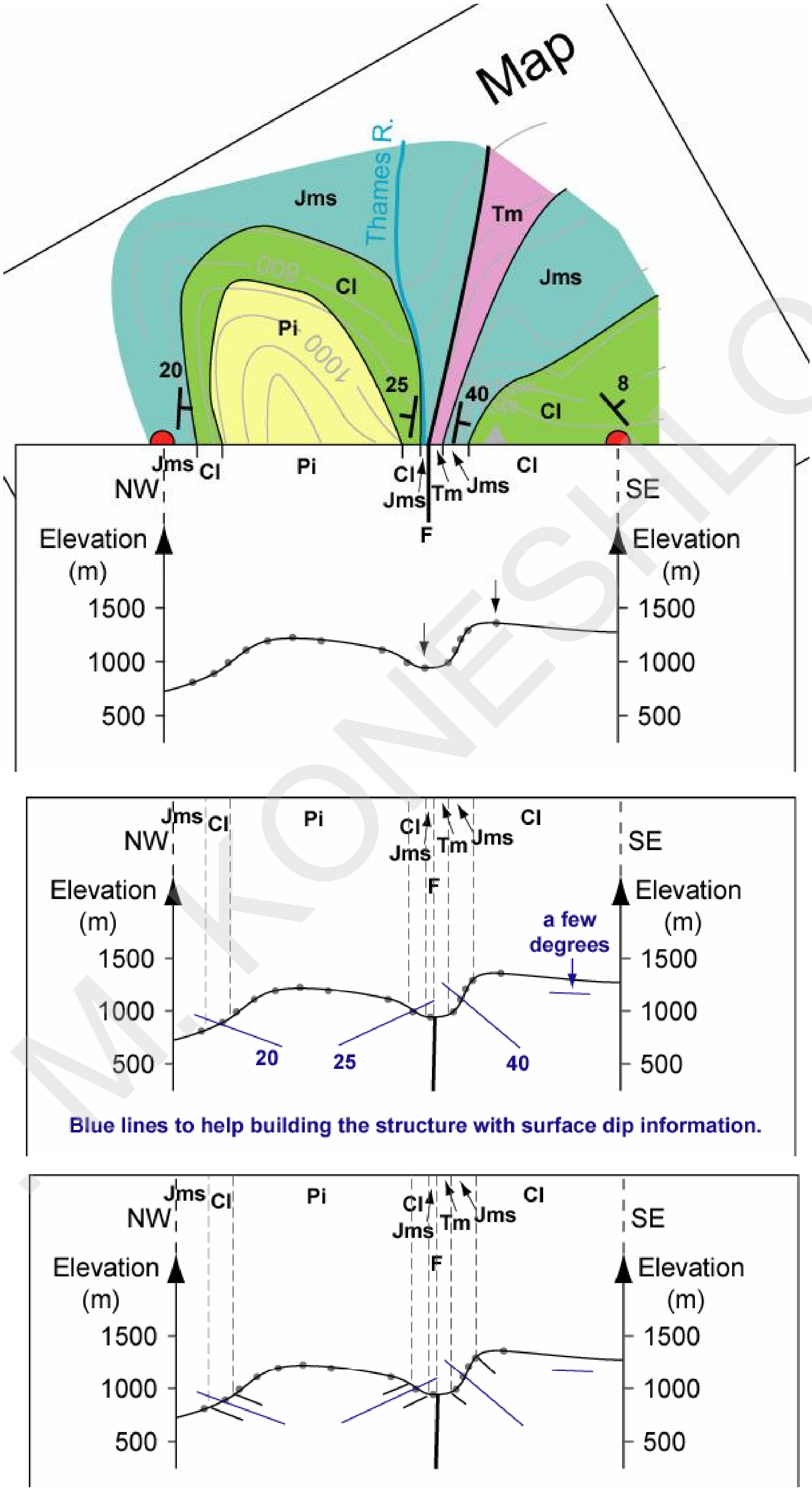


α = true dip,
α' = apparent dip along line of section (B),
Φ = angle between line of section and dip direction.

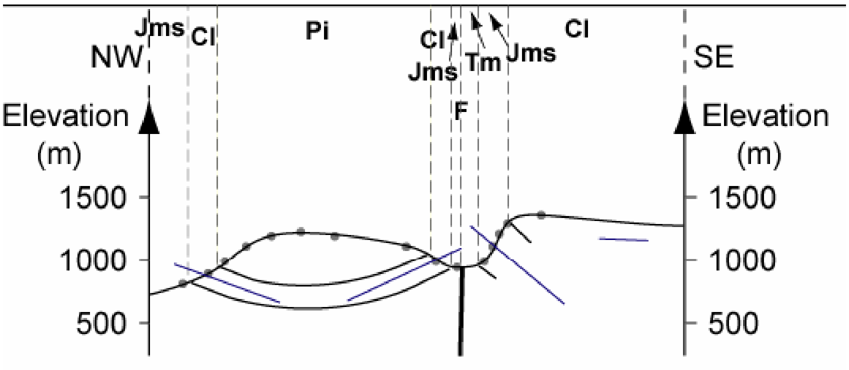
$\tan \alpha' = X/B$
$= X/A * A/B$
$= \tan \alpha * \cos \Phi$

True Dip α:	If angle between line of section and dip direction Φ is: 10°	30°	50°	70°	90°
	then apparent dip in section α' is (in °):				
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	-

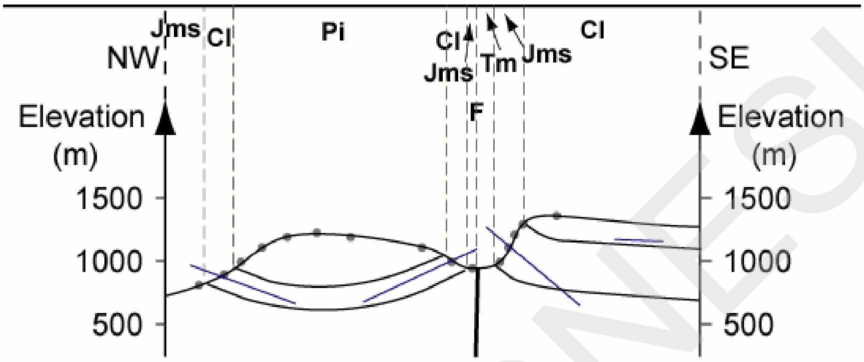
With these rules in mind, you can begin building your cross-section:
(1) Place faults and report your contacts on the cross-section. Trace the contacts a few millimetres under the cross-section (see diagrams next page).


Map
Thames R.
Jms
Tm
Jms
Cl
Pi
800
1000
20
25
40
8
Cl
Jms
Cl
Pi
Cl
Jms
Tm
Jms
Cl
NW
SE
F
Elevation (m)
1500
1000
500
Elevation (m)
1500
1000
500
a few degrees
20
25
40
Blue lines to help building the structure with surface dip information.

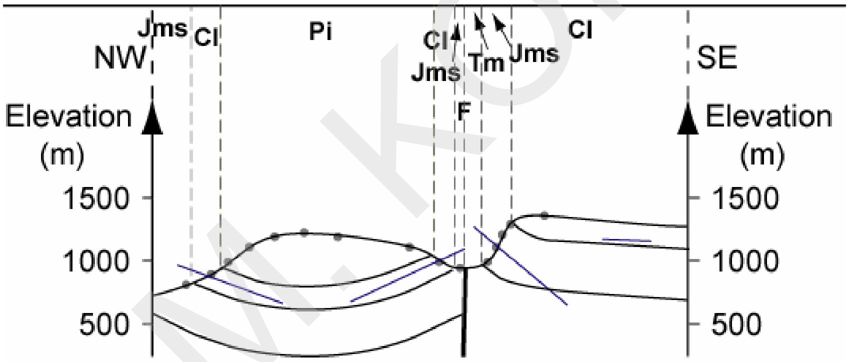
(2) Fill the landscape with the different units from youngest to oldest. Trace the contacts underground and try to keep the thickness of the units constant.



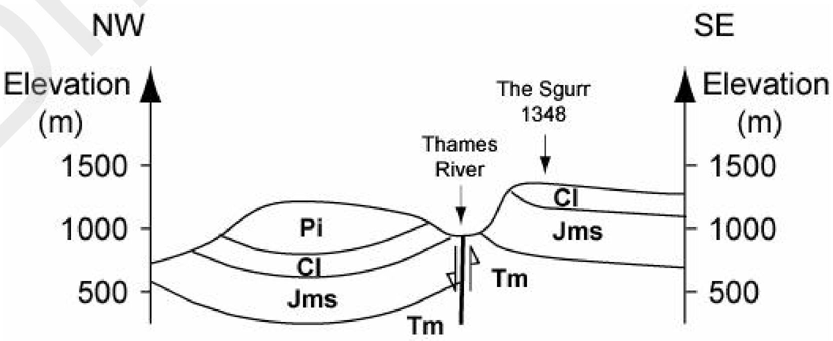
On the left hand side of the fault, you can easily constrain the shape of the syncline seen on the map. You can also determine the thickness of unit *Cl*: ~200 m. This will help building the contacts on the right hand side of the fault: *Cl* can't be thicker than 200m



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). Note: on the diagram to the left, I have put the name of each unit for illustration purpose only. On your cross-section, you will use geological patterns (see further).



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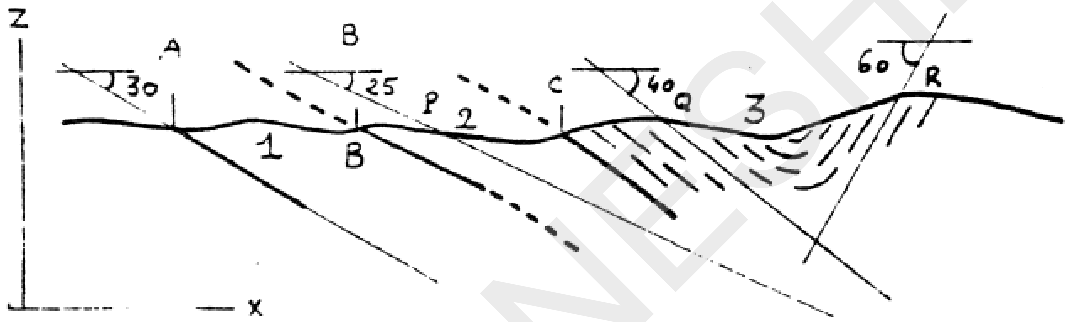
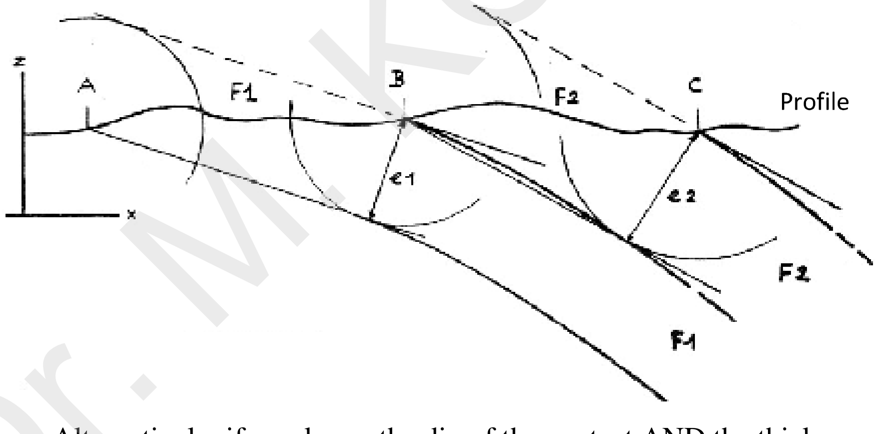
Remarks:

- 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:



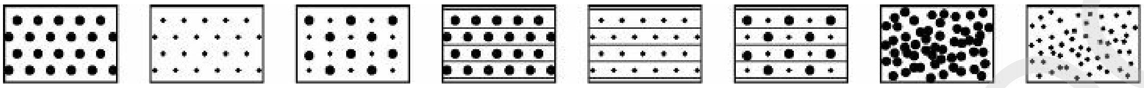
If you don't know the dip of the contacts, you can use a calliper to build the layers F_1 and F_2 of thickness e_1 and e_2, respectively. The contacts will be tangent to the circles traced.

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)

<u>TO FINISH THE GEOLOGICAL CROSS-SECTION:</u>

(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:

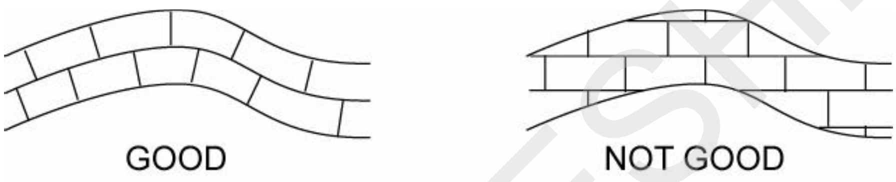
- 8 different sandstone units in your cross-section; you need to be able to distinguish between them so you may have to create different patterns with dots, e.g.:



- 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.

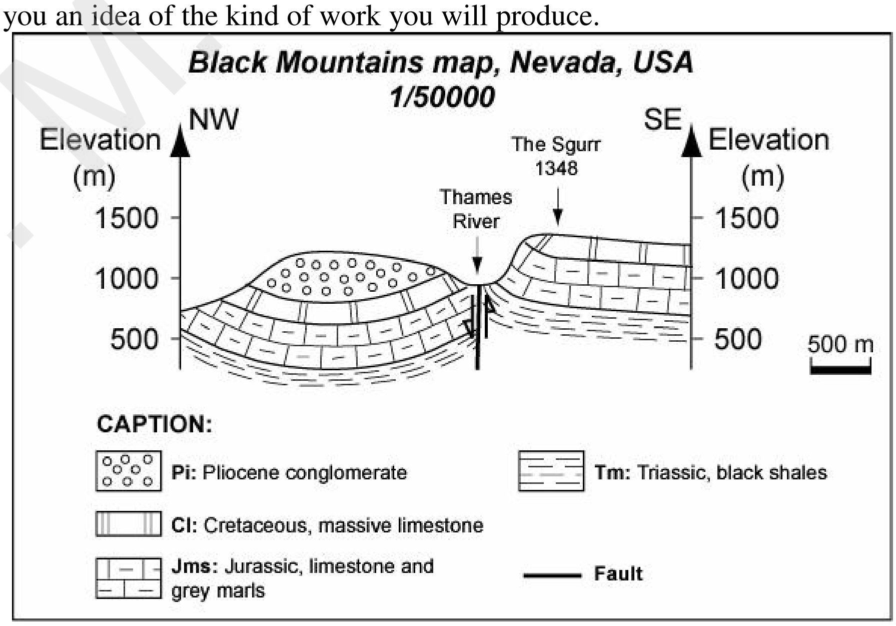
Patterns must follow the curvature of the beds:



(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. <u>The youngest must be at the top left and the oldest at the bottom right</u>. 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 WebCT. 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.



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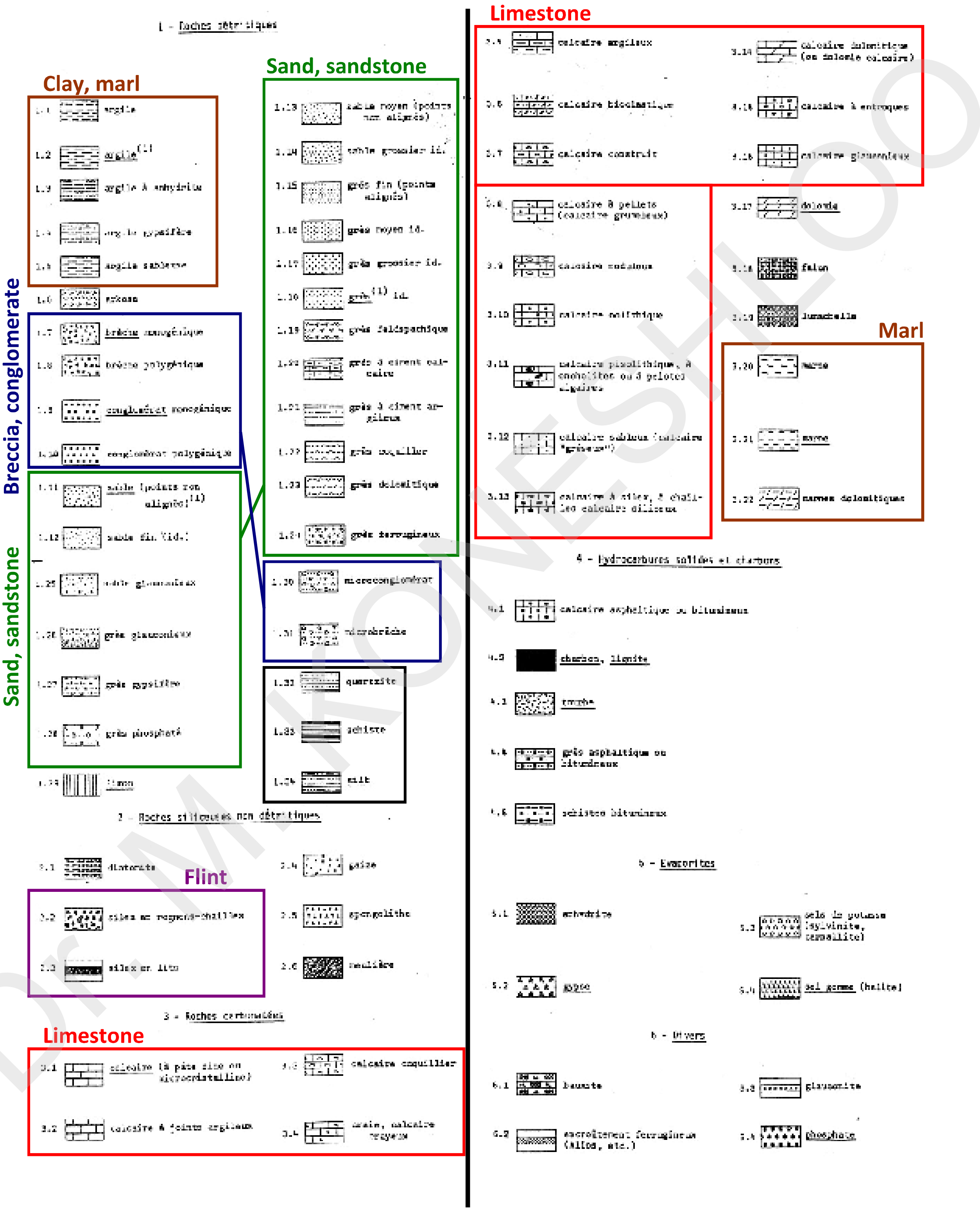
Below: chart of patterns for sedimentary rocks (in French, sorry). 1. Clastic rocks. 2. Non-clastic siliceous rocks. 3. Carbonates. 4. Solid hydrocarbon and coal. 5. Evaporites. 6. Others. The most frequent rock types are highlighted and grouped in categories (boxes).



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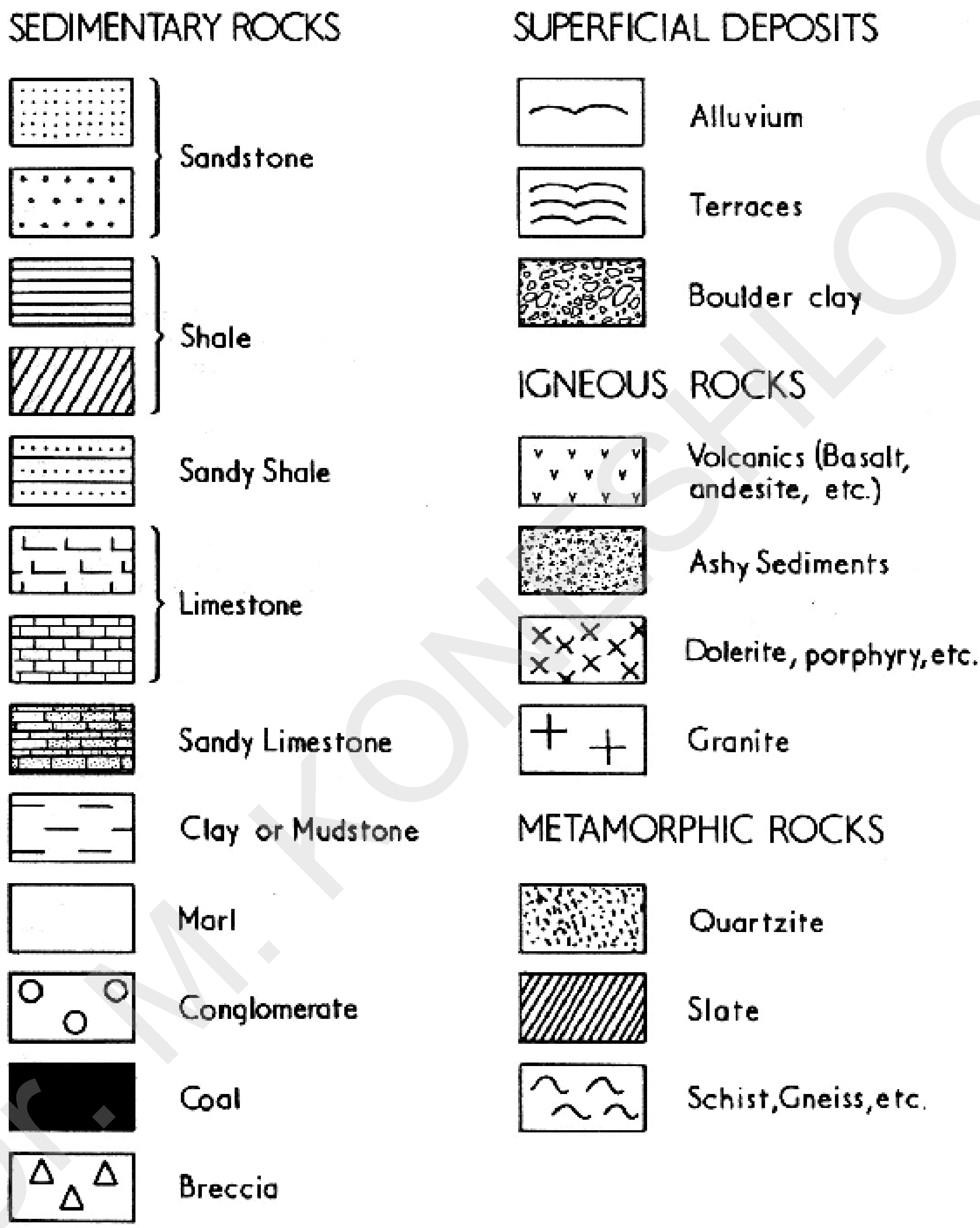
Below: chart of patterns for various types of rocks (from Bennison, G. M., "An introduction to geological structures and maps").

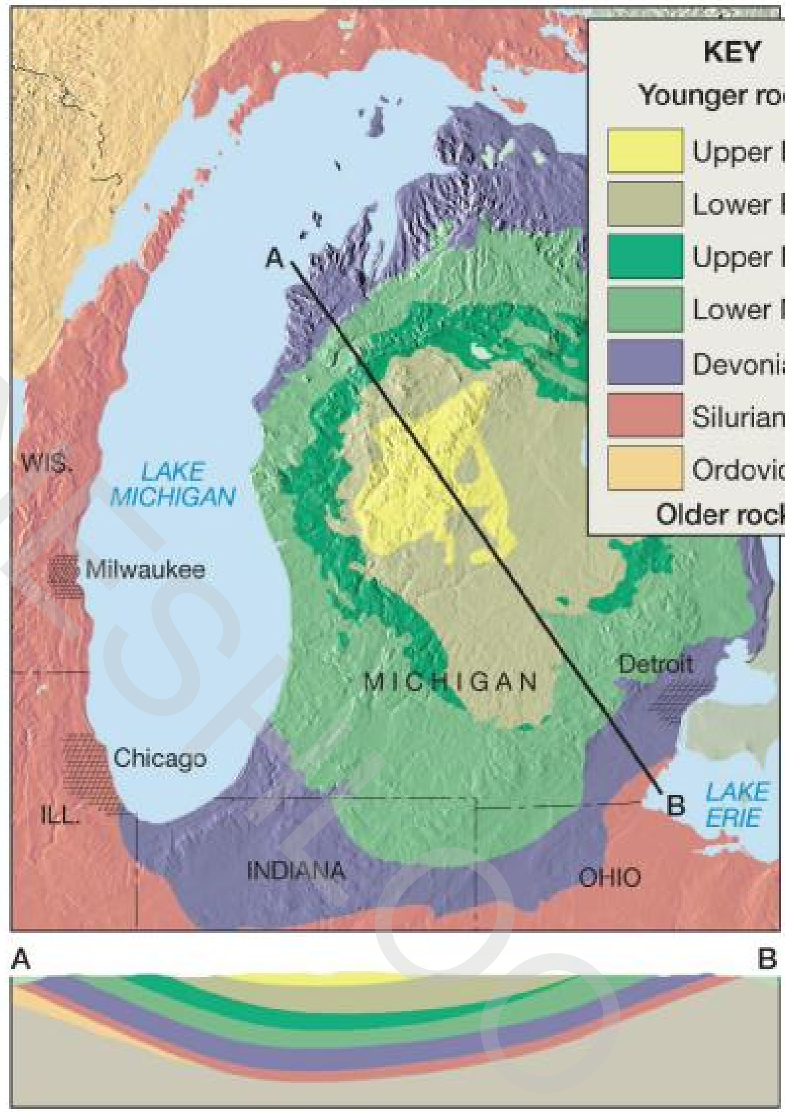


M. Attal, Nov. 2010

Acknowledgments: many diagrams have been taken from handouts from the Ecole Nationale Supérieure de Géologie de Nancy (France).

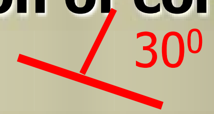
Geologic Maps and Cross Sections

- **Topographic maps vs. geologic maps.**
  - Horizontal vs. tilted layers in geol. maps (visualize!)
  - Older layer tilts to younger
- **How you can construct a geologic cross section from a geologic map and vice versa.**
  - Geologic map can depicts underlying structures



Geologic Structures

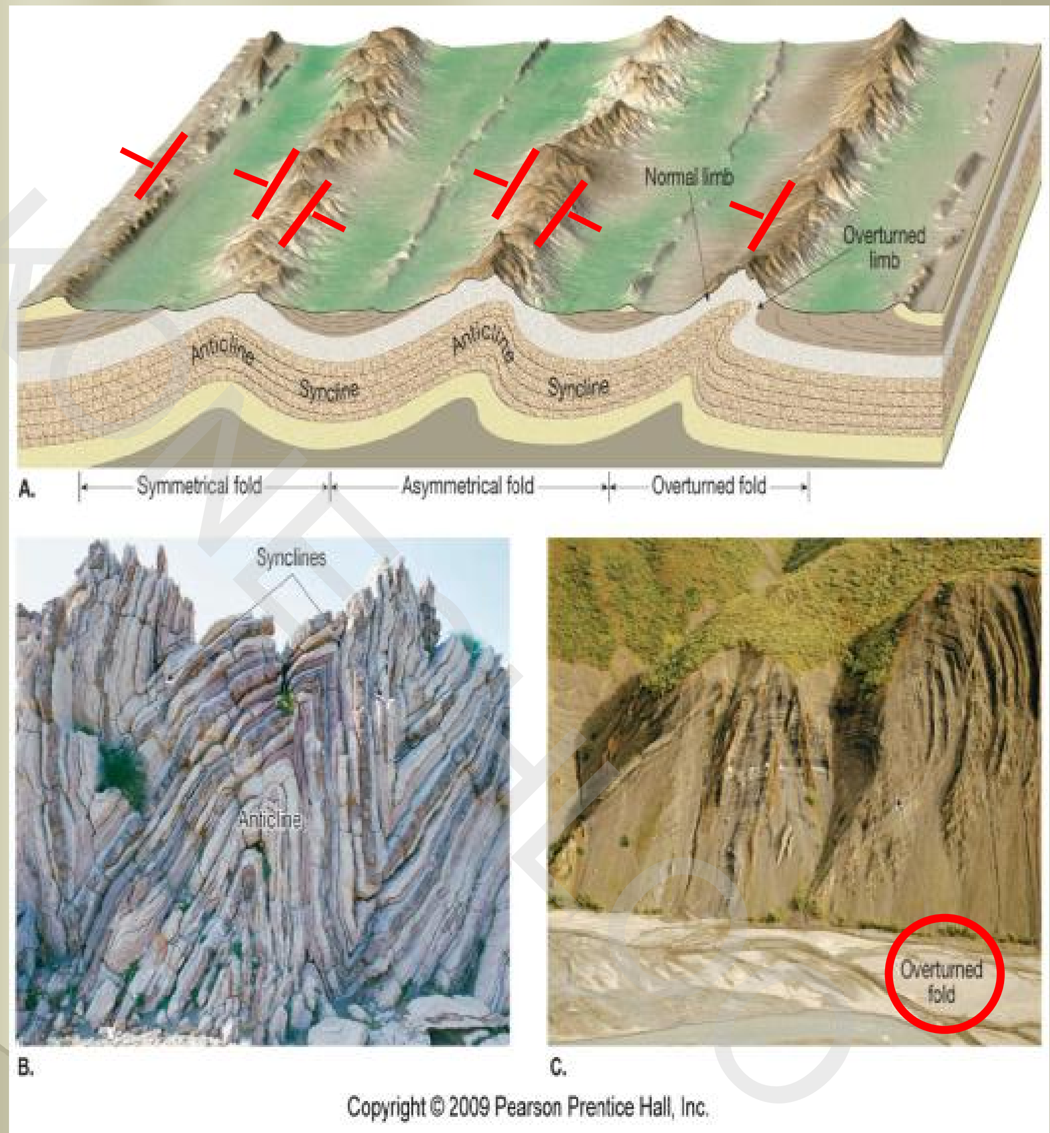
- **Types of stress and resulting structures:**
  - **Compressional, tensional, and shear**
  - Folding (ductile) vs. faulting (brittle rocks)
- **What are three components of attitude or orientation of a layer?**
  - **Make sure to adjust for magnetic declination of compass**
  - **Strike**
    - **Compass direction of a horizontal line on bedding plane (following the "Right Rule" – i.e. dips to right)**



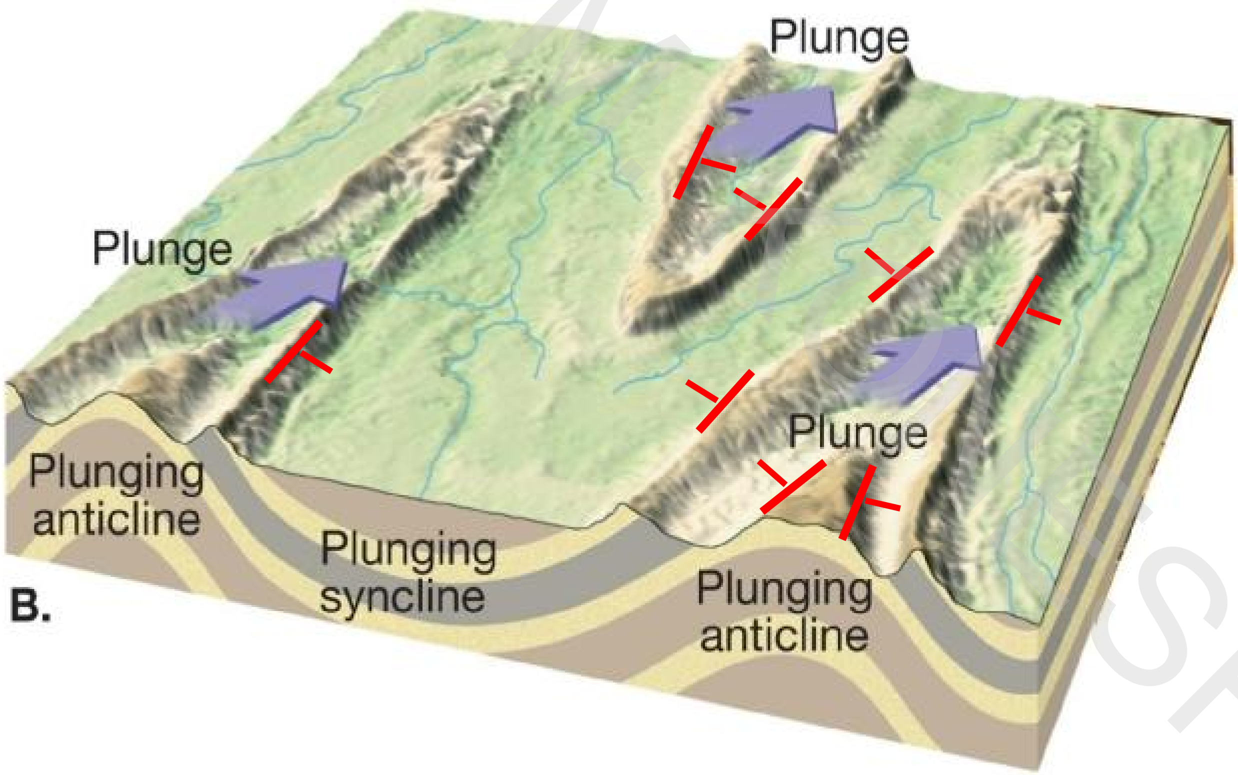
  - **Dip direction**
    - **perpendicular to strike direction**
  - **Dip angle**
    - **actual amount of tilt of the layer**

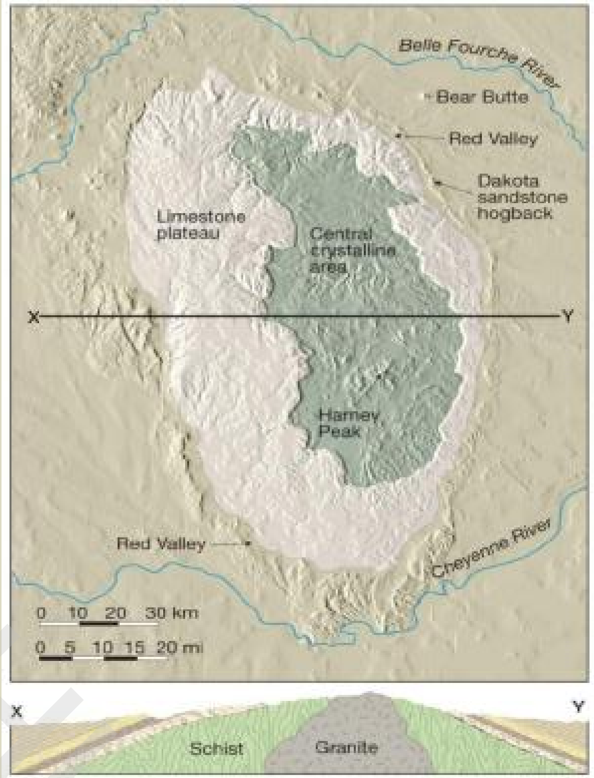
Crustal Deformation - Foldings

- **How do folds form?**
  - (Geoscience animation CD)
- **Tectonics proposes, erosion disposes**
- **Difference between:**
  - **Anticline (older rocks in center)**
  - **Syncline (younger rocks in center)**
  - **Monocline**
    - **in terms of their attitudes shown on map and cross sections.**



Special Types of Foldings



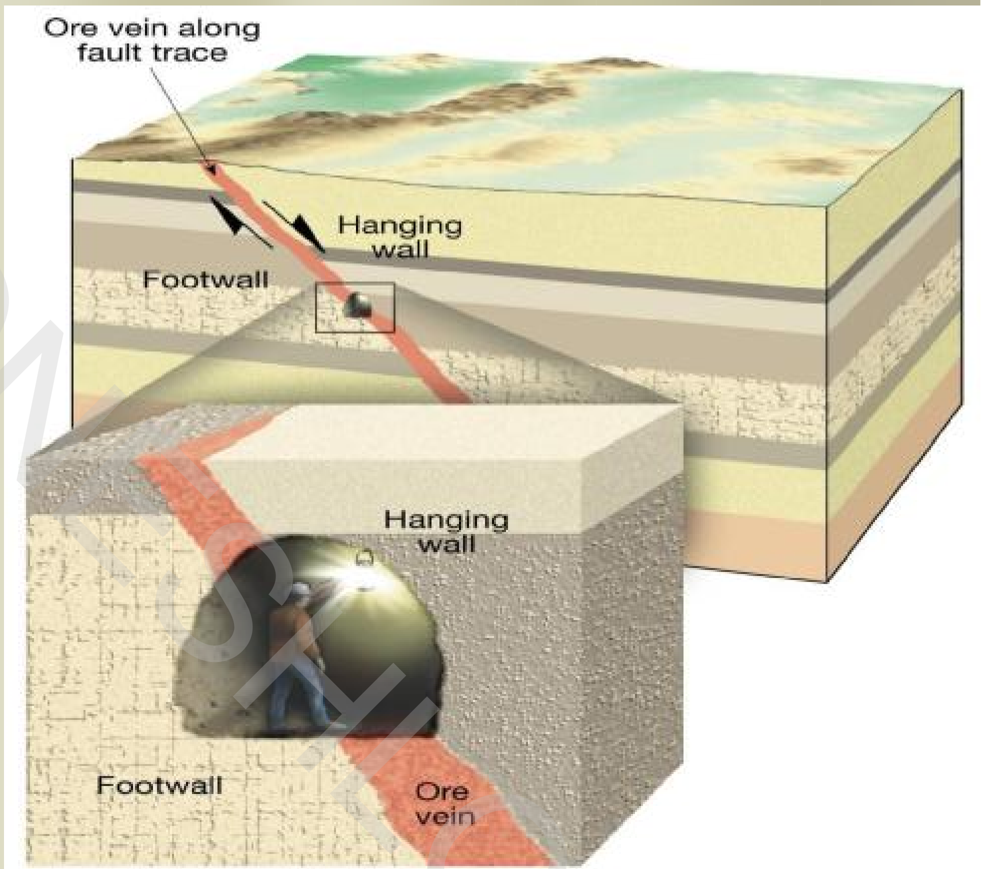


Special Folds

- Asymmetric vs. symmetric folds
- Plunging folds
- recumbent folds
- Overturned folds
- Topographic hill – structural syncline
- Topographic valley – structural anticline (like in central PA)

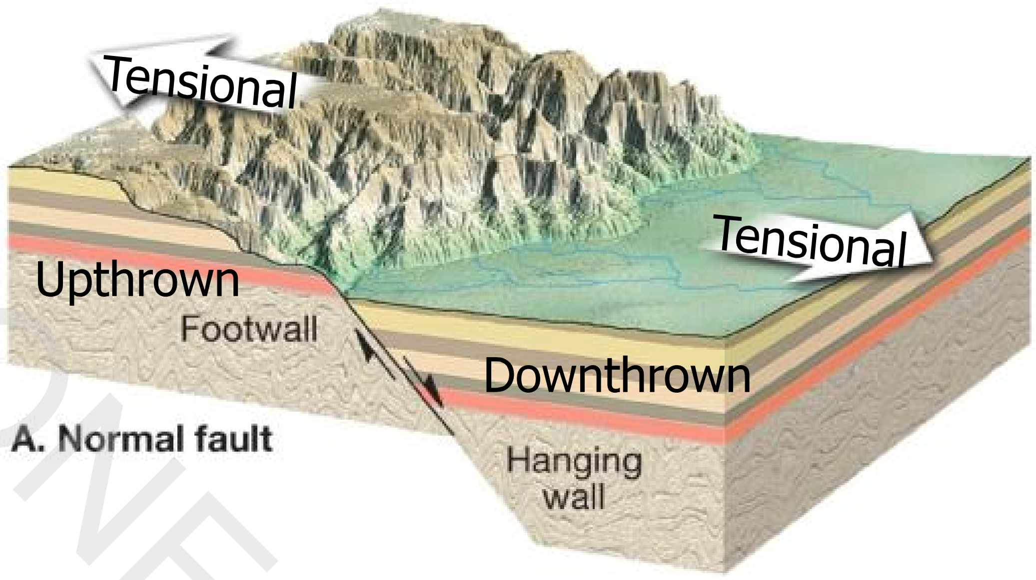
Crustal Deformation: Faults

- **How do faults form?**
  - (Geoscience animation CD)
- **What elements are needed to determine the difference between a normal and reverse fault?**
  - **Hanging wall & footwall**
  - **Upthrown & downthrown blocks**

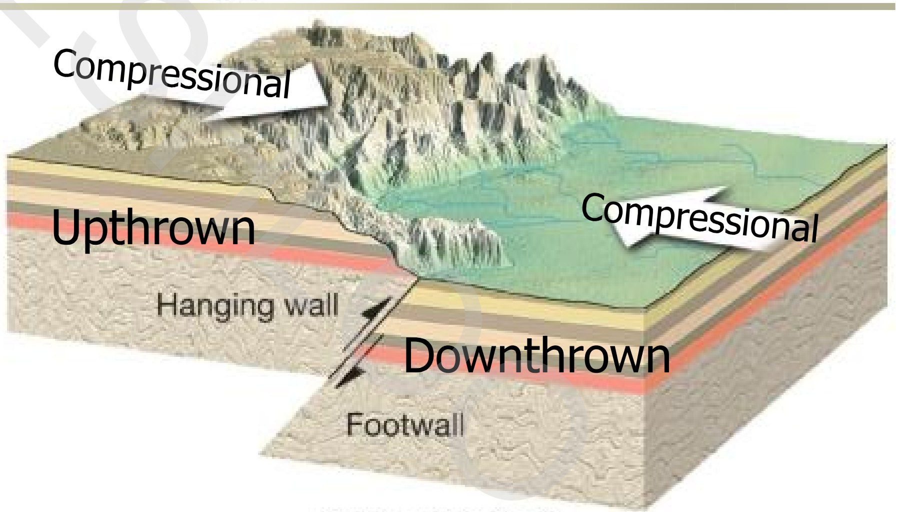


Normal vs. Reverse Faults

- **F**ootwall **U**pthrown = **N**ormal (FUN)
- **F**ootwall **D**ownthrown = **R**everse (FDR)
  - Same layer reverses within fault plane



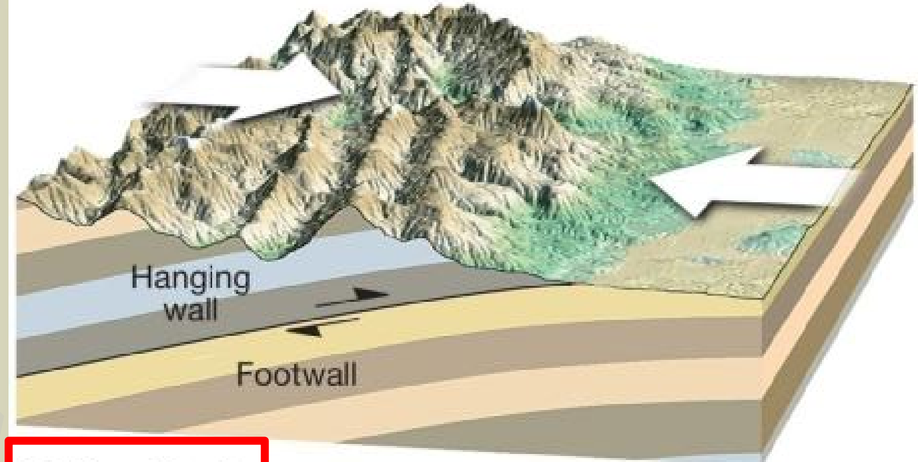
A. Normal fault



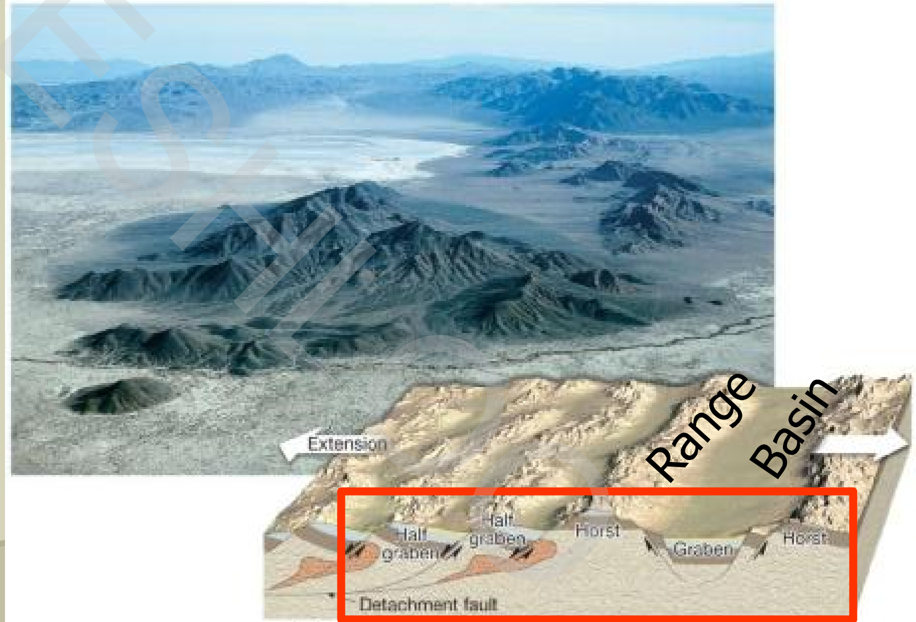
B. Reverse fault

Special Types of Faults

- **Special cases of folding/faulting?**
  - **Thrust fault,**
  - **horsts, grabens (e.g. basin & ranges),**
  - **semi-graben-shaped rift valleys** (Triassic Rift Valley)

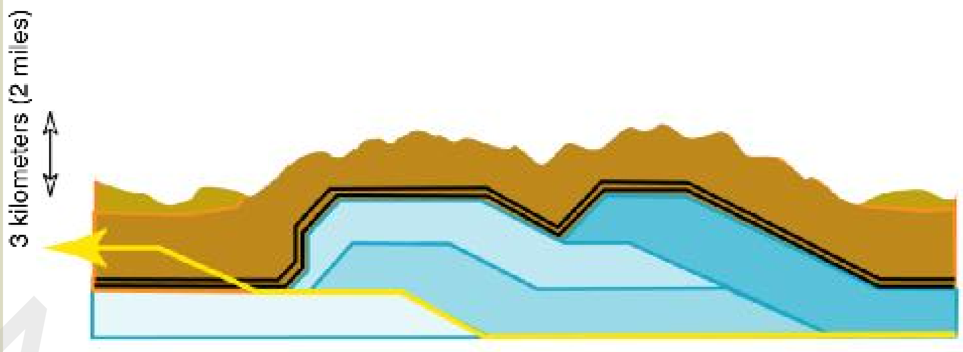


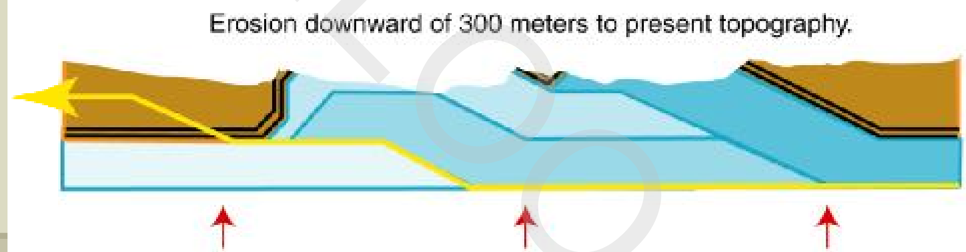
C. Thrust fault



Special Faults (cont'd)

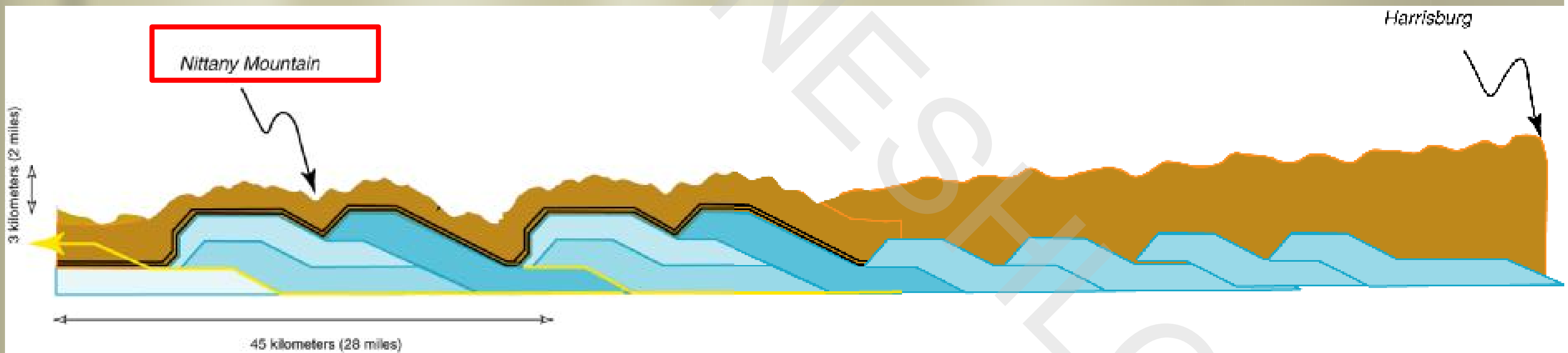
- **Decollement (in PA)**
  - Thrust faults that are not connected to layers above and below
  - Involves long distance movement (25-100 km)
  - Almost horizontal
- **Nappe (in Alps)**
  - Sheet-like allochthonous layer involving recumbent fold & thrust fault
- **Klippe (Hamburg, PA)**
  - Erosional remnant of a thrust fault (outlier of a nappe)



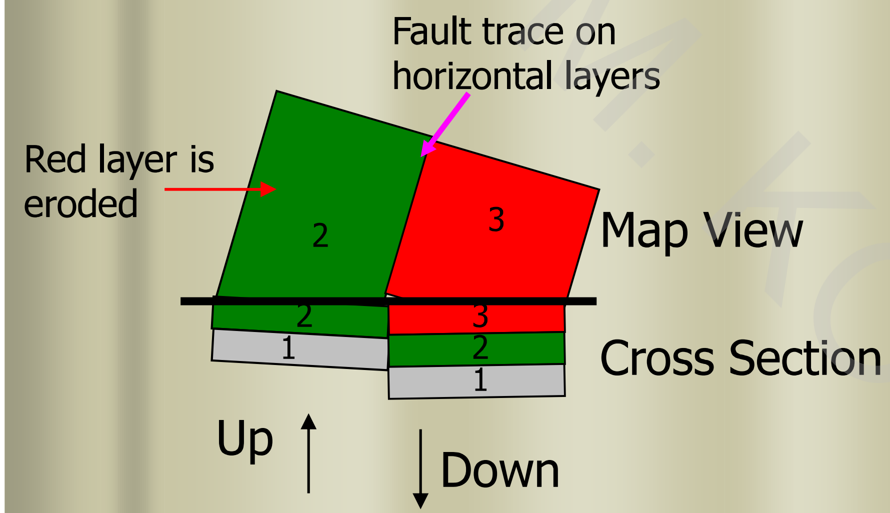


Cross Section of PA

- Valley and Ridge folded by Africa pushing into North America
- Substantial horizontal movement (~100 km)



Faults on Geologic Maps

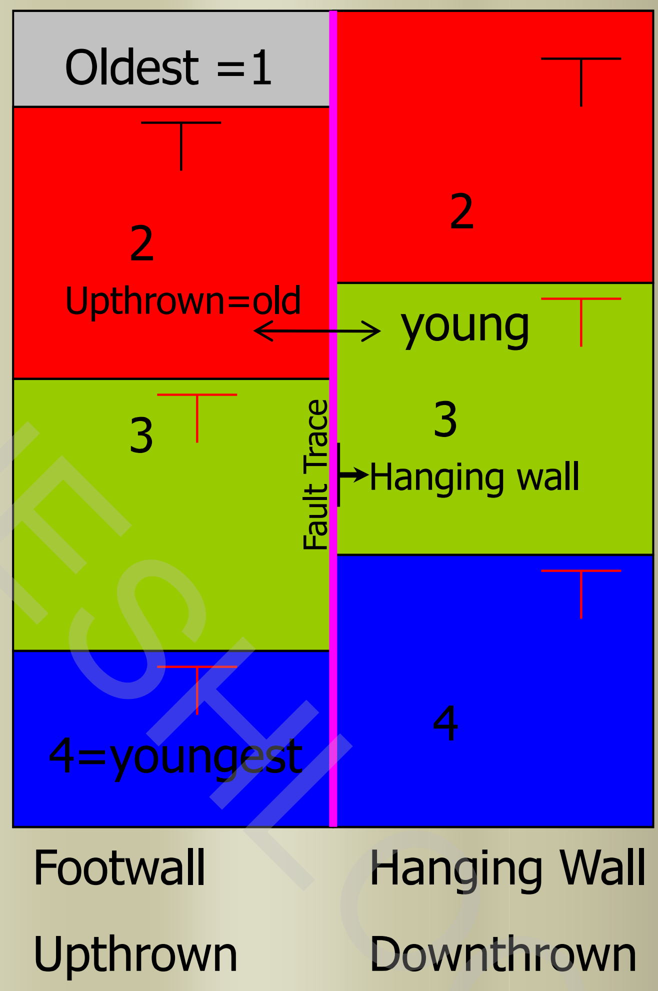


- Upthrown block places older rocks (layer 2) against younger rocks (layer 3) at the same elevation (on surface)

- Let's say, the layers are horizontal both on map and in X-section.
- What does the geologic map (on left) tell you about the structure (fold, fault, intrusion)?
- What type of fault is it?

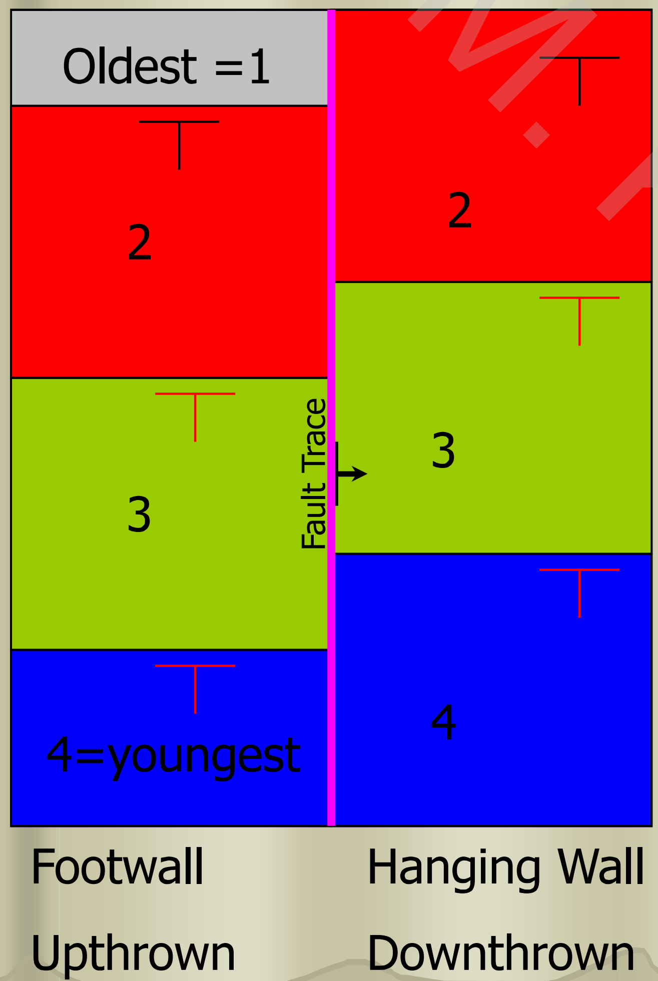
Faults in Geologic Maps

- **How can you recognize titled & faults in a geologic map?**
  - Need to determine dip of fault plane, which points to hanging wall
  - When stand astride a fault trace on a map; older rocks are on upthrown block
- Upthrown rocks are eroded down over time
- Position of tilted rocks shifts with erosion
- **What type of fault is it?**
- Why is this not a transform fault?



Geologic map of titled/faulted layers

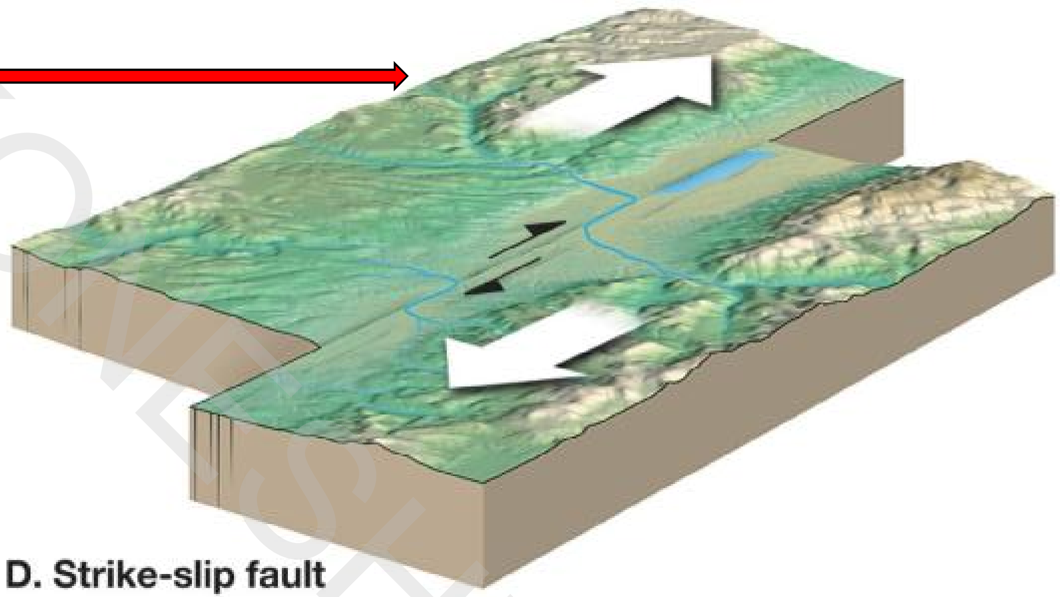
Questions?



- How will a cross sections (looking at the left side and at the front side) of this geologic map look like?
- Draw two sketches and handed them to me with your name on it.

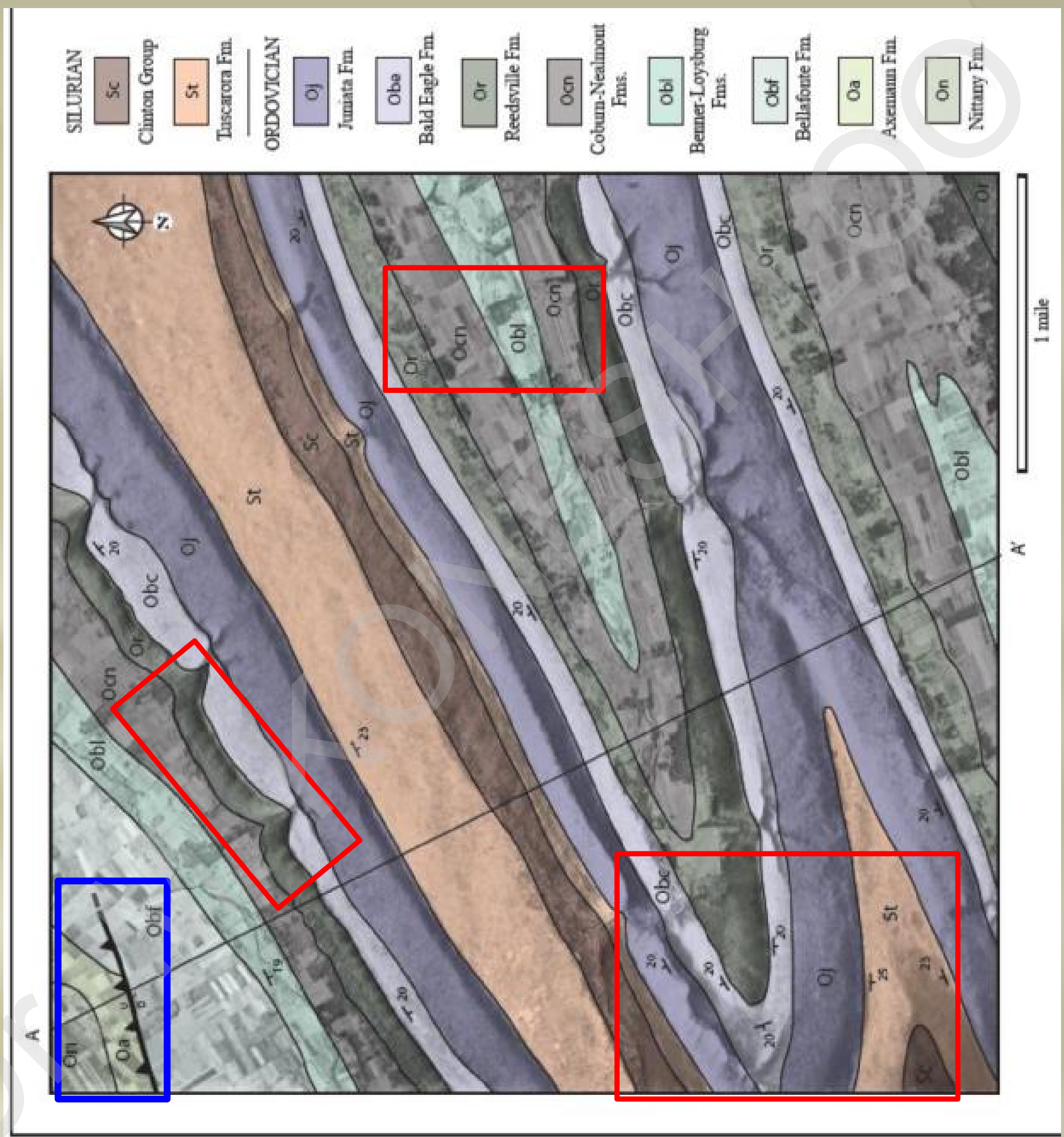
Strike Slip Fault (Transform)

- **How do left-lateral and right-lateral strike-slip faults vary from each other.**
  - Transform faults cuts through lithosphere
  - Fault plane is vertical (i.e. no footwall, hanging wall, upthrown or downthrown blocks))



D. Strike-slip fault

Example Geologic Map



Let's pay attention to the marked areas