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.

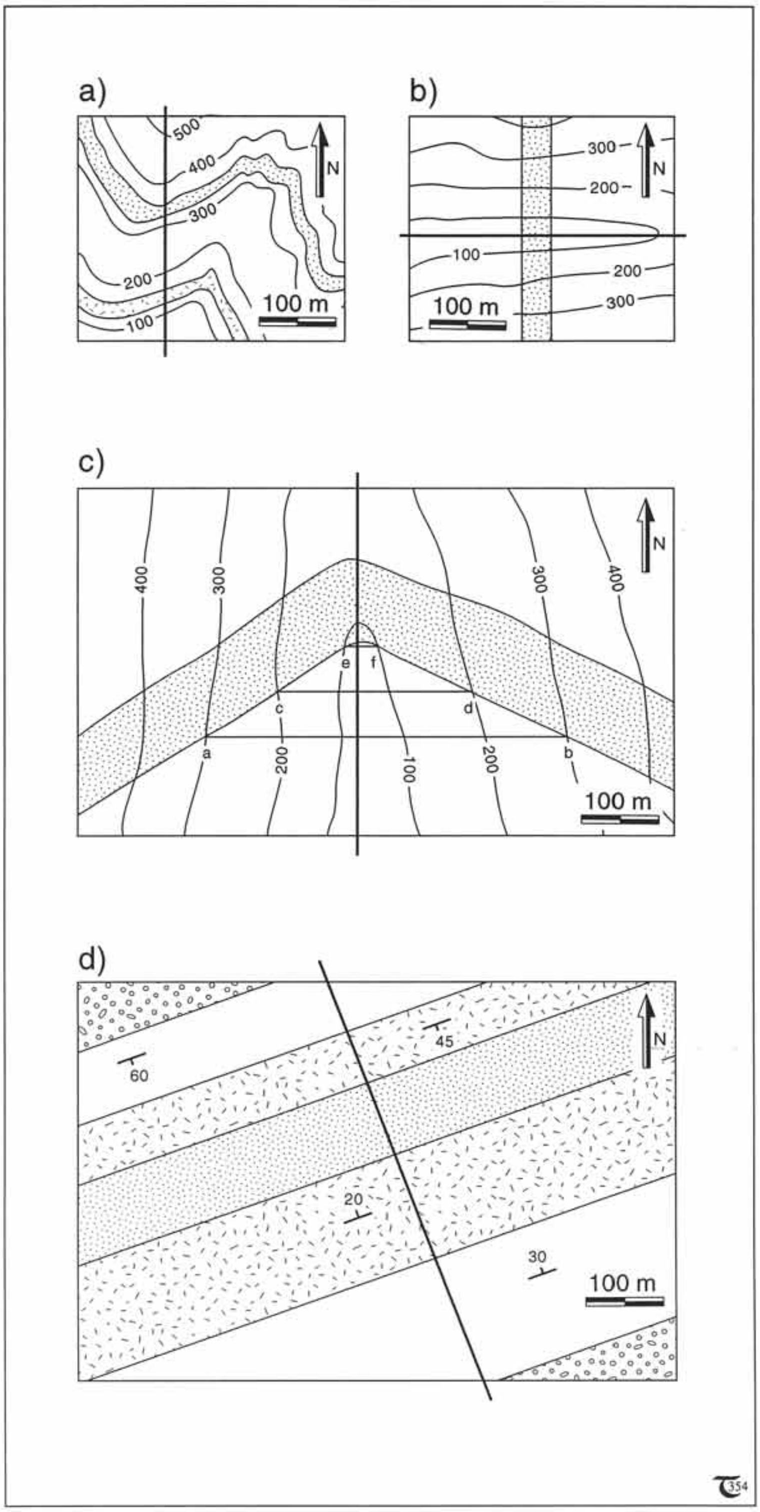


Figure 4-1: *a) to d) Four geological maps, each representing a different structure, but the best section line is consistently normal to the strike of the strata.*

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,

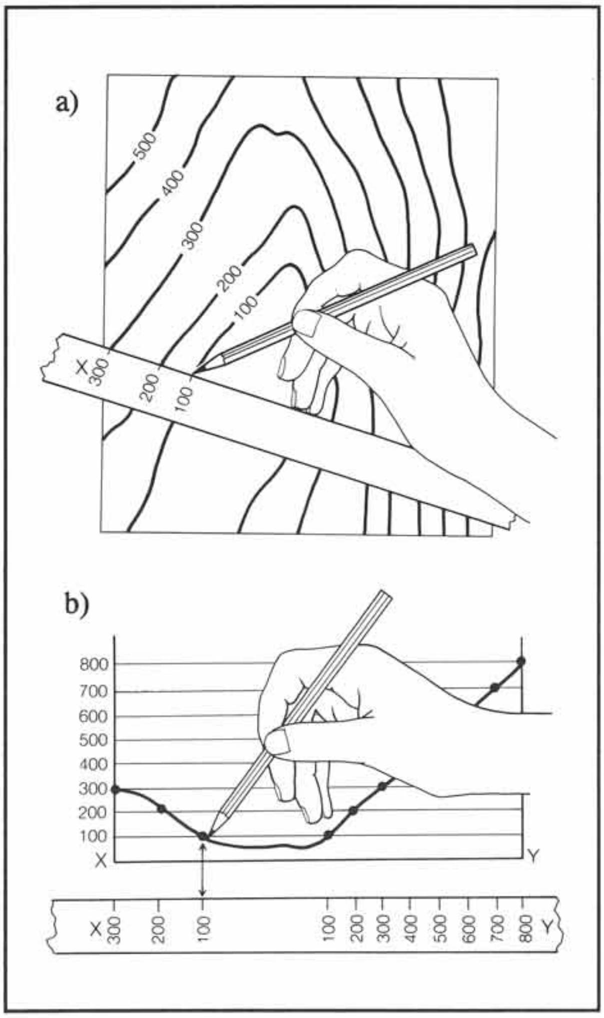


Figure 4-2: *a) & b) Steps involved in construction of a topographic cross-section.*

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.

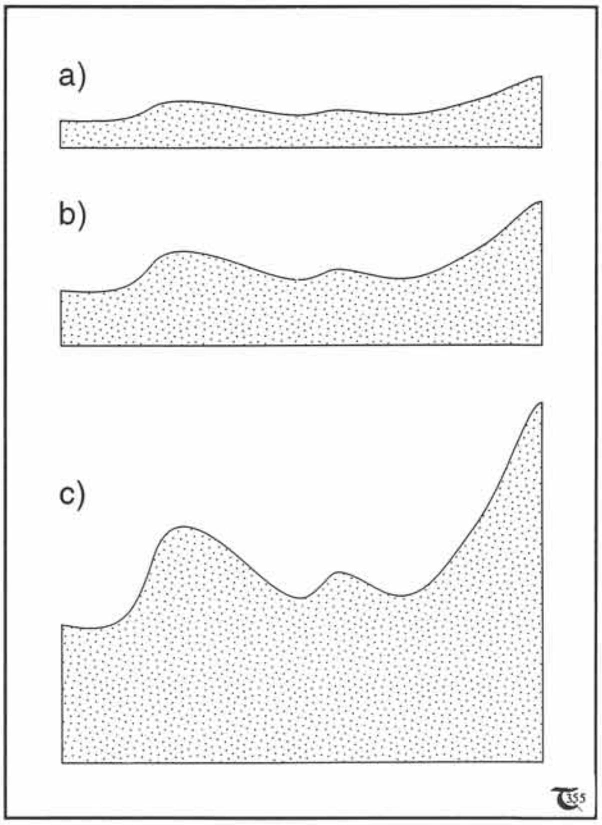
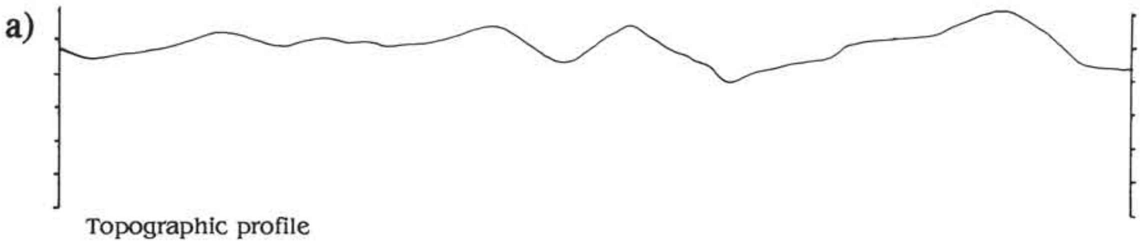


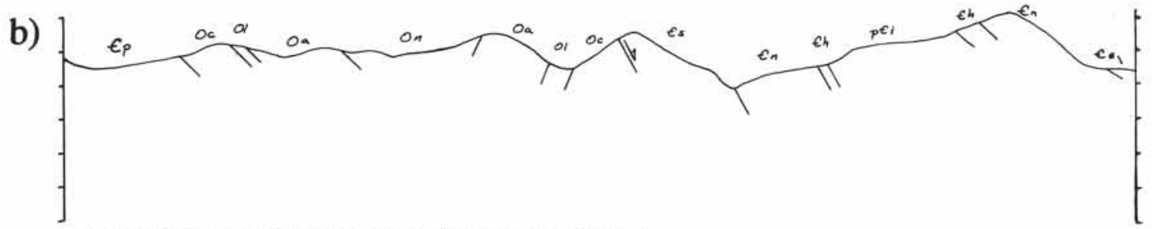
Figure 4-3: *Visual effects of variable horizontal and vertical scaling. a) Vertical scale is half the length of the horizontal scale. b) Isometrically scaled. c) Vertical scale is extended 2.5 times.*

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."

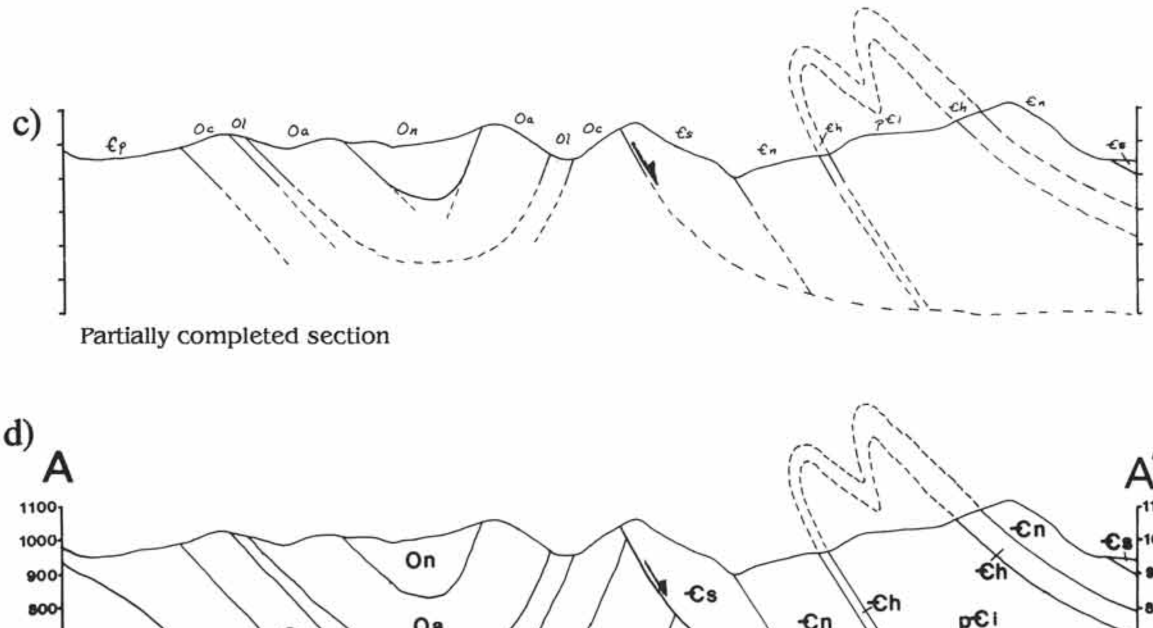
Once the topographic section is completed (Fig. 4-4a), the geological contacts are transferred to the surface of the section (Fig. 4-4b). This can be achieved by marking contacts on a slip of paper placed along the line of section on the geological map. Use colors to distinguish the rock units separated 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



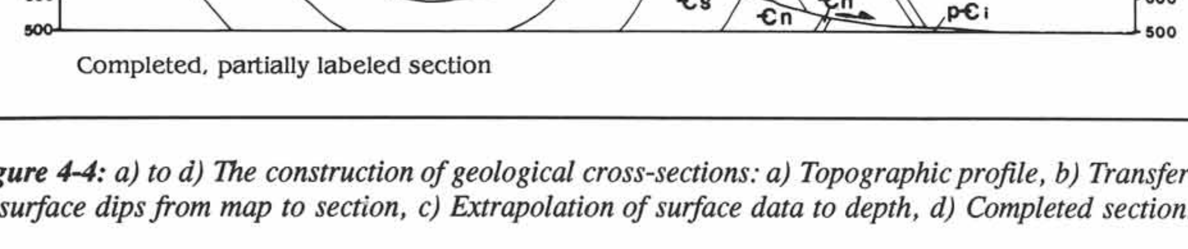
Topographic profile



Contacts (at correct angles) and temporary labels



Partially completed section



Completed, partially labeled section

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).

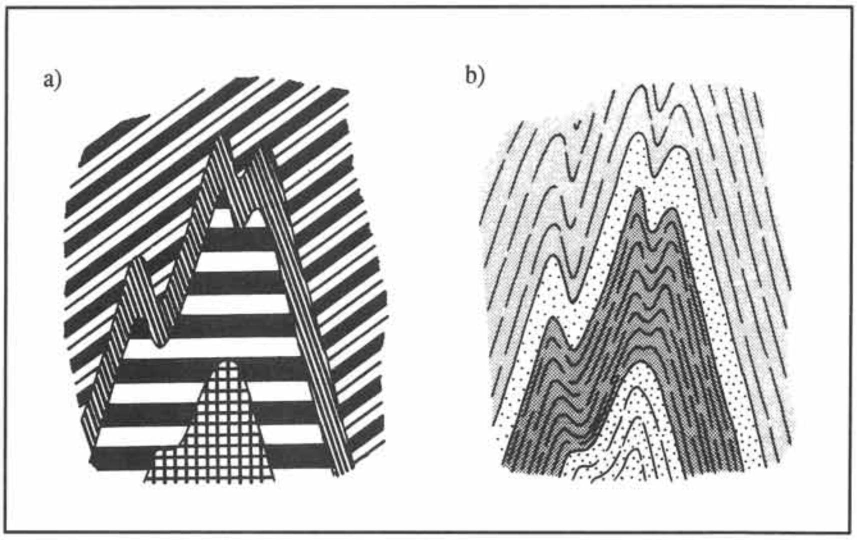


Figure 4-5: a) & b) Symbols in cross-sections: a) Inappropriate use of symbols. b) Properly used symbols follow form lines of the bedding.

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.

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.

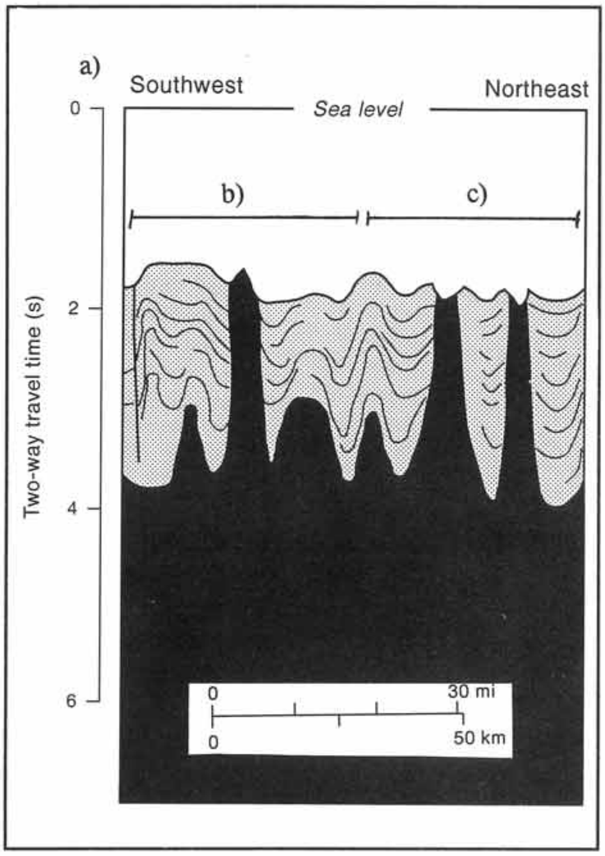


Figure 4-6a: *Seismic section through salt domes (black), piercing a sedimentary sequence (gray shade). The steepness of the domes is entirely artificial, due to exaggeration of the depth scale.*

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

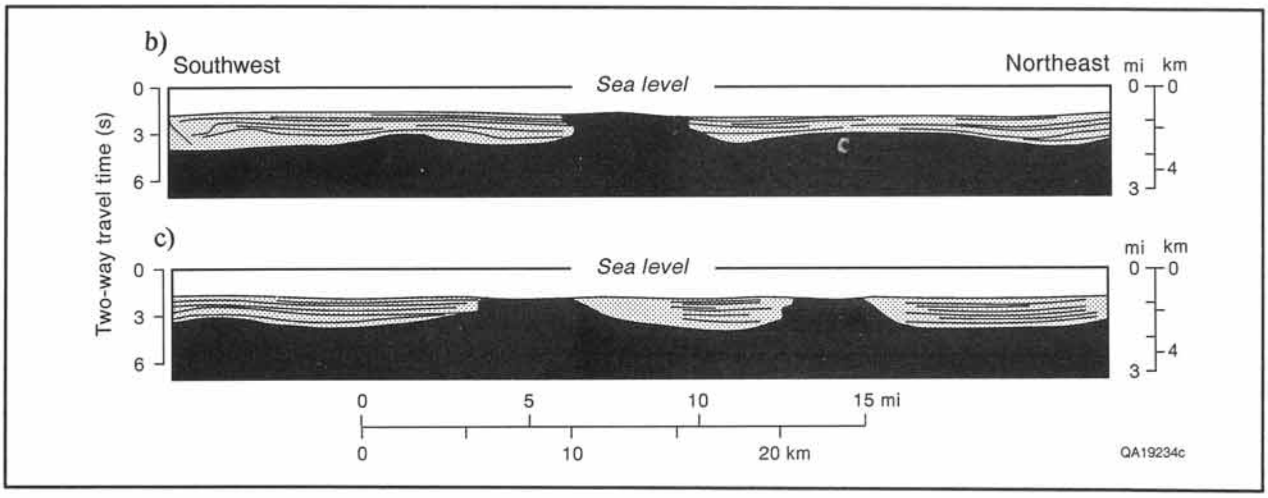


Figure 4-6: *b) & c) Restoration of the same seismic section to equidimensional or isometric scales.*

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.

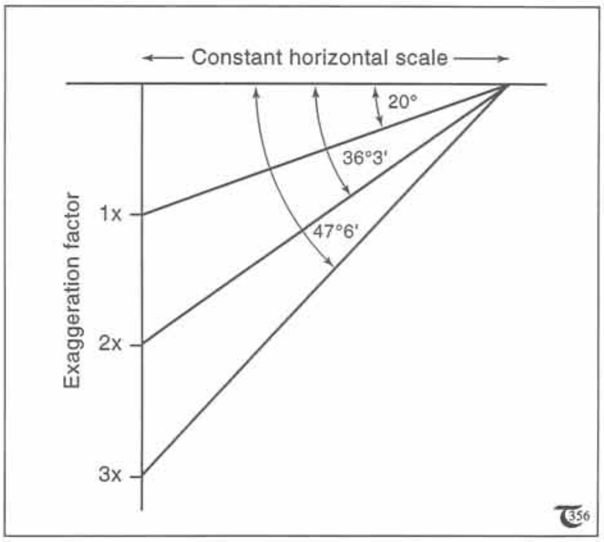


Figure 4-7: *The angle of dip increases if the vertical scale of seismic and other cross-sections is exaggerated. See eq. (4-1).*

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:

$$\tan \alpha^* = V \tan \alpha \quad (4\text{-}1)$$

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°.

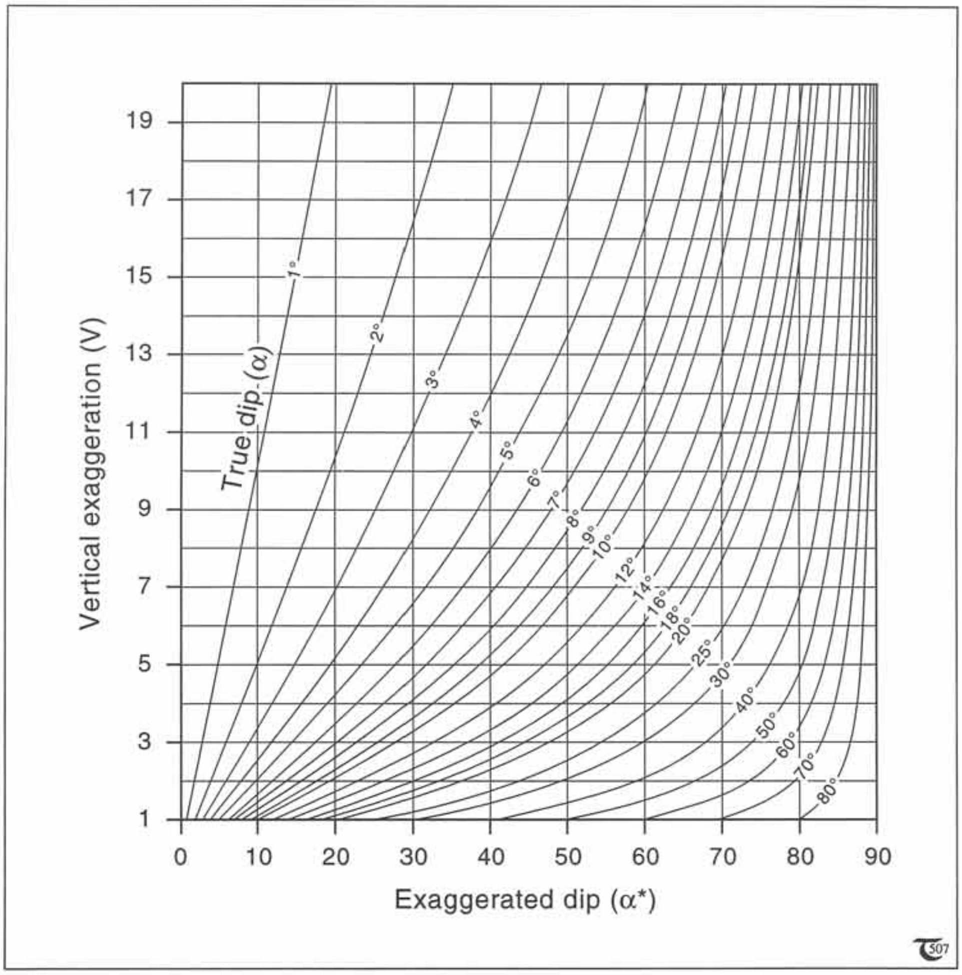


Figure 4-8: Nomogram relating the true dip, α, to the exaggerated dip, α^*, for a range of vertical exaggeration factors [eq. (4-1)].

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.

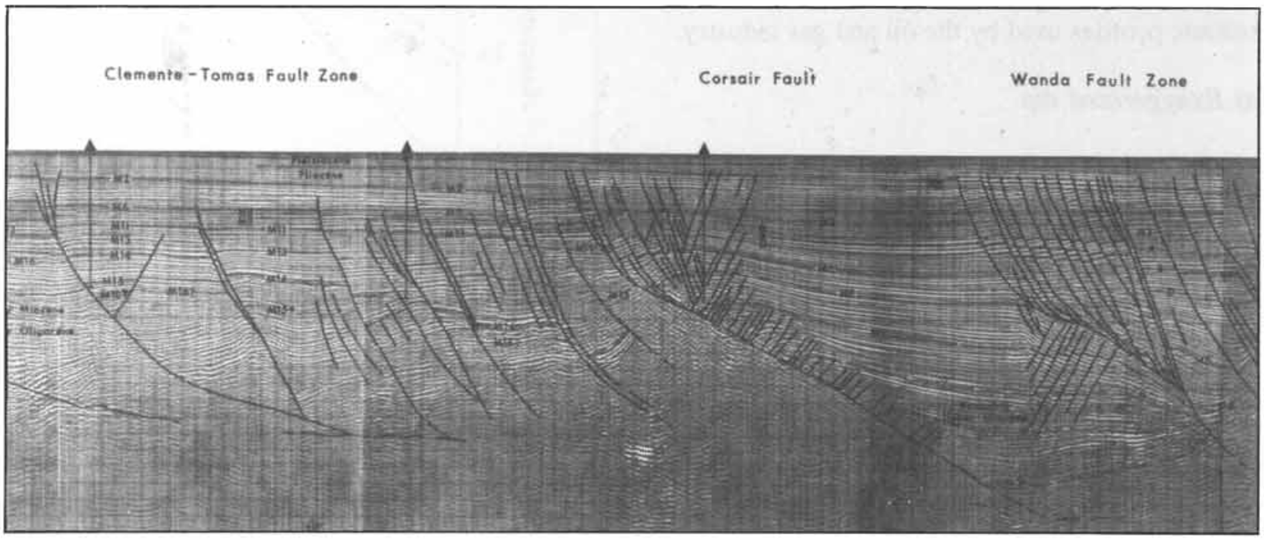


Figure 4-9a: Original seismogram across the Clemente-Tomas, Corsair, and Wanda fault systems in the Gulf of Mexico, off-shore Texas.

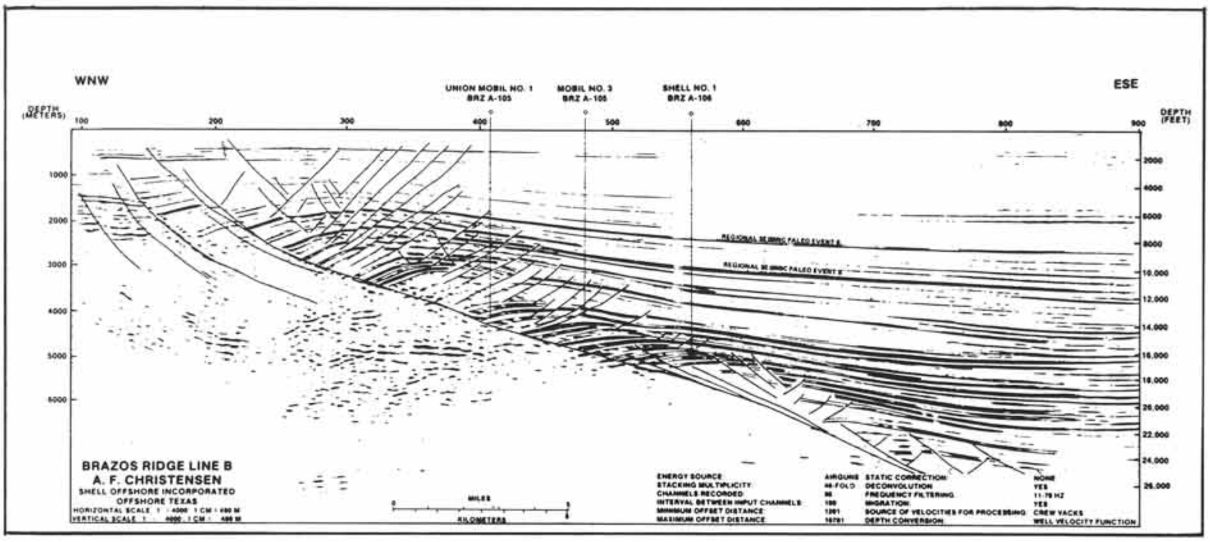


Figure 4-9b: Restored section of the Corsair fault system with the horizontal and vertical scales equal.

☐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-

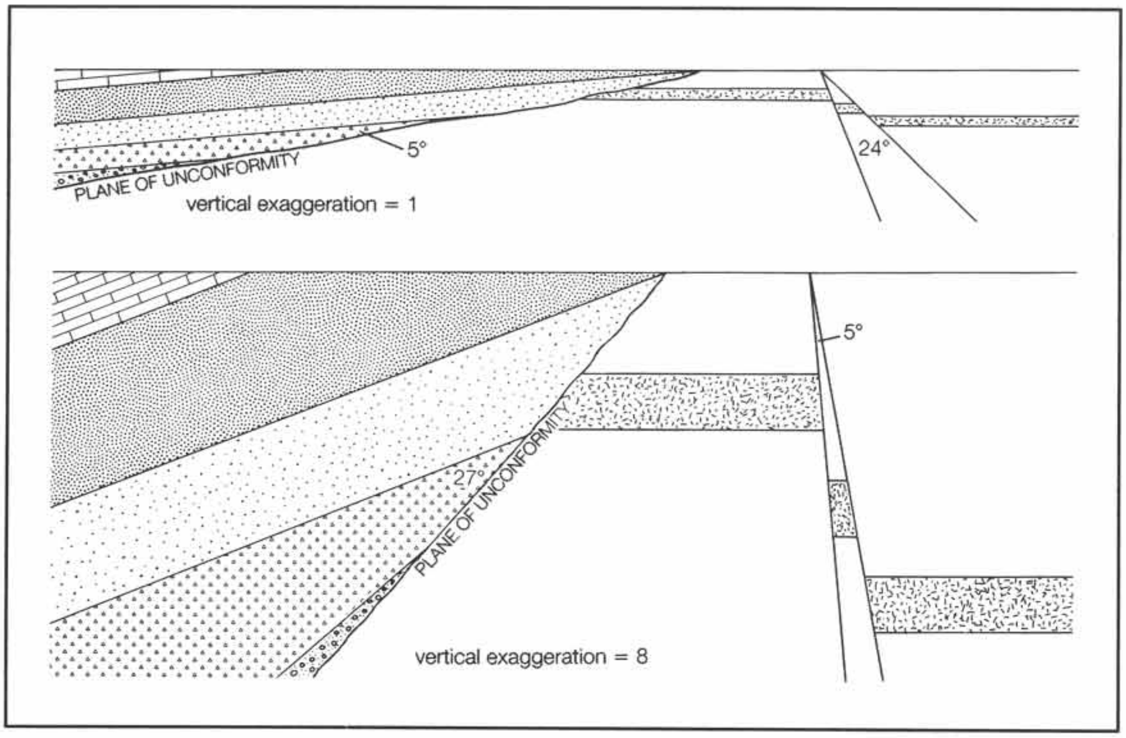


Figure 4-10: *a) & b) Distortion of angles occurs in non-isometrically scaled sections. a) Original isometric section. b) Same section with vertical exaggeration factor of eight.*

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.

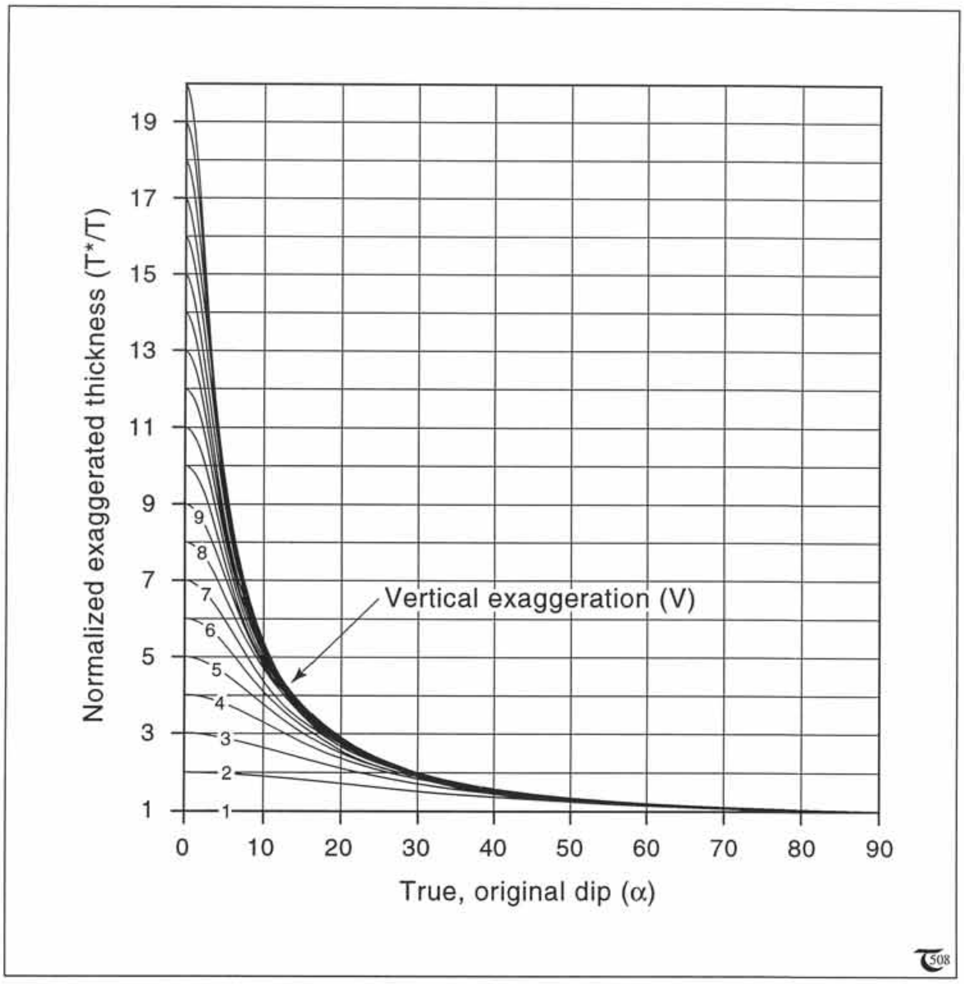


Figure 4-11: Nomogram relating the true dip, α, to the normalized exaggerated thickness of a layer, T/T, for a range of vertical exaggeration factors, V. See eq. (4-2).*

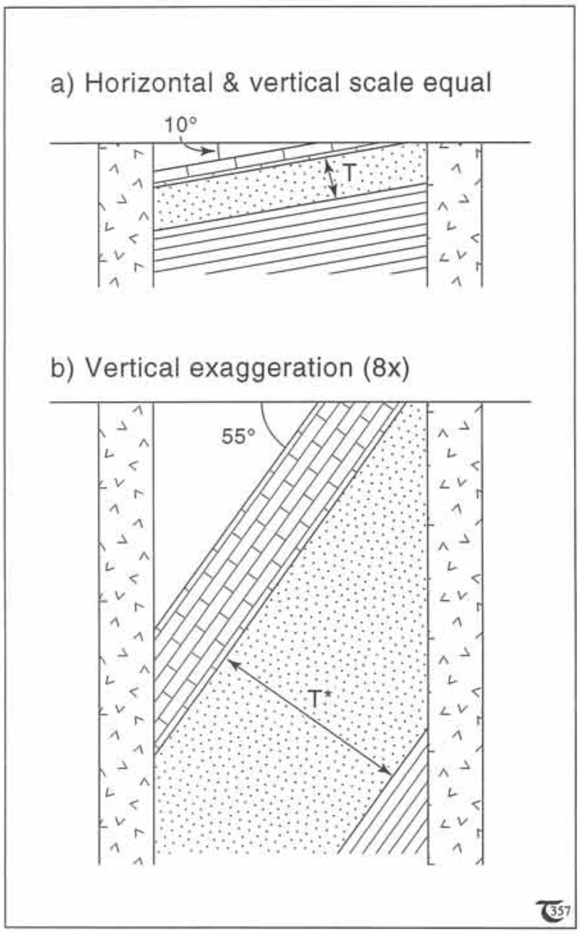


Figure 4-12: a) & b) Isometric and vertically exaggerated cross-sections (V=8). The layer thickness, T, is artificially enhanced in the exaggerated section to T. See exercise 4-4.*

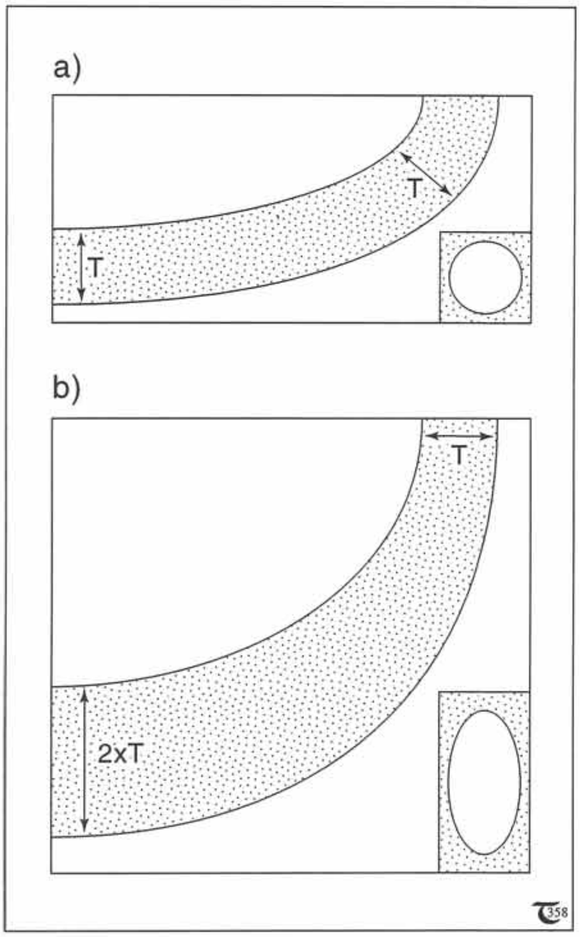


Figure 4-13: a) & b) Appearance of folded layer of constant thickness in: (a) isometrically scaled, and b) vertically exaggerated cross-section, twofold (V=2). The strain ellipse scales the exaggeration.

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:

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

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

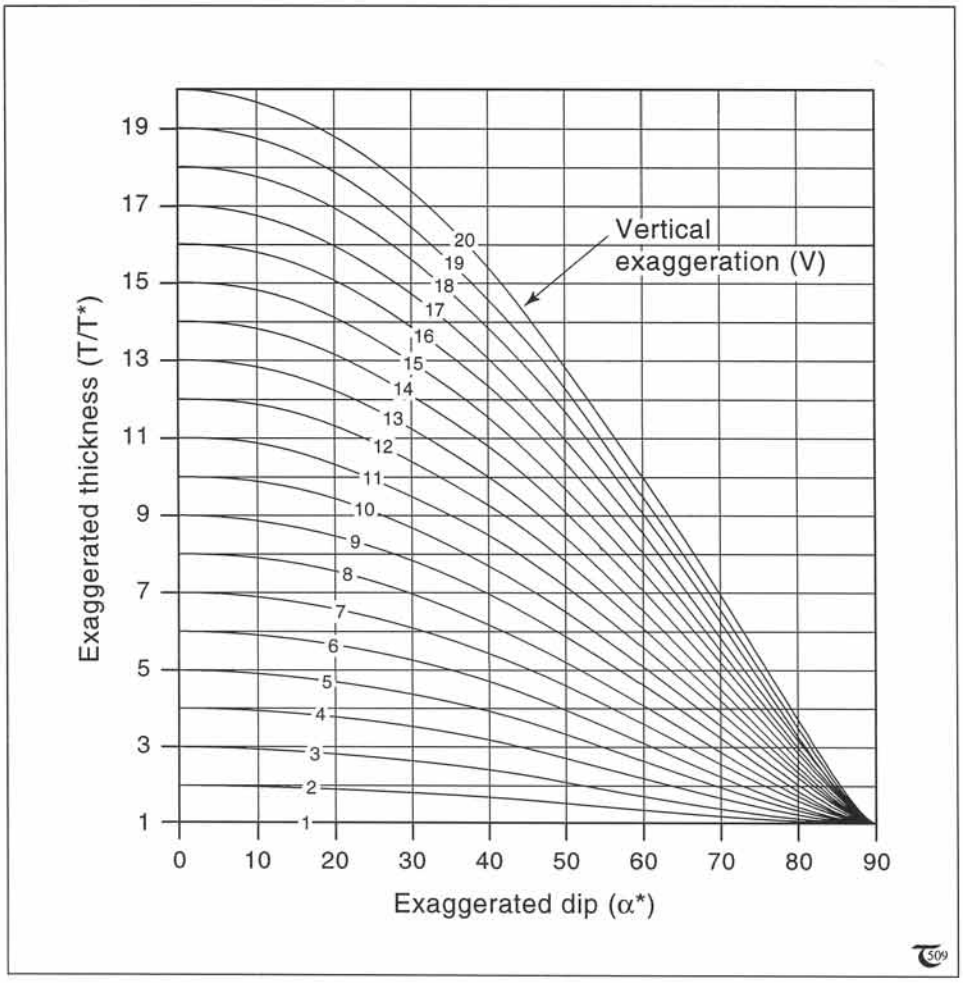
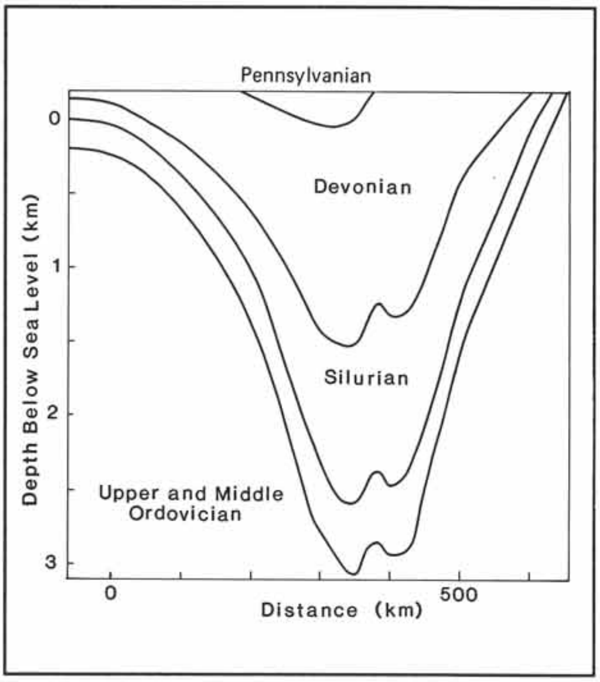


Figure 4-14: *Nomogram relating the exaggerated dip, α*, to the normalized exaggerated layer thickness, T*/T, for a range of vertical exaggeration factors, V. See eq. (4-3).*

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.

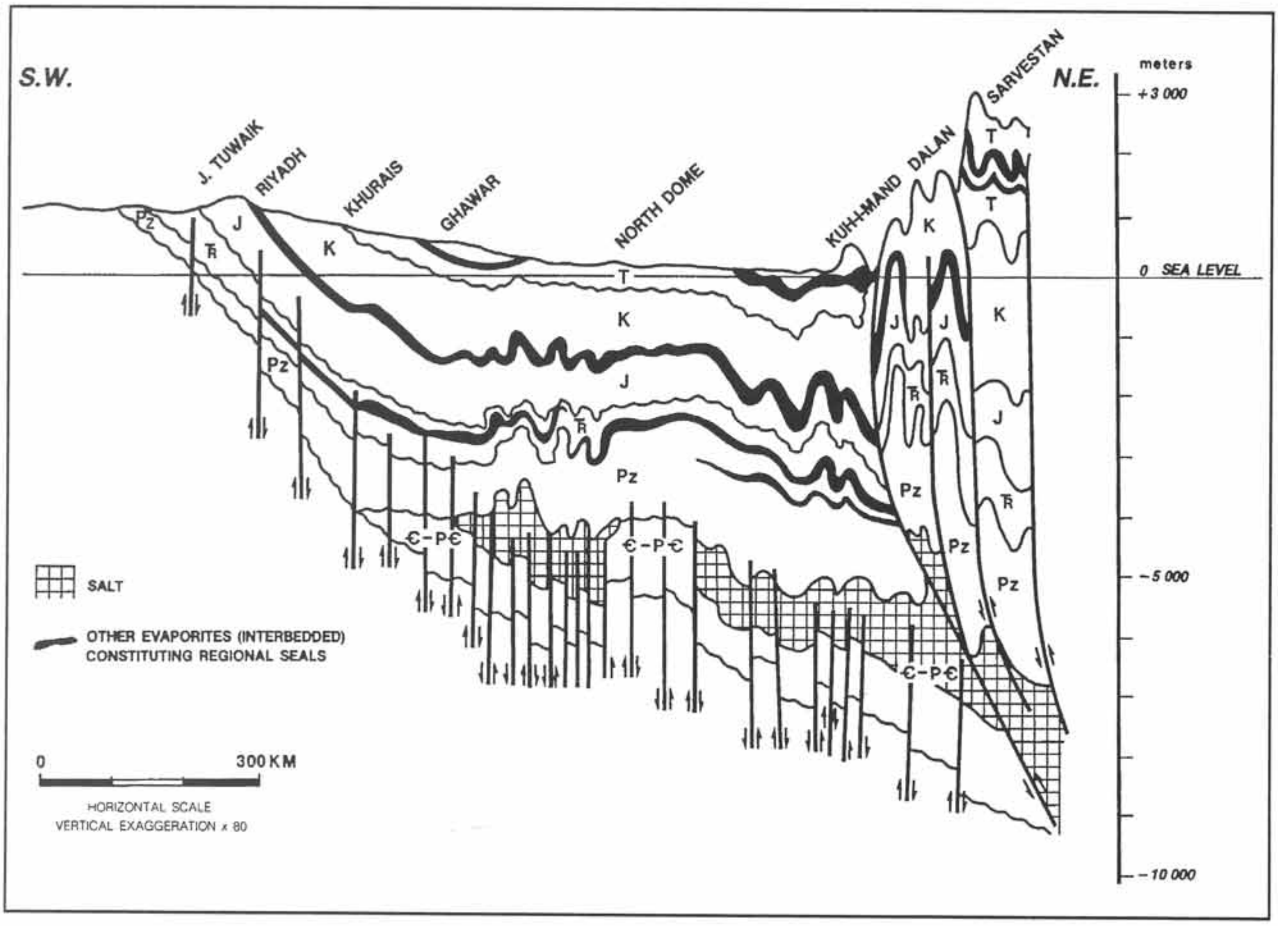


Figure 4-16: Cross-section, eighty times vertically exaggerated, of the Arabian platform sequence, adjacent to the Zagros Mountains in the northeast.

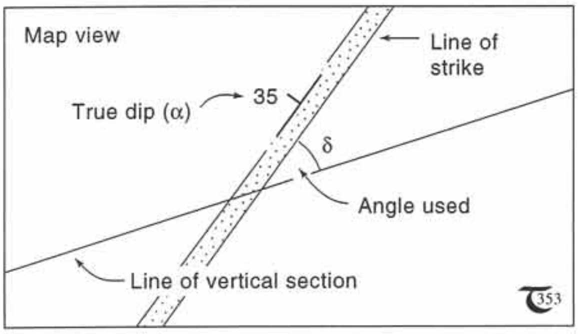


***Figure 4-17:** The angle, δ, is measured in map views between the strike of a bed and the section line. Thickness exaggeration relates to the true dip, α, through the section angle, δ.*

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-

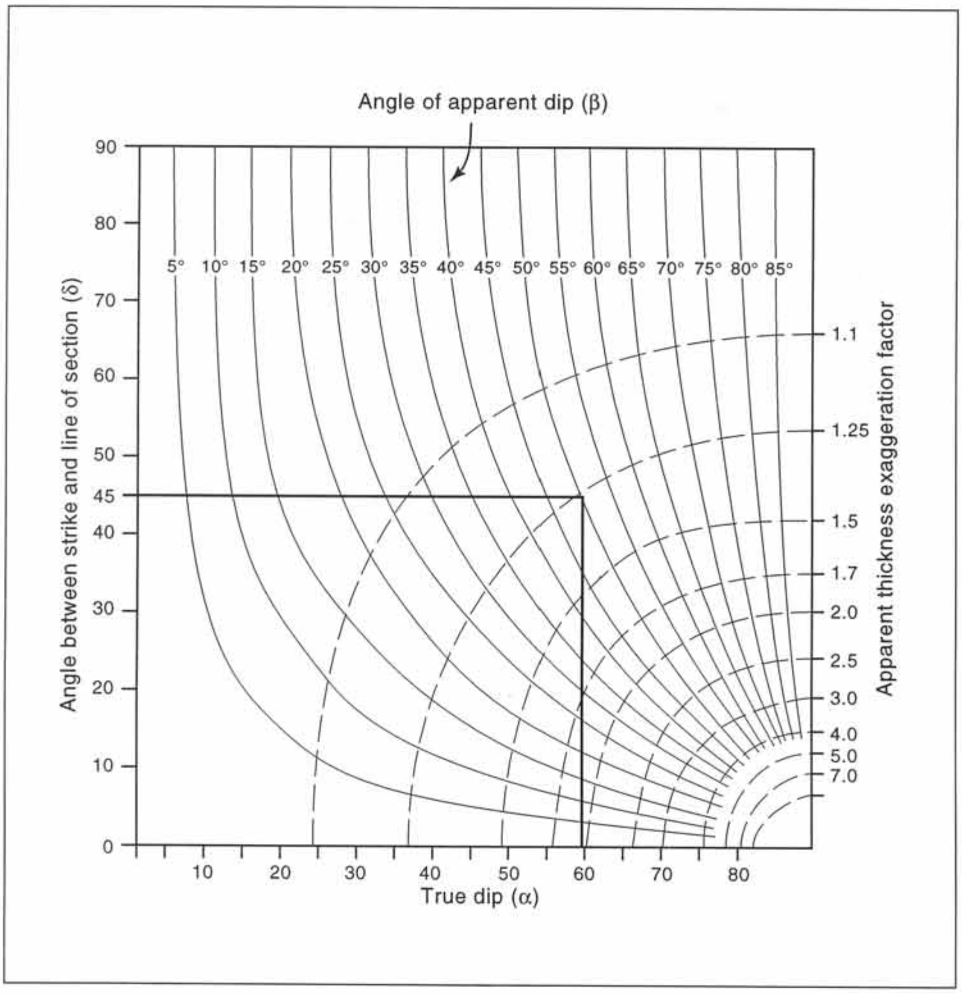


Figure 4-18: *Nomogram relating true and apparent dip, including the exaggeration factor for the apparent thickness of beds in sections oblique to the structural strike.*

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.