Structure Contouring

3.1 Introduction

This chapter covers the basic techniques for contouring continuous surfaces and for the construction of composite-surface maps. The contouring of faults and faulted surfaces is treated in Chap. 7.

3.2 Structure Contouring

A structure contour map is one of the most important tools for three-dimensional structural interpretation because it represents the full three-dimensional form of a map horizon. The mapping techniques to be discussed are equally applicable in surface and subsurface interpretation. The usual steps required to produce a structure contour map are:

1. Plot the points to be mapped.
2. Determine an appropriate contour interval.
3. Interpolate the locations of the contour elevations between the control points. There are several techniques for doing this and they may give very different results when only a small amount of data is available.

A structure contour map is constructed from the information at a number of observation points. The observations may be either the *xyz* positions of points on the surface, the attitude of the surface, or both. A relatively even distribution of points is desirable and which, in addition, includes the local maximum and minimum values of the elevation. If the data are from a geologic map or from 2-D seismic-reflection profiles, a very large number of closely spaced points may be available along widely spaced lines that represent the traces of outcrops or seismic lines, with little or no data between the lines. The number of points in a data set of this type will probably need to be reduced to make it more interpretable. Even if the contouring is to be done by computer, it is possible to have too much information (Jones et al. 1986). This is because the first step in contouring is always the identification of the neighboring points in all directions from a given data point and it is difficult and usually ambiguous to choose the neighbors between widely spaced lines of closely spaced points. Before contouring, the lines of data points may need to be resampled on a larger interval that is still small enough to preserve the form of the surface.

A series of rules for contouring has been developed over the years to produce visually acceptable maps that reasonably represent the surface geometry. The reference frame for a contour map is defined by specifying a datum plane, such as sea level. Elevations are customarily positive above sea level and negative below sea level. The contour interval selected depends on the range of elevations to be depicted and the number of control points. There should be more contours where more data are available. The contour interval should be greater than the limits of error involved. Errors of 20 ft (7 m) are typical in correlating well logs and as a result of minor deviations of a well from vertical. Uncertainties in locations in surface mapping are likely to produce errors of similar magnitude. The contour interval should be small enough to show the structures of interest. The map can be read more easily if every fifth or tenth contour is heavier. The map should always have a scale. A bar scale is best because if the map is enlarged or reduced, the scale will remain correct.

The contour interval on a map is usually constant; however, the interval may be changed with the steepness of the dips. A smaller interval can be used for low dips. If the interval is changed in a specific area, make the new interval a simple multiple (or fraction) of the original interval and clearly label the contour elevations and/or show the boundaries of the regions where the spacing is changed on the map.

The contours must obey the following rules (modified from Sebring 1958; Badgley 1959; Bishop 1960):

1. Every contour must pass between points of higher and lower elevation.
2. Contour lines should not merge or cross except where the surface is vertical or is repeated due to overturned folding or reverse faulting. The lower set of repeated contours should be dashed.
3. Contour lines should either close within the map area or be truncated by the edge of the map or by a fault. Closed depressions are indicated by hash marks (tic marks) on the low side of the inner bounding contour.
4. Contour lines are repeated to indicate reversals in the slope direction. Rarely will a contour ever fall exactly on the crest or trough of a structure.
5. Faults cause breaks in a continuous map surface. Normal separation faults cause gaps in the contoured horizon, reverse separation faults cause overlapping contours and vertical faults cause linear discontinuities in elevation. Where beds are repeated by reverse faulting, it will usually be clearer to prepare separate maps for the hangingwall and footwall.
6. The map should honor the trend or trends present in the area. Crestal traces, trough traces, fold hinges and inflection lines usually form straight lines or smooth curves as appropriate for the structural style.

Mapping by hand usually should begin in regions of tightest control and move outward into areas of lesser control. It is usually best to map two or three contours simultaneously in order to obtain a feel for the slope of the surface. The contours will almost certainly be changed as the interpretation is developed; therefore, if drafting by hand, do the original interpretation in pencil. The map should be done on tracing paper or clear film so that it can be overlaid on other maps.

3.3 Structural Style in Contouring

Contouring may be done using different styles, each of which produces its own characteristic pattern (Handley 1954). With a large amount of evenly spaced data, the difference between maps produced by different styles will usually be small. Contouring by any method must be viewed as a preliminary interpretation because unknown structures can always occur between widely spaced control points. The characteristics of the common styles of contouring are summarized next. Contours are usually shown as smooth curves although this should depend on the structural style (Sect. 3.3.4). The following examples (Figs. 3.1–3.2) are based on exactly the same points in order to demonstrate the differences that can be achieved by different methods.

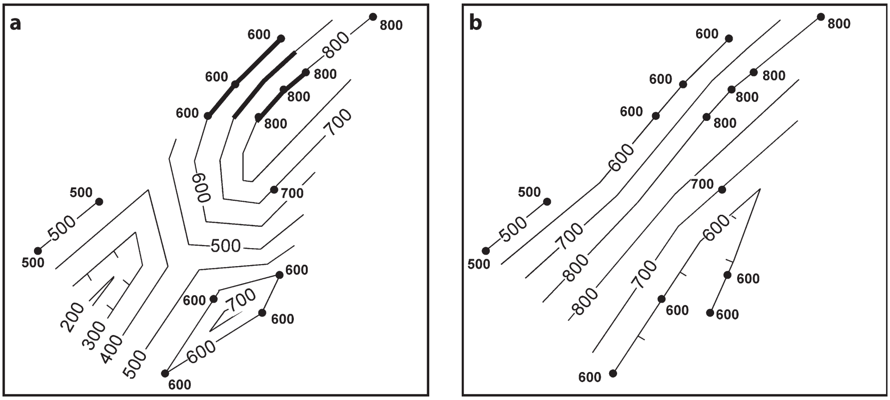


Fig. 3.1. Different contouring methods applied to the same control points (*solid circles*). **a** Equal-spaced contouring. The dip to be maintained (*heavy contours*) is chosen in the region of tightest control. **b** Parallel contouring

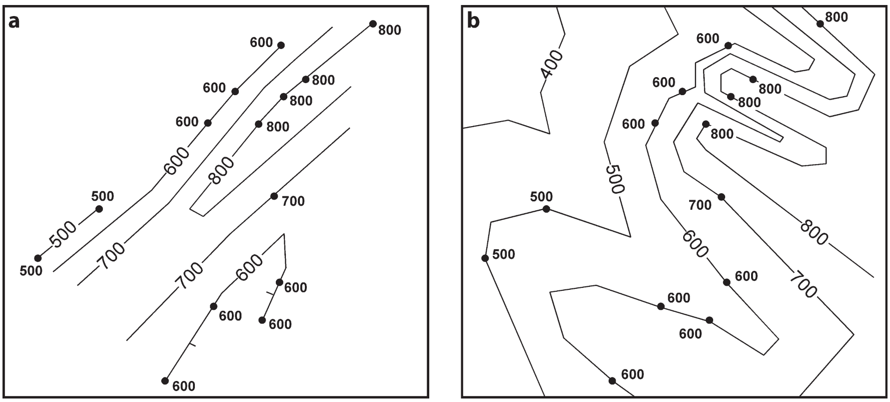


Fig. 3.2. Interpretive contouring; **a** based on interpretation that regional trends are northeast–southwest; **b** based on the interpretation that the regional trends are northwest–southeast

3.3.1 Equal Spacing

Equal-spaced contouring (Fig. 3.1a) is based on the assumption of constant dip magnitude over as much of the map area as possible. In the traditional approach, the dip selected is determined in an area of tightest control. The same dip magnitude is then used over the entire map (Handley 1954; Dennison 1968). Find the dip from the control points with the three-point method (Sect. 2.4), or, if the dip is known, as from an outcrop measurement or a dipmeter, find the contour spacing from the dip (Eq. 2.21). This approach projects dips into areas of no control or areas of flat dip and so will create large numbers of structures that may be artifacts (Dennison 1968). Because of the great potential for producing nonexistent structural closures, this method is usually not preferred (Handley 1954).

Equal-spaced contouring of the Mtfp (Fig. 3.1a) produces multiple closures, two anticlines and a syncline that is much lower than any of the data points. The anticlinal nose defined by the 800-ft contour is reasonable but the closed 700-ft anticline to the south and the syncline bounded by the 200-ft contour on the southwest are forced into regions of low dip or low control.

3.3.2 Parallel

Parallel contouring is based on the assumption that the contours are parallel, in other words, a strong linear trend is present. The contours are drawn to be as parallel as possible and the spacing between contours (the dip) is varied as needed to maintain the parallelism (Dennison 1968). The resulting map may contain cusps and sharp changes in contour direction, but is good for areas with prominent fold trends (Tearpock 1992). The method tends to generate fewer closures between control points than equal-spaced contouring and more than linear interpolation (Tearpock 1992).

The parallel contouring of the top of the Mtfp (Fig. 3.1b) is strongly influenced by the parallelism of the contours that can be drawn through the data points on the northwest limb and on the southeast limb of the major anticline. This method suggests an elongate northeasterly trending anticline in the center of the map and a southwest-plunging syncline on the southeast. The syncline is in the same position as the anticline predicted by the equal-spaced method (Fig. 3.1a).

3.3.3 Interpretive

Interpretive contouring reflects the interpreter's understanding of the geology. The preferred results are usually regular, smooth and consistent with the local structural style and structural grain. Generally, the principle of simplicity is applied and the least complex interpretation that satisfies the data is chosen.

Interpretive contouring (Fig. 3.2a) incorporates the knowledge that the structural grain is northeast–southwest and that the regional plunge is very low. The main anticline seen in each of the other techniques is present and is interpreted to be closed to the southwest, although there is no control as to exactly where the fold nose occurs. The northwestern contours are all interpreted to lie on the limb of a single structure, just as inferred by parallel contouring (Fig. 3.1b). The group of 600-ft contours in the southeast remains a problem. A syncline seems possible.

It is possible to obtain dramatically different results by "highly" interpretive contouring of sparse data (Fig. 3.2b). The two maps in Fig. 3.2 are completely different, although they are derived from exactly the same data. The difference between the two maps reflects the different assumed regional trends. There is no basis for choosing which map is better, given the available information. The simplest and most useful additional information for selecting the best interpretation is the bedding attitude, because the attitudes should indicate the trend direction (Sect. 3.6.1).

3.3.4 Smooth vs. Angular

Structure contours are usually drawn as smooth curves. This is appropriate for circular-arc and other smoothly curved fold styles. Many folds, however, are of the dip-domain style for which the structure contours should be relatively straight between

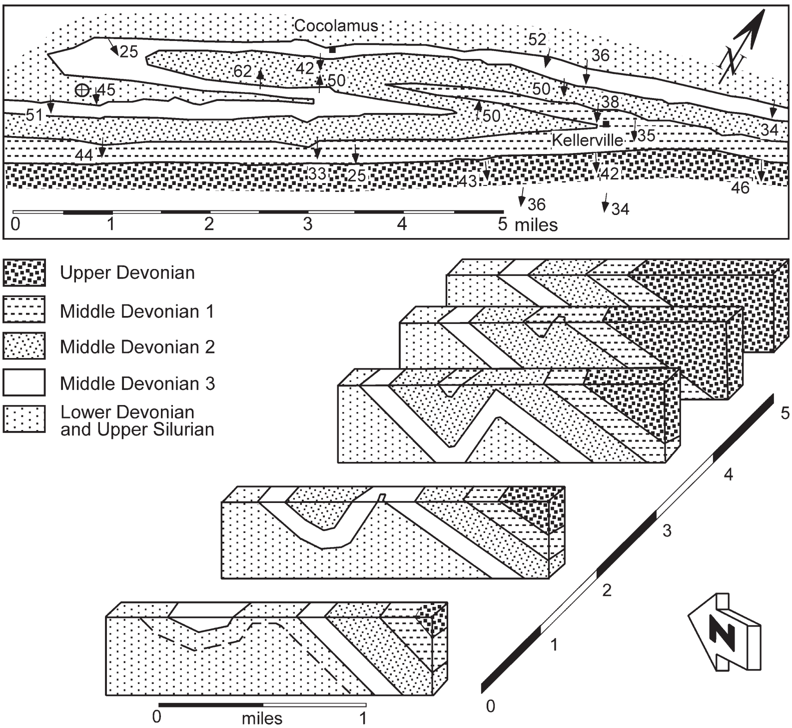


Fig. 3.3. Map and cross sections of dip-domain style folds in the Appalachian fold-thrust belt in Pennsylvania. (After Faill 1969)

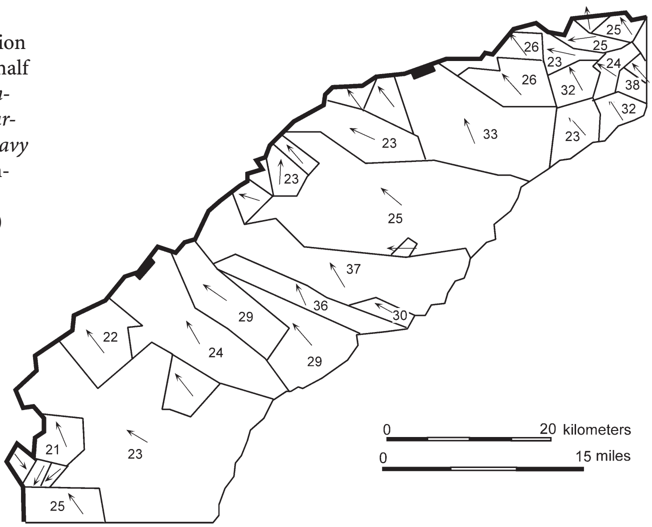


Fig. 3.4.
Dip-domain map of a portion of the Triassic Gettysburg half graben, Pennsylvania. *Numbers* are domain dips and *arrows* are dip directions. *Heavy line* is a normal fault, downthrown to the southeast. (Modified from Faill 1973b)

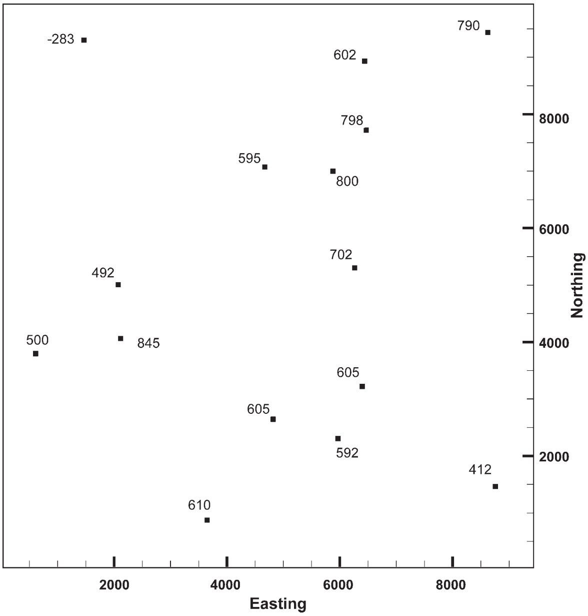
sharp hinges and have sharp corners on the map. The characteristic dip-domain geometry is regions of planar dip separated by narrow hinges. A map of dip-domain compressional folds in the central Appalachian Mountains (Fig. 3.3a) shows long, relatively planar limbs and very narrow, tight hinges. The cross sections (Fig. 3.3b) show a chevron geometry. Extensional folds may also have a dip-domain geometry. The extensional dip domains in a portion of the Newark-Gettysburg half graben (Fig. 3.4) have been synthesized from numerous outcrop measurements. Structure contour maps with straight lines and sharp bends are appropriate for dip-domain structures.

Computer programs may allow smoothing to be performed after contouring, if smoother surfaces are desired. For structural interpretation it is recommended that the unsmoothed contours should always be examined first because they provide more insight into the interpretation of the data points themselves.

3.4 Contouring Techniques

A given set of points can be contoured into a nearly infinite number of shapes, depending on the methodology followed. There is no absolute best technique for contouring and the overall appearance of the map is not necessarily an indication of its quality (Davis 1986). Geological interpretation must ultimately be part of the process. It is usually a good idea to start the interpretation process with a map that is constructed using standardized and reproducible procedures. Data points may either be contoured directly, using the triangulated irregular network (TIN) method, or can be interpolated into the elevations at the nodes of a grid (gridding) and then contoured (Jones and Hamilton 1992). In order to illustrate the process of constructing a structure contour map, the points in Fig. 3.5 will be treated as if they come from locations where there is no knowledge of the shape of the surface between the points.

Fig. 3.5.
Elevations of the top of a marker unit that will be contoured using different techniques in Figs. 3.6–3.13



3.4.1
Choosing the Neighboring Points: TIN or Grid?

Drawing a contour between control points requires first deciding which control points from the complete data set are to be used. This decision is not trivial or simple. The choice of neighboring points between which the contours are to be drawn has a major impact on the shape of the final surface. Two procedures are in wide use, triangulation and gridding. Triangulation involves finding the TIN network of nearest neighbors in which the data points form the nodes of the network (Fig. 3.6a). Gridding involves superimposing a grid on the data (Fig. 3.6b) and interpolating to find the values at the nodes (intersection points) of the grid. Many different interpolation methods are used in gridding. Most involve some form of weighted average of points within a specified distance from each grid node (Hamilton and Jones 1992). Contours developed from either type of network may be smoothed, either as part of the contouring procedure or afterward.

The first decision is whether the contouring will be based on a TIN or on a grid. The most direct relationship is to connect adjacent points with straight lines, producing a TIN. This has long been a preferred approach in hand contouring and is also popular in computer contouring (Banks 1991; Jones and Nelson 1992). The primary advantages of the method are that it is very fast, the contoured surface precisely fits the data, and it is easy to do by hand. For structural interpretation, fitting the data exactly, including the extreme values, is a valuable property, because the extreme values may provide the most important information. Plotted in three dimensions, the TIN network alone will show the approximate shape of the surface. The advantage of gridding is that once the

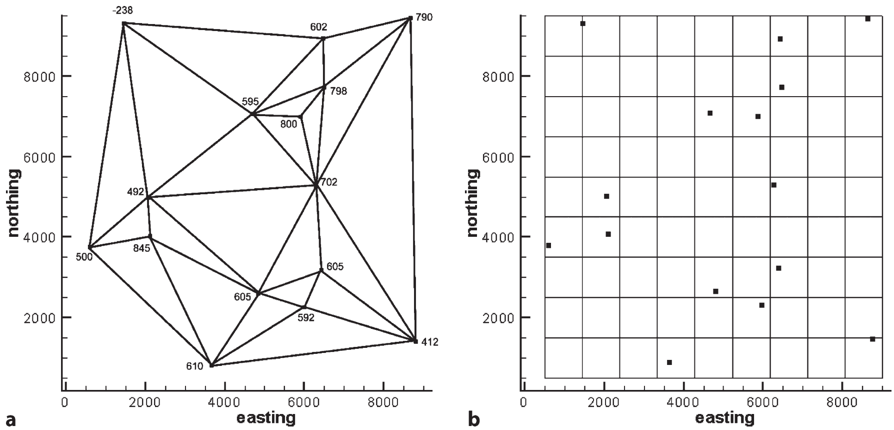


Fig. 3.6. Methods for relating control point elevations to each other. **a** Triangulated irregular network (TIN) with data points at the vertices. **b** Grid superimposed on the data, elevations will be interpolated at the grid nodes

data are on a regular grid, other operations, such as the calculation of the distance between two gridded surfaces, are relatively easy. The major disadvantage is that the contoured surface does not necessarily go through the data points and it may be difficult to make the surface fit the data.

3.4.2 Triangulated Irregular Networks

Creating a TIN requires determining the nearest neighbor points, between which the contours will be located. The possible choices of nearest neighbors are seen by connecting the data points with a series of lines to form triangles (Fig. 3.7a). The points could be connected differently to form different networks. Delauney triangles and greedy contouring are two unbiased approaches to choosing the nearest neighbors. The commonest form of triangulation is in two dimensions and considers only the proximity of the points in a plane, such as x and y but not z. Triangulation in three dimensions considers the xyz location of points and can be generalized to interpret very complex surfaces (Mallet 2002).

3.4.2.1 Delauney Triangles

A Delauney triangle is one for which a circle through the three vertices does not include any other points (Jones and Nelson 1992). In Fig. 3.7b, the solid circle through vertices a, b and c is a Delauney triangle because no other points occur within the circle. The vertices of the triangle are nearest neighbors. The dashed circle through vertices a, b and d (Fig. 3.7b) includes point c and therefore does not define a Delauney triangle. This method is not as practical for use by hand as the next technique.

3.4.2.2
Greedy Triangulation

A triangulation method suitable for use by hand as well as by computer is known as "greedy" triangulation (Watson and Philip 1984; Jones and Nelson 1992). The criterion is that the edge selected is the shortest line between vertices. No candidate edge is included if there is a shorter candidate edge that would intersect it (Jones and Nelson 1992). Figure 3.8a shows a network of candidate edges with the longer edges dashed. The TIN produced by this method is shown in Fig. 3.8b. This method is both logical and convenient for use by hand and is the approach generally used in this book as the first step in the interpretation.

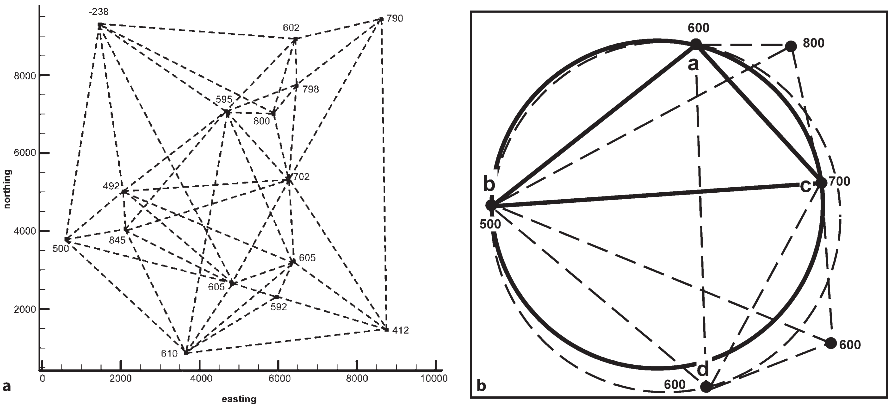


Fig. 3.7. Nearest neighbors in a TIN network. **a** Possible nearest neighbors connected by *dashed lines*. **b** Four potential neighbor points *a–d*. The *solid circle* includes three points (*a–c*) that define a Delauney nearest-neighbor triangle (*heavy lines*). The *dashed circle* through *a*, *b*, and *d* includes one point inside the circle

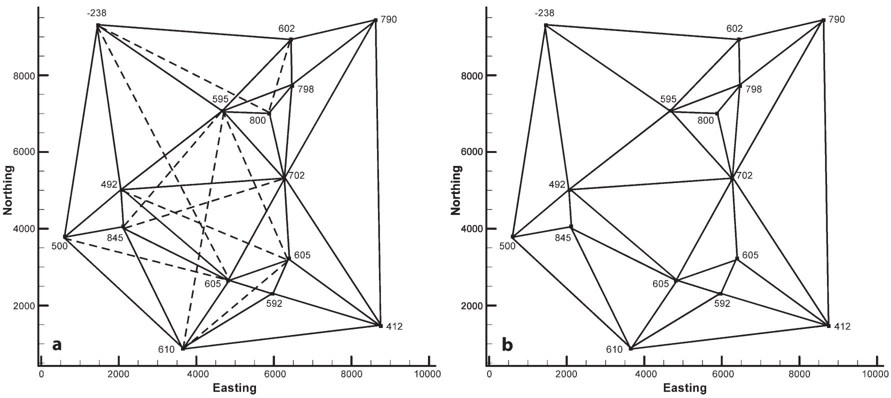


Fig. 3.8. Greedy triangulation. **a** Alternative nearest neighbors. Longer edges *dashed*. **b** Longer edges removed to define nearest neighbors

3.4.3 Interpolation

All contouring methods require interpolation between control points in order to find the structure contours. Discussed here are linear interpolation between nearest neighbor points in a TIN network and interpolation to a grid.

3.4.3.1 Linear Interpolation

Linear interpolation is based on the assumption that slope between the data points is a straight line. As a contouring technique it is also called mechanical contouring (Rettger 1929; Bishop 1960; Dennison 1968). This is a standard approach for producing topographic maps where the high points, low points, and the locations of changes in slope are known, allowing accurate linear interpolation between control points (Dennison 1968). This method may produce unreasonable results in areas of sparse control (Dennison 1968; Tearpock 1992). The resulting map is good in regions of dense control and is the most conservative method in terms of not creating closed contours that represent local culminations or troughs. The method tends to de-emphasize closed structures into noses, is good for gently dipping structures with no prominent fold axes, and is often used in litigation, arbitration and oil-field unitization (Tearpock 1992). This method is applied to the example data in Fig. 3.9. The contours suggest an anticline with two separate culminations.

3.4.3.2 Interpolation to a Grid

Mapping by gridding requires interpolation between and extrapolation beyond the control points to define values at the grid nodes prior to contouring. Gridding variables always include the choice of the grid spacing and the interpolation technique. A typical characteristic of gridded data is that the original control points do not fall on the contoured surface. The reason for this is that the control points are not used to make the final map.

The simplest gridding technique is linear interpolation. The structure contour map in Fig. 10a is the result of linear interpolation to the nodes of a 10×10 grid, then linear-interpolation contouring between the nodes. The best-controlled part of the structure resembles the triangulated map of Fig. 3.9. The contouring algorithm for this technique forces all contours to close within the map area which is not a geologically realistic assumption.

Another simple interpolation technique is the inverse distance method. In this method the value at a grid node is the average of all points within a circle of selected radius around the node, weighted according to distance, such that the farther-away points have less influence on the value. The weighting function is usually an exponential, such as one over the distance squared (Bonham-Carter 1994). Figure 3.10b is a structure contour map produced by inverse-distance interpolation. The contours are significantly more curved than those produced by linear interpolation of the TIN (Fig. 3.9) or the linear interpolated grid (Fig. 3.10a). The side view of the inverse-distance interpretation (Fig. 3.10c) shows that the control points do not all lie on the interpolated surface.

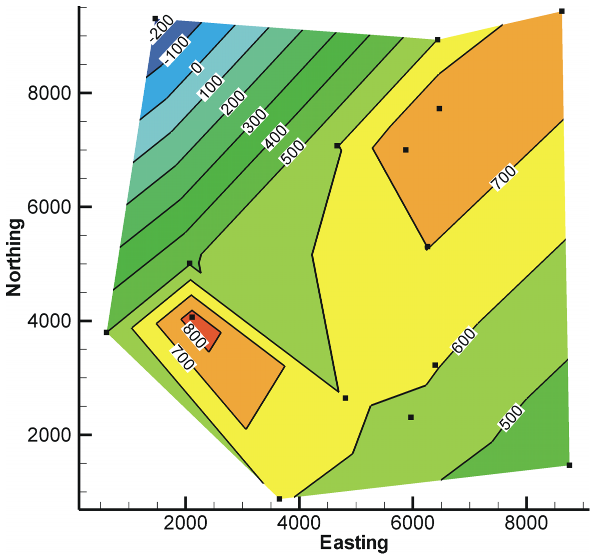


Fig. 3.9.
Structure contour map of the triangulated data in Fig. 3.8b. Contours produced by linear interpolation between nearest neighbors

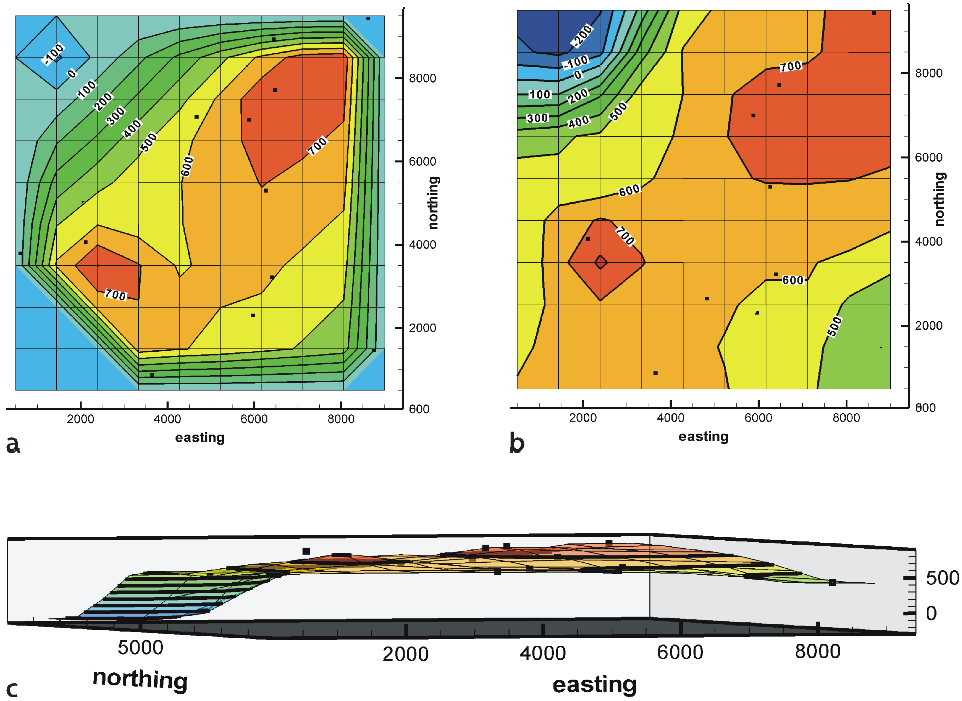


Fig. 3.10. Simple grid-based contouring techniques using a 10×10 grid, control points from Fig. 3.5. *Squares* are data points. **a** Linear interpolation. **b** Inverse-distance interpolation, weighting exponent 3.5. **c** Oblique view to NW of inverse-distance interpolation

Kriging is an interpolation method in which the value at a grid node is a weighted sum of points within a zone of influence, like the inverse-distance method, but with a more complex weighting system (Bonham-Carter 1994). There are several kriging parameters (Davis 1986) that must be set to obtain a result. In the program used to produce the maps below, these parameters are: *range* = distance beyond which the values of the points become insignificant in the average; *drift* = the overall trend of the surface, which can be either zero, linear or quadratic; *zero value* = semi-variance of source points = certainty that the value is correct on a scale of zero to one (zero means the point is exact). Setting the trend to be quadratic trend allows the final surface to be more complex. Larger values of the zero value lead to smoother surfaces.

A range of kriging results as a function of the choices of mapping parameters is illustrated in Fig. 3.11. For each map the zero value is set to zero and the effects of grid spacing and drift are explored. Both surfaces generated with linear drift (Fig. 3.11b,c)

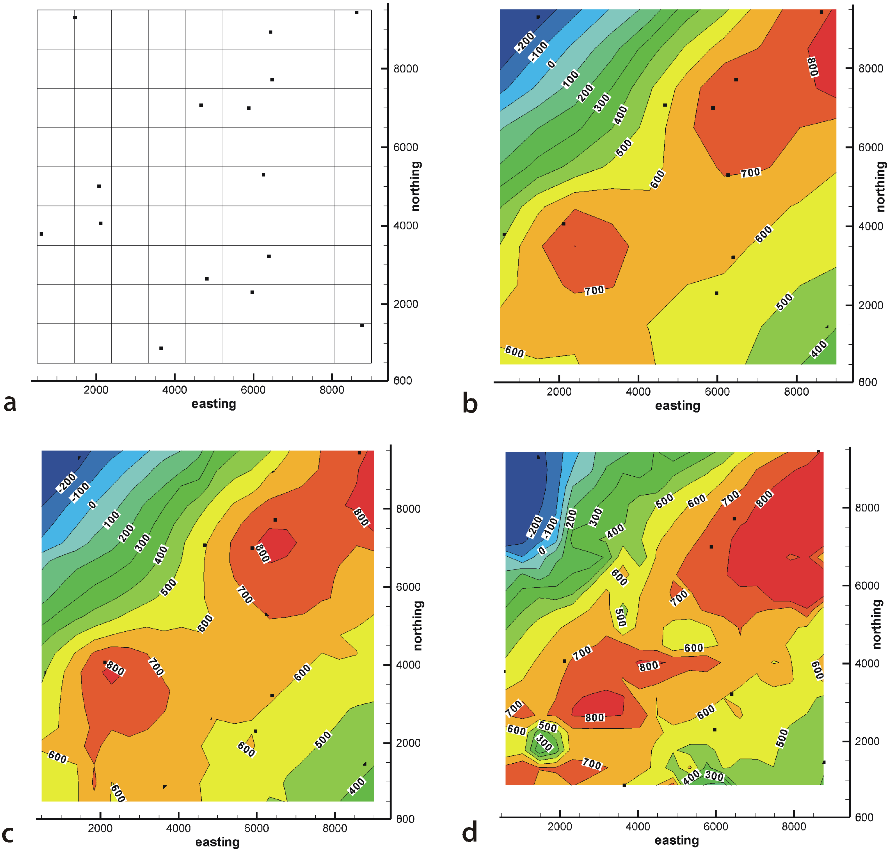


Fig. 3.11. Kriging of the data in Fig. 3.5. *Solid squares* are control points. **a** 10×10 grid with control points. **b** Mapped to a 10×10 grid, range = 0.3, drift = linear. **c** Mapped to a 20×20 grid, range = 0.3, drift = linear. **d** Mapped to a 20×20 grid, range = 0, drift = quadratic

indicate an anticline with two local closures and a pronounced saddle between them, similar to the inverse-distance result (Fig. 3.10b). Decreasing the grid spacing from 10×10 (Fig. 3.11b) to 20×20 (Fig. 3.11c) increases the complexity of the surface, but only slightly. Increasing the drift from linear (Figs. 3.11b,c) to quadratic (Fig. 3.11d) greatly increases the complexity of the surface, resulting in numerous small closures on the bigger structure, analogous to those produced by the equal-spaced contouring style. An oblique view (Fig. 3.12) shows that the control points may lie at significant distances from the interpolated surface. For further discussion of working with grid-based computer contouring, see Walters (1969), Jones et al. (1986), and Hamilton and Jones (1992).

3.4.4 Adjusting the Surface Shape

In order to achieve the desired result (interpretive contouring) with computer contouring, it may be necessary to introduce a bias in the choice of nearest neighbors or to introduce pseudopoints. A biased choice of neighbors is used in forming a TIN to control the grain of the final contours or to overcome a poor choice of neighbors that results from inadequate sampling of the surface. Pseudopoints can be used to insure

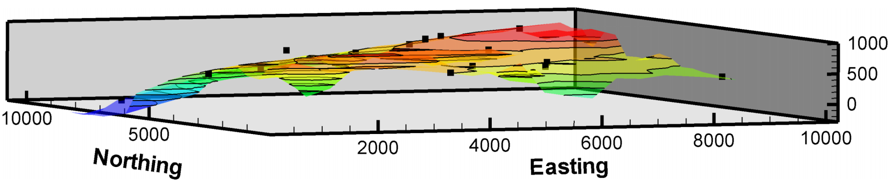


Fig. 3.12. 3-D oblique view to the NE of the kriged surface in Fig. 3.11d showing that some control points (*squares*) lie above or below surface

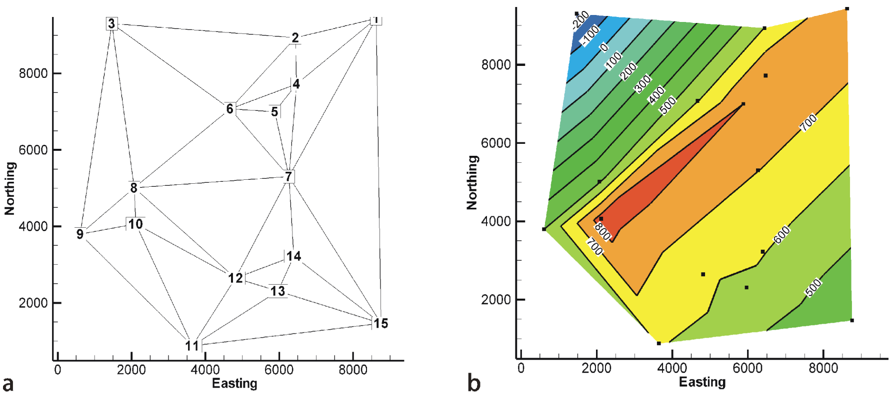


Fig. 3.13. Reinterpretation of the of the triangulation network in Fig. 3.8b. **a** Revised TIN network, nodes are numbered. **b** Linear interpolation contouring of network in **a**

that the surface goes above or below the extreme values of the data points. It is important to carefully label pseudopoints in the data base so that they will not be mistaken for real data.

The relative spacing of grid nodes can be altered to produce a trend. Changing, for example, from a 10×10 grid to a 10×20 grid in the same area will alter the surface. Rotating the grid directions will also have an effect.

A TIN network can be edited to change the nearest neighbors, which will then change the resulting surface. Suppose that the map of the anticline in Fig. 3.9 would be better interpreted without a saddle between separate closures. The control point that creates the saddle should have nearest neighbors on the southeast limb, not the northwest limb of the anticline. The desired result is obtained by re-defining the nearest neighbor network (Fig. 3.13a), resulting in a new map (Fig. 3.13b).

3.5 Mapping from Profiles

Frequently structure contour maps are derived from data distributed along linear traverses, rather than from randomly spaced points. This is particularly true when working with 2-D seismic-reflection profiles, ground penetrating radar profiles, or predictive cross sections (Sect. 6.4). If the profile trend is not parallel or perpendicular to the structural trend, the map may contain apparent structures related to the traverse orientation. The effect is shown by obliquely sampling a cylindrical, sinusoidal fold that has a horizontal axis with a north-south trend (Fig. 3.14). When the traverse data are interpolated by the inverse-distance technique (Fig. 3.15), the correct general form of the anticline is produced but smaller-scale NE and NW trends are superimposed. The oblique trends are most evident in the low-dip region near the crest of the anticline. Triangulation shows even more pronounced oblique trends near the crest (Fig. 3.16a). The triangulation network (Fig. 3.16b) shows the reason for the oblique trends. Nearest neighbors are controlled by the traverse spacing, not the underlying

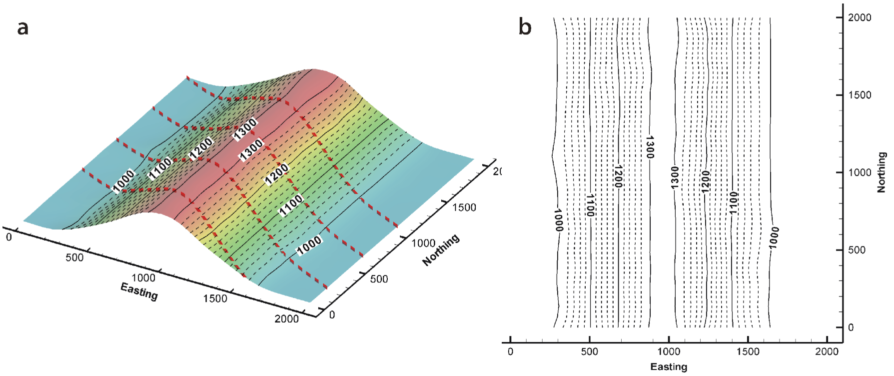


Fig. 3.14. Source data: non-plunging, sinusoidal anticline. **a** Oblique view showing section traces. **b** Structure contour map

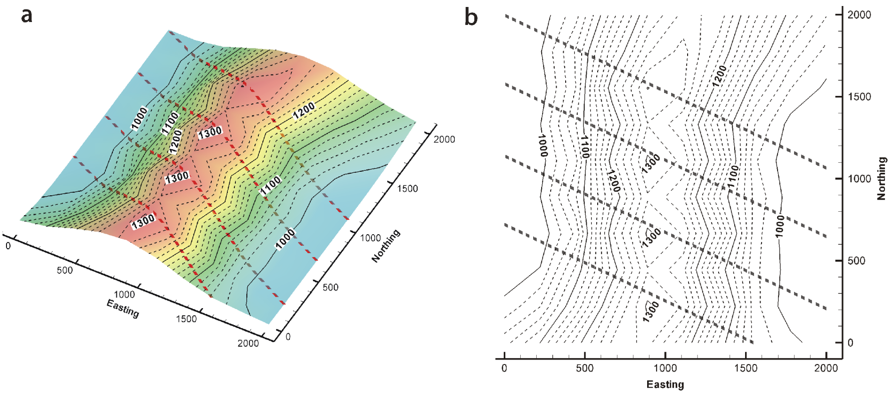


Fig. 3.15. Map made by inverse-distance interpolation (weighting exponent 3.5) of points along cross sections from data in Fig. 3.14. *Lines of black squares* are control points. **a** Oblique view. **b** Structure contour map

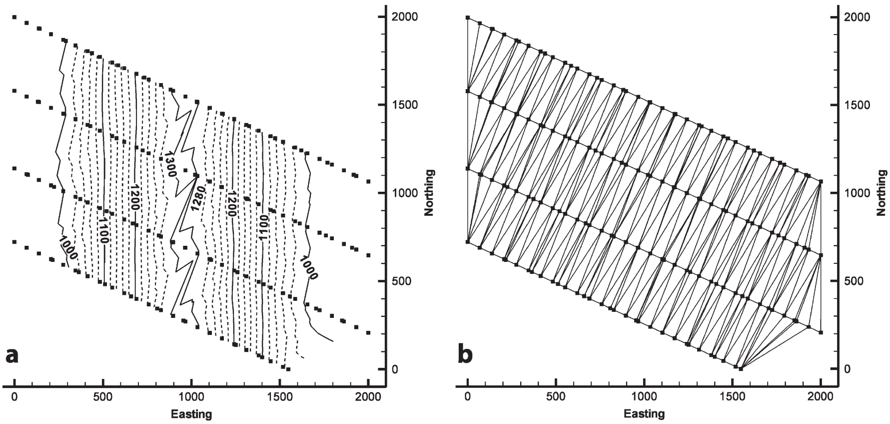


Fig. 3.16. Map made by triangulation of points along cross sections from data in Fig. 3.14. *Lines of black squares* are control points. **a** Structure contour map. **b** TIN network

structural trend. Nearest neighbors are the closest points on adjacent traverses. This problem can be overcome by orienting traverses parallel and/or perpendicular to the structural trend, or by mapping based on the structural trend (Sect. 5.5).

Non-cylindrical folds pose a greater challenge for accurate mapping. The fold in Fig. 3.17a is a simple flat-topped anticline with limbs that converge to the south and disappear, giving a conical geometry. Sampled along three traverses perpendicular to the average crestal trend, the reconstruction does only a fair job of reproducing the original geometry. The fold limbs are reproduced but the flat crest and the plunging nose are misrepresented. Mapping based on 3-D dip domain interpretation (Sect. 6.7) is the most accurate approach for this style of structure.

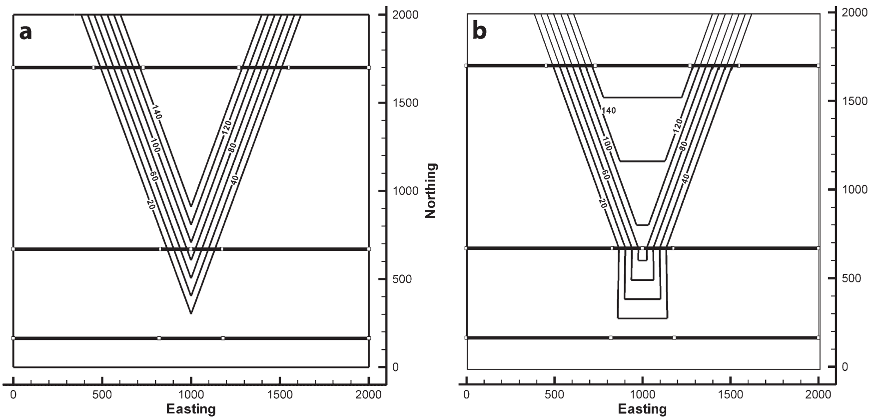


Fig. 3.17. Structure contour maps of a conical, dip-domain anticline. **a** Original map showing three traverses where elevations have been extracted (*heavy EW lines*). **b** Map constructed by triangulating points extracted from the three profiles in **a**

3.6 Adding Information to the Data Base

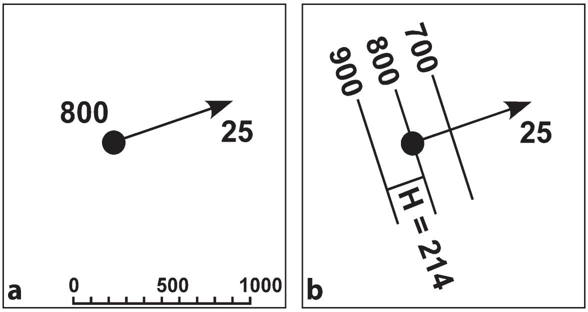
Structure contour maps can be based on a significant amount of information in addition to the elevations on a single horizon. The shape of the contoured surface can be controlled using the attitudes of bedding, data from multiple stratigraphic horizons, and from pore-fluid behavior such as different groundwater levels or the presence or absence of hydrocarbon traps as indicated by shows of oil and gas in wells. Finding the structural trend and mapping based on trend are discussed in Chap. 5 and 6.

3.6.1 Bedding Attitude

If the bedding attitude is known from outcrop or dipmeter measurements (Fig. 3.18a), it can be incorporated into the contouring. Attitudes at the well-bore or outcrop scale can give insight into the shape of the surface but are subject to influence by small-scale structures. The contours are not required to have the same dip everywhere on the map. The contour spacing will change as the dip changes. Structure contours are perpendicular to the bedding dip. The distance between the contours is given by Eq. 2.21. In the example of Fig. 3.18, for a contour interval of 100 and dip of 25°, the spacing between the contours at map scale is 214, giving the structure contour map in the vicinity of the control point shown in Fig. 3.18b.

If mapping is customarily done at a standard scale, then a map-spacing ruler (Fig. 3.19) can be useful. A contour-spacing ruler shows the spacing between contours for a variety of dips, given the map scale and the contour interval. It is constructed using Eq. 2.21. The ruler is oriented perpendicular to the structure-contour (strike) trend and the contour spacing for a given dip is easily plotted or the dip determined from the contour spacing.

Fig. 3.18.
Structure contour direction and spacing from an attitude measurement. **a** Dip vector at a point having an elevation of 800. **b** Structure contours in the vicinity of the point. For $I = 100$, $H = 214$



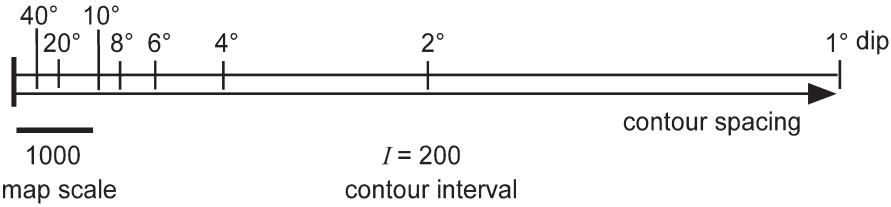


Fig. 3.19. Contour-spacing ruler

3.6.2
Projected and Composite Surfaces

A projected surface is a structure contour map derived entirely by projecting data from other stratigraphic levels. A projected marker is sometimes called a ghost horizon. Usually a projected surface is below the lowest control points. A typical use is to project the subsurface location of an aquifer or an oil reservoir from outcrop or shallow subsurface information.

A composite surface is a structure contour map derived using data from multiple stratigraphic horizons, including the horizon being mapped. One horizon is selected as the reference surface and data from other stratigraphic horizons are projected upward or downward to this horizon, using the known stratigraphic thicknesses. The best choice of a reference horizon is one for which there is already a significant amount of control and that minimizes the projection distance. Usually a reference horizon that is stratigraphically in the middle of the best-controlled units should be selected. The data from multiple horizons provide increased control on the interpretation of the shape of the reference horizon. This type of map is particularly useful in the interpretation of outcrop data because the locations of all formation boundaries can be used to provide control points, greatly increasing the areal distribution of data.

An elevation on a marker surface is transformed into an elevation on a projected surface by adding or subtracting the vertical distance between the two (Fig. 3.20). The projection is made from a point where the elevation of the marker is known. This may be the location of a surface outcrop (as in Fig. 3.20) or the elevation of a contact in a well. The distance to the projected horizon is derived from the thickness of the unit by

$$d = t / \cos \delta \quad , \tag{3.1}$$

where d = vertical distance between the surfaces, t = true thickness, and δ = true dip (Badgley 1959). The projection can be either up or down from the known point, that is, from the marker horizon in Fig. 3.20 to either a or b. Be sure to use the same datum (i.e., sea level) for all measurements. Projections from a surface map need to use the topographic elevation to find the elevation with respect to sea level. Projections above the surface of the earth are as valid as projections below the surface; it is not necessary that the reference surface be confined to the subsurface.

If regional thickness variations are present, the thickness used for projection must be adjusted according to the location. An isopach map (Chap. 4) provides the information necessary to determine the thickness at specific points. In regions of low dip, the difference between the vertical distance and the true thickness is small. In this situation an approximate projected surface can be derived by simply adding or subtracting the thickness between the units to or from the elevation of the marker to obtain the projected surface (Handley 1954; Jones et al. 1986; Banks 1993).

Projected data can greatly augment the information on a single horizon and can lead to a significant improvement in the interpreted geometry of the structure. The increase in data available for contouring may significantly improve the map on the reference horizon. Inconsistent data on different horizons can be more easily recognized when all data are projected to the same surface. Accurate projection requires accurate knowledge of the unit thickness and the dip, both of which are likely to contain uncertainties and so a certain amount of "noise" is to be expected in the projected data set. The interpreted surface and the data will be iteratively improved as the inconsistencies are eliminated.

The creation of a composite surface map allows utilization of stratigraphic markers that are not formation boundaries. The location of any marker horizon separated from the reference surface by a known stratigraphic interval can be converted to an elevation on the reference horizon. Even if the marker is not usually mapped, it will provide important information.

The construction of a projected or composite-surface includes assumptions that must be considered in each application. Projection with Eq. 3.1 requires that the dip and

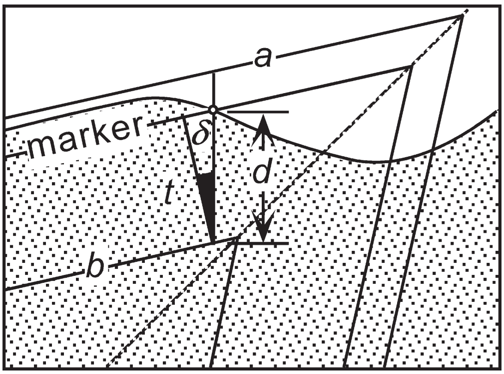


Fig. 3.20.
Vertical cross section showing the projected distance from a point (*small circle*) on a marker horizon to reference surface. Projections may be done either upward (to *a*) or downward (to *b*). The region below ground level is *patterned*; *d:* vertical distance between surfaces; *t:* true thickness; *δ:* true dip

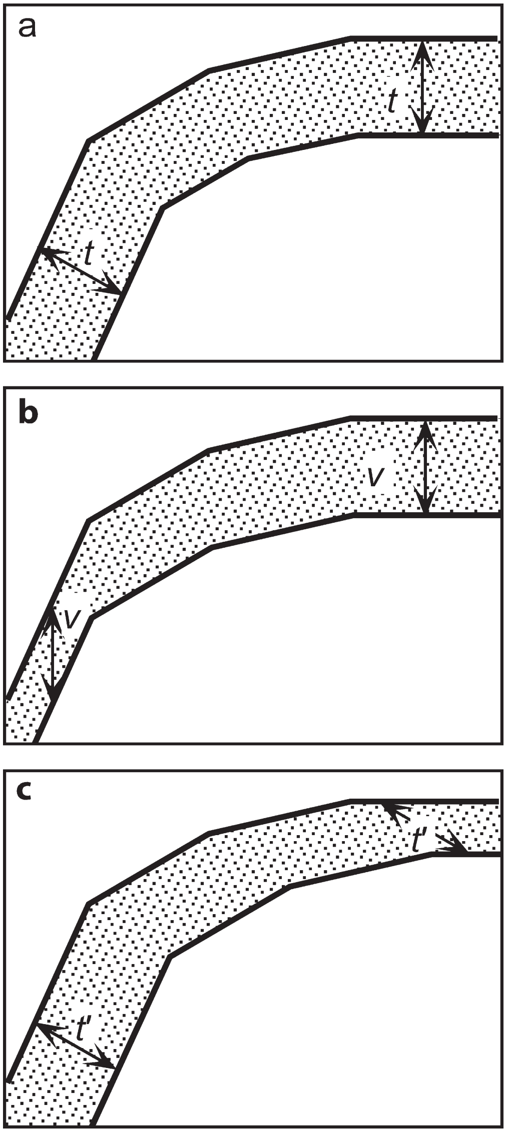


Fig. 3.21.
Cross sections showing directions of constant thickness. The dips are identical in each cross section. **a** Constant bed thickness (*t*). **b** Constant vertical thickness (*v*). **c** Constant apparent thickness (*t*') in an inclined direction

thickness remain constant and the units unfaulted over the projection distance. The most definitive check on the validity of a projected or composite surface is to construct a cross section that shows all the horizons from which data have been obtained (Chap. 6), as in Figs. 3.21 and 3.22. Any projection problems should be reasonably obvious on the cross section.

Folding may produce thickness changes that are a function of position within the fold and the mechanical stratigraphy. Equation 3.1 is based on the assumption that

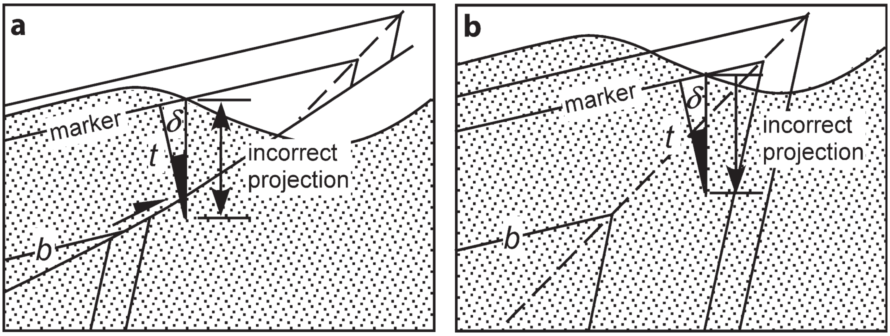


Fig. 3.22. Vertical cross sections showing incorrect projections across discontinuities. **a** Projection across a fault. **b** Projection across an axial surface. The region below ground level is *patterned*. *δ:* dip; *t:* thickness of the interval being projected

bed thickness remains constant throughout the fold for all units being projected (Fig. 3.21a), in other words, that all the horizons are parallel. This is called parallel folding, and is only one of the possible fold styles. Deformation can change the thicknesses, especially the thicknesses of thick soft units between stiffer units. The direction of constant thickness is an element of the fold style. A similar fold maintains constant thickness parallel to the axial surfaces. Constant vertical thickness projection (Handley 1954; Banks 1993) is strictly appropriate only for similar folds that have vertical axial surfaces (Fig. 3.21b). The resulting thinning on steep limbs is a common feature of compressional folds, even in those that maintain constant bed thickness elsewhere. If the axial surfaces of a similar fold are inclined, the direction of constant thickness is inclined to the vertical (Fig. 3.21c). Projection of surfaces is probably best restricted to situations in which bed thicknesses are approximately constant (Fig. 3.21a).

Projection of thickness is based on the further assumption that the stratigraphy between the projection point and the composite surface is an unbroken sequence of uniform dip. If the vertical line of projection crosses a fault (Fig. 3.22a) or an axial surface (Fig. 3.22b), then the projection will be incorrect. The shorter the projection distance, the less likely these problems are to occur.

The value of a composite-surface map in structural interpretation is shown by the composite surface of the Mtfp (Fig. 3.23) in the Blount Springs map area. The projected points allow a structure contour map to be constructed for the top of a centrally located stratigraphic horizon (top Mtfp). This map was produced by first interpolating the dip values between control points and then projecting all the points on each contact to the top of the Mtfp. Projecting using very steep dips provided some unrealistic results because the long vertical projection distances cross gently dipping axial surfaces, invalidating the result as in Fig. 3.22b. The obviously incorrectly projected points have been removed. The square points in Fig. 3.23a are the locations of dip measurements and approximately indicate the limits of control. The complex structure northwest of the anticline and the flat surface to the southeast are artifacts of the contouring process (kriging) and do not represent real structure.

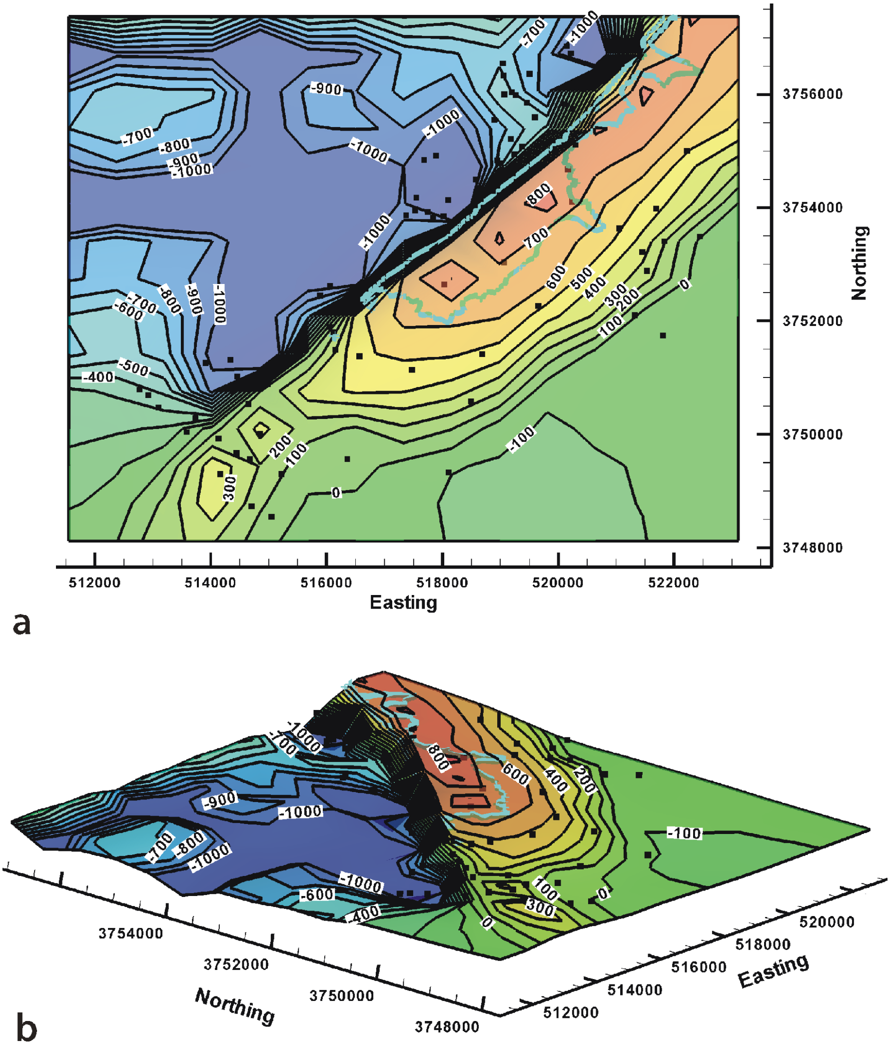


Fig. 3.23. Composite-surface map of the top Mtfp, Blount Springs map area of Fig. 2.4. The outcrop trace of the top Mtfp is a *wide, light gray line*. Thicknesses used for projection are: Mpm = 108 ft and Mh = 105 ft, calculated from the geologic map (Fig. 2.4); Mtfp = 245 ft from a well in the area; Mb = 625 ft from the outcrop just southeast of the map area. Map coordinates are UTM in meters and contour elevations are in feet. *Squares* are locations of dip measurements. **a** Map. **b** Oblique 3-D view to the northeast

The major northeast-southwest trending structure (Fig. 3.23) is the Sequatchie anticline, now clearly shown to be an asymmetric anticline with a steep forelimb on the northwest. The internal consistency of the data appears to be good, confirming the general validity of all the mapped outcrop traces. The flattening and spreading of the anticline at its southwest end is real, and represents a saddle where the fold crest steps to the northwest.

3.6.3 Fluid-Flow Barriers

Fluid movement, or the lack of it, through porous and permeable units can indicate the connectivity or the lack of connectivity between wells. A *show* is a trace of hydrocarbons in a well, and can indicate the presence of a nearby hydrocarbon trap that is otherwise unseen. Different water levels, oil-water contacts, or fluid pressures in nearby wells can indicate a barrier between the wells. The structure contour map in Fig. 3.24a and the corresponding cross section in Fig. 3.25a show four wells that appear to define a region of uniform dip. Suppose, however, that an oil or gas show is present in the downdip well but not in the updip wells. The show suggests proximity to a hydrocarbon trap, yet the map does not indicate a trap. The map must be revised to include some form of barrier because of this additional information (Sebring 1958). Possible alternatives that could produce an oil or gas show in the downdip well include a hydro-

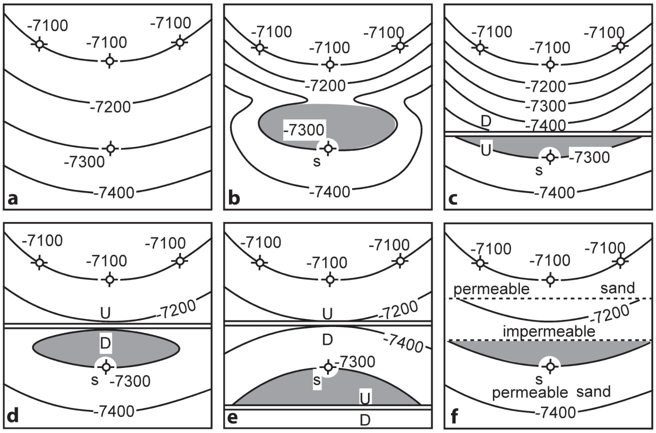


Fig. 3.24. Alternative maps honoring the same data points. **a** Map based on the four wells being dry holes. **b–f** Maps based on presence of an oil show in the well labeled *s*, implying presence of a barrier between this well and the three updip dry holes. Hydrocarbon accumulations are *shaded*. Figure 3.25 shows the corresponding cross sections. (After Sebring 1958)

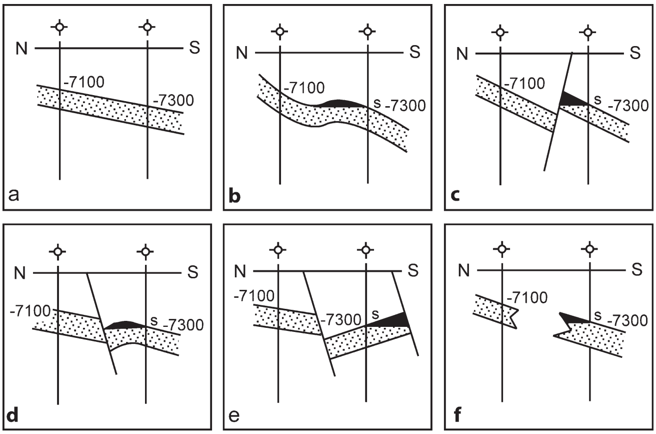


Fig. 3.25. Alternative cross sections in the dip direction honoring the same data points. **a** Section based on the four wells being dry holes. **b–f** Sections based on presence of an oil show (*s*) in the downdip well, implying a barrier between this well and the updip wells. Hydrocarbon accumulations are *shaded*. Figure 3.24 shows the corresponding structure contour maps. (After Sebring 1958)

carbon-filled structural closure up the dip (Figs. 3.24b, 3.25b), different types of faults between the downdip well and the updip wells (Figs. 3.24c–e, 3.25c–e) or a stratigraphic permeability barrier (Figs. 3.24f, 3.25f). A stratigraphic barrier does not necessarily require the structure to be changed from the original interpretation. The structural configuration is the same in Figs. 3.24f and 3.25f as in Figs. 3.24a and 3.25a.

3.7 Exercises

3.7.1 Contouring Styles

Use the data from the Weasel Roost Formation (Fig. 3.26) to try out different contouring techniques and to see the effect of trend biasing. Use interpretive contouring and assume a surface with no grain. Contour by parallel contouring: *(a)* assuming a northwest-southeast grain; *(b)* assuming a northeast-southwest grain. Draw crestal and trough traces on the structure contour maps just completed. Use interpretive contouring and assume a northeast-southwest grain. Define a TIN using greedy triangulation and contour by linear interpolation.

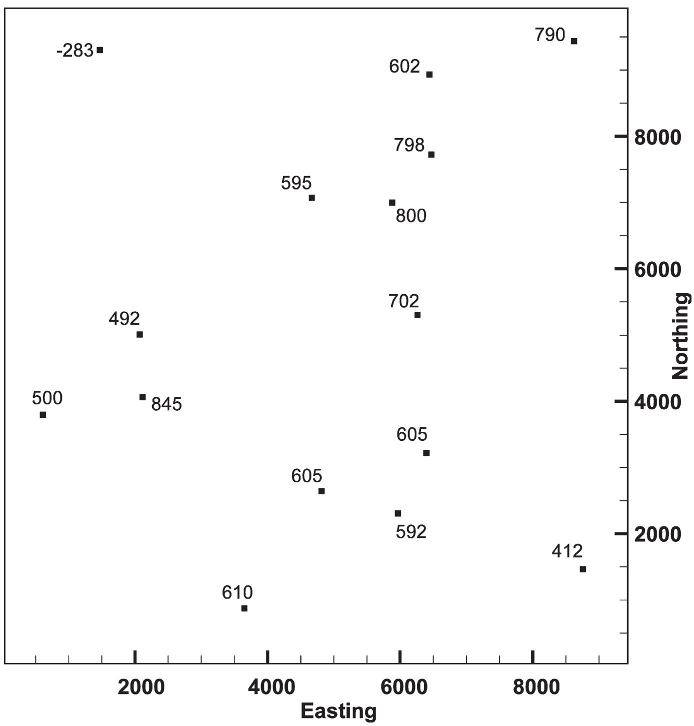


Fig. 3.26. Map of elevations (feet or meters) of the top of the Weasel Roost Formation

3.7.2
Contour Map from Dip and Elevation

Contour the top of the Tuscaloosa sandstone in Fig. 3.27 using the bedding attitudes to help generate the contour orientations and spacings. The elevations are in meters.

3.7.3
Depth to Contact

Find the elevation of the top of the Mtfp below the dot in Fig. 3.28. The thickness of the Mpm is 97 ft and the dip is 04°.

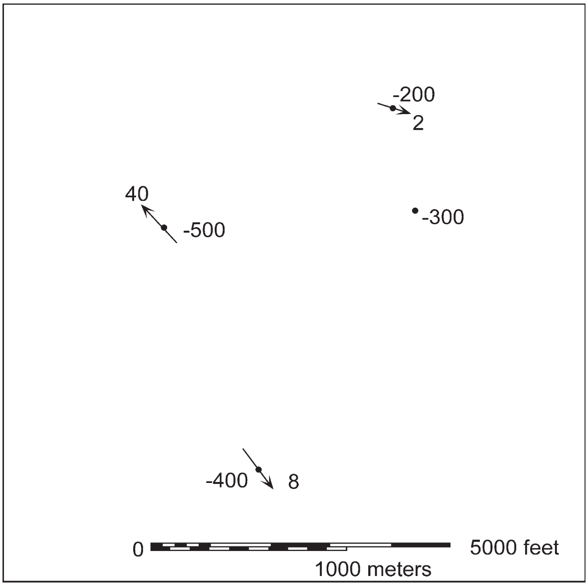


Fig. 3.27.
Map of the top of the porous Tuscaloosa sandstone. Negative elevations are below sea level; azimuth of bedding dip is indicated by *arrows*

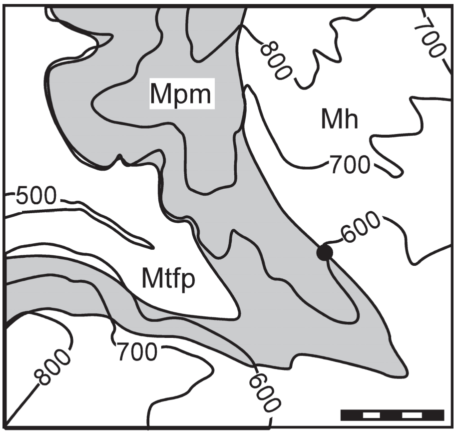


Fig. 3.28.
Geologic map of the Mill Creek area. Topographic elevations are in feet and the scale bar is 1 000 ft

3.7.4
Projected-Surface Map

Use the geologic map of Fig. 3.29 to construct a projected structure contour map of the top of the Fairholme, a potential hydrocarbon reservoir. Use every point where a

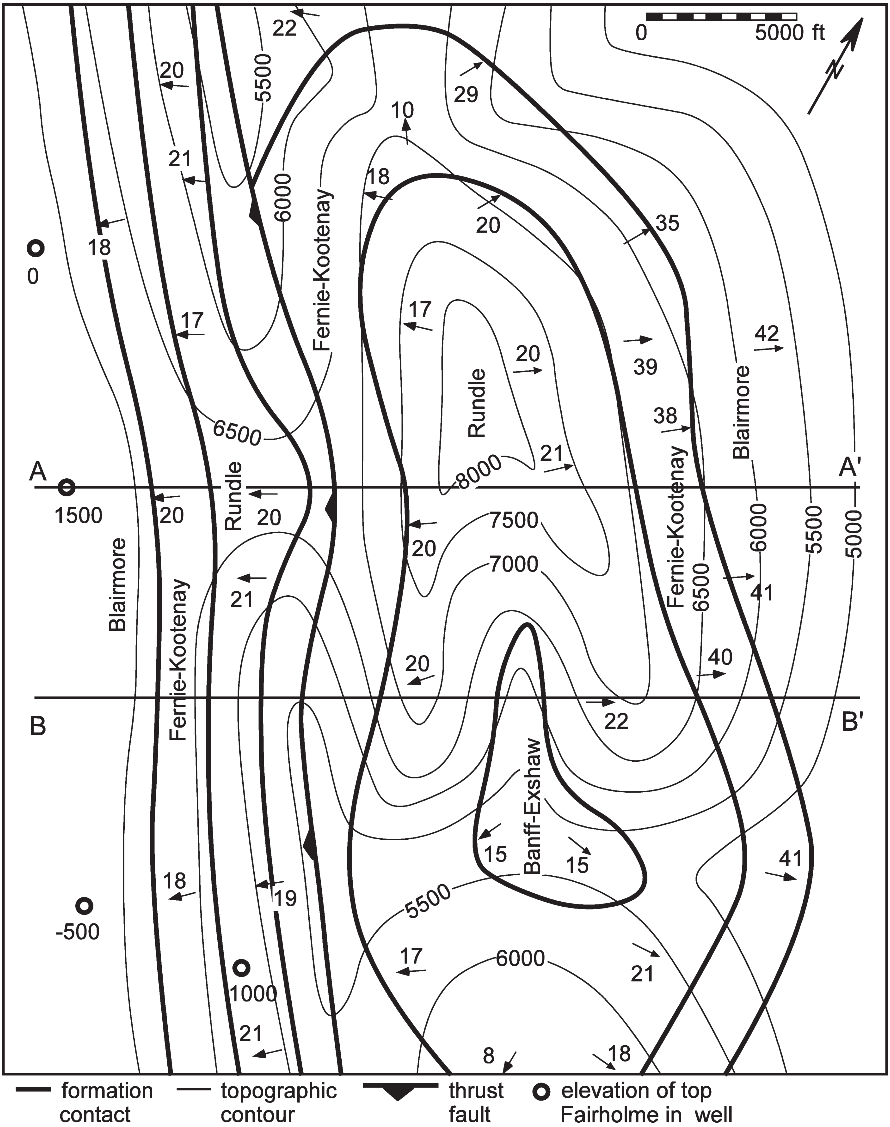


Fig. 3.29. Geologic map from the Canadian Rocky Mountains. All dimensions are in feet. The stratigraphic column (with thickness) from top to base is: Blairmore (2 400), Fernie-Kootenay (700), Rundle (900), Banff-Exshaw (900), Palliser (800), Fairholme (1 200). (After Badgley 1959)

formation boundary crosses a topographic contour. Post all the elevations on your map before contouring. What is the best method for contouring this map? Explain your reasons. Is the geological map correct? Why or why not? Does the projected structure-contour map agree with the drilled depths to the top of the Fairholme? The wells to the Fairholme were drilled to find a hydrocarbon trap but were not successful. What is a structural reason for drilling the wells and what is a structural reason why they were unsuccessful?