

STRUCTURAL ANALYSIS

Structural geology uses micro- and meso-scale structures found in the rocks to elaborate tools and methods enabling to identify structures too large to be directly observed, although satellite imagery now may help in this task. This lecture summarises standardised techniques used to unravel the shape, extent, and arrangement of structures on a regional scale, together with the relative time sequence in which the structures have appeared. **Structural analyses** designate investigations of geometric features in the rocks to elucidate large-scale structures and tell their history.

Basic concepts

The study of primary and secondary structures is not a straightforward undertaking because outcrops are often scarce or not available in critical areas, which makes direct observation of large structures impossible and correlative interpretation, therefore, necessary. Furthermore, the geological observation is essentially two dimensional because the relief is generally small compared to the map area. Consequently, interpretation is still necessary to produce a three-dimensional picture, even in areas of almost continuous outcrop.

Structural geologists must additionally reconstruct the deformation history of the rocks from the patterns of primary and secondary structures found in the field. This aim implies **fieldwork**, i.e. direct observation of rocks in their natural environment (outcrops, landscapes, drill cores). The belief is that every feature is the record of an event that the scrutinized outcrop has experienced. It is assumed that changes of structural orientations preserve changes in strain or stress axes. Thus, elucidating the deformation history depends on the recognition of the relative age of different structures, such as faults, folds and fabrics, using crosscutting or overprinting relationships.

In short, a successful structural analysis produces:

- 1) A geometric model, which is a three-dimensional picture that adequately describes the spatial problems on the studied area.
- 2) A kinematic model, which is an account of the successive stages through which the studied structure developed.
- 3) An indication of the directions and senses of the local movements that have affected the rocks.
- 4) A mechanical model, which attempts to determine the strain or stress history of the region.

We start by presenting basic concepts that are essential in deciphering the structural history of an area. We then discuss the techniques traditionally employed in the interpretation of areas that have suffered a single episode of deformation and areas that have been subjected to multiple deformations. We will see that these concepts rely on often non-reciprocal propositions, which means that answers are correct but not unique.

Analytic elements

Techniques appropriate to the study of simple areas, where structures have constant trends in rocks with continuous bedding, formed the basis of structural analyses. They consider several types of structural elements.

Scale

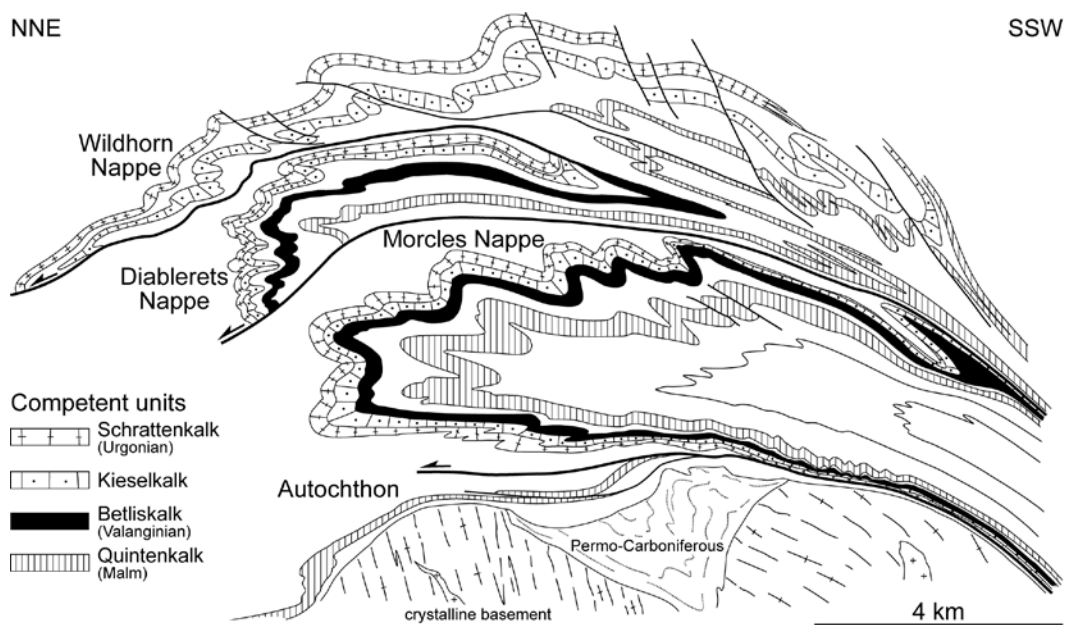
There are classically three scales of investigation: macroscopic, mesoscopic, and microscopic.

- **Microscopic** scale pertains to any structure so small ($<10^{-2}$ m) that it requires to be examined with an optical or electron microscope.

Microscopic structures
 From Bard 1990: *Microtextures des roches magmatiques et métamorphiques*. Masson, Paris, 208p.



- **Mesoscopic** scale pertains to any structure that can be observed without the aid of the microscope on a hand specimen or a single outcrop (10^{-2} to 10^2 m).
- **Macroscopic** scale pertains to structures that are too large ($>10^2$ m) to be completely exposed in one outcrop, which implies the interpretative step of reconstructing the structure from data collected at a number of outcrops.



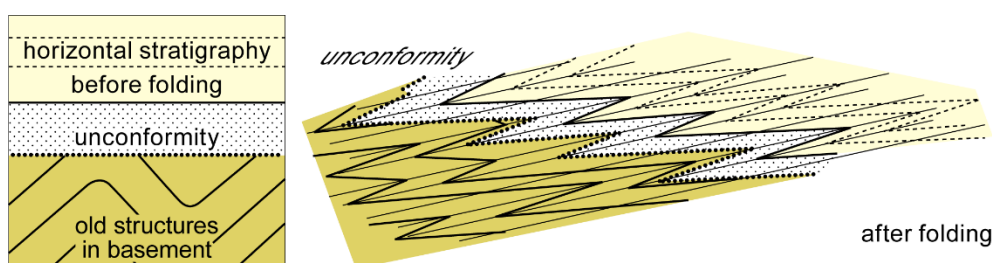
Profile across the Helvetic Nappes in western Switzerland
 after Ramsay 1981 *Geol. Soc. London Spec. Pub.* 9, 293-309

In understanding the structure of an area, the geologist is concerned principally with the mesoscopic and macroscopic scales. Microscopic observations better establish the detailed characteristics of features, such as foliations, that are visible on a mesoscopic scale. The concept of scale is very important in structural geology. One must be constantly aware of the relationships between structures at all scales, and intellectually jump from one scale observation to another to solve the geometrical problems met in the field.

Stratigraphic sequence - Lithology

The establishment of the lithological and/or stratigraphic sequence is a prerequisite in interpreting the large-scale structure and the history of an area. Any structural information has little meaning out of its lithological (sedimentological or petrological) and age (paleontological or radiometric) context.

- An interruption of stratigraphic contacts points to faults or unconformity that may not outcrop.
- Repetition of a stratigraphic sequence helps perceiving the positions of folds or thrusts.



Structural reconstruction of a folded and foliated unconformity

The warning point concerns sequences of lithological units. For example, layering in deformed metamorphic rocks does not necessarily represent bedding. Thus it is important, wherever possible, to demonstrate the existence of bedding and stratigraphy, which can be obtained by identification of sedimentary structures that define the “way up” of the beds. Selecting a distinctive marker horizon is useful to picture regional structures.

Remember also triviality: a deformation structure is necessarily younger than hosting rocks and an unconformity marks the time of a major tectonic event.

Mapping - Collection of Data

Geologic mapping is the foundation of any geological work because it is the only way to (1) make an inventory of rock units and describe them; (2) recognise structures, document their complexity and measure their orientations; (3) observe the nature of contacts between rock units and, in turn, disclose the sequential history of major events; (4) make and check first hypotheses in the field and, finally (5) construct cross sections to investigate the three-dimensional geometry of an area. These aspects require iteration to develop a dynamic or kinematic history of the rock.

A field map represents as many measurements as possible and shows the distribution of the outcrops. All data must be plotted at the site of observation on the map. They comprise:

- Stratigraphic data, including directions of younging, which is very important to discover the geometrical configuration of a complexly deformed region.
- The trace and orientation of any structure. Penetrative structures are too thin to be drawn exactly to scale and are generally treated as conventional symbols.

Modern geological mapping often combines satellite imagery or aerial photography with ground operations.

The resulting geological map shows with colours and/or appropriate patterns the distribution of rock formations at the earth’s surface. Accompanying structural maps display directional symbols that enable identifying at a glance the dip direction of bedding and foliation planes and areas in which they are folded. They also reveal the local vergence of small folds and the traces of axial plane foliations.

Orientation data

Dips and strikes and other orientation data must be reported on geological maps. In complex, ‘polyphase’ areas systematic measurement is very important because late structures generally disperse attitudes of earlier-structures, thus produce a wide variation in orientation data. In addition to field measurements, fabric analysis can be obtained from the study of orientated samples. A structural sample is actually always orientated.

The widespread belief is that orientation can assist in grouping structures of the same generation. However, the fact that two structures have the same orientation does not necessarily mean that they belong to the same group or family and conversely structures of a given group need not have the same orientation (the variability in orientation structure). Always remember that the orientation of late fold

axes may also depend on the orientation of earlier structures (e.g. inherited dip of a refolded plane affects the orientation of fold axes).

Planar elements

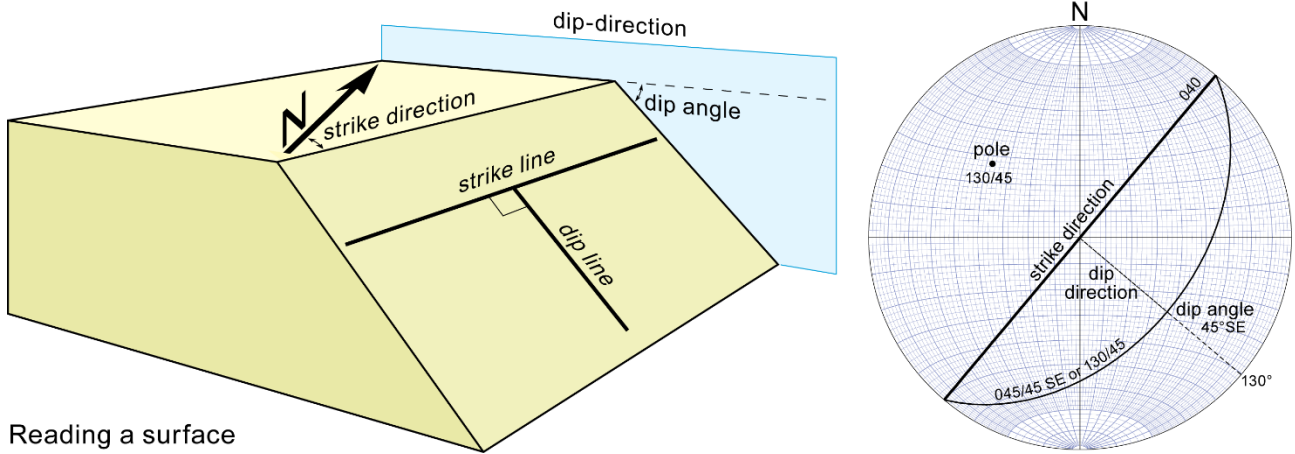
The **attitude** of any planar element (bedding, foliations, etc...) is represented by its strike and by its dip.

Remember:

- the strike is the compass direction of the horizontal line lying in an inclined plane;
- the dip is the large angle made by the plane with the horizontal and is measured perpendicular to strike in the vertical plane.

For convenience, some geologists measure directly the dip-direction and the dip.

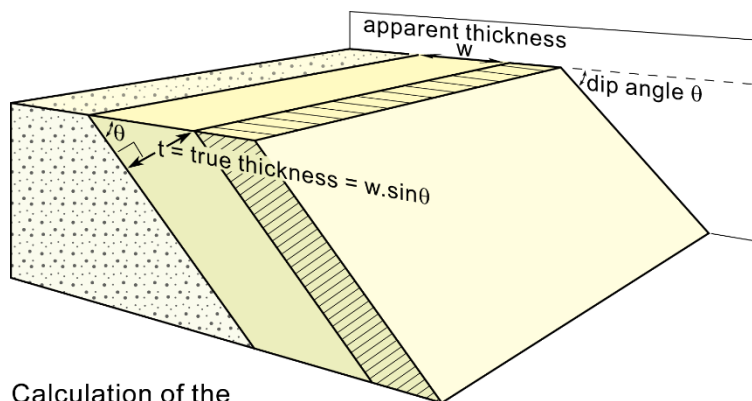
The international convention is to draw a T on the map with the top line parallel to the strike of the plane and the leg indicating the dip direction of the bed. The azimuth is indicated by a three-figure number recording the degrees clockwise beginning at north (thus ranging from 000 to 360), and the dip by a two figure number that varies from 00 to 90, complemented with the approximate down-dip direction (e.g. N). Azimuths must be expressed as 3-digit numbers (e.g. 045, not 45) to avoid confusion of < 90 directions with dips.



Reading a surface

The apparent width w of a layer on map is related to its thickness t and its dip θ by the simple trigonometric equation:

$$t = w \cdot \sin \theta$$



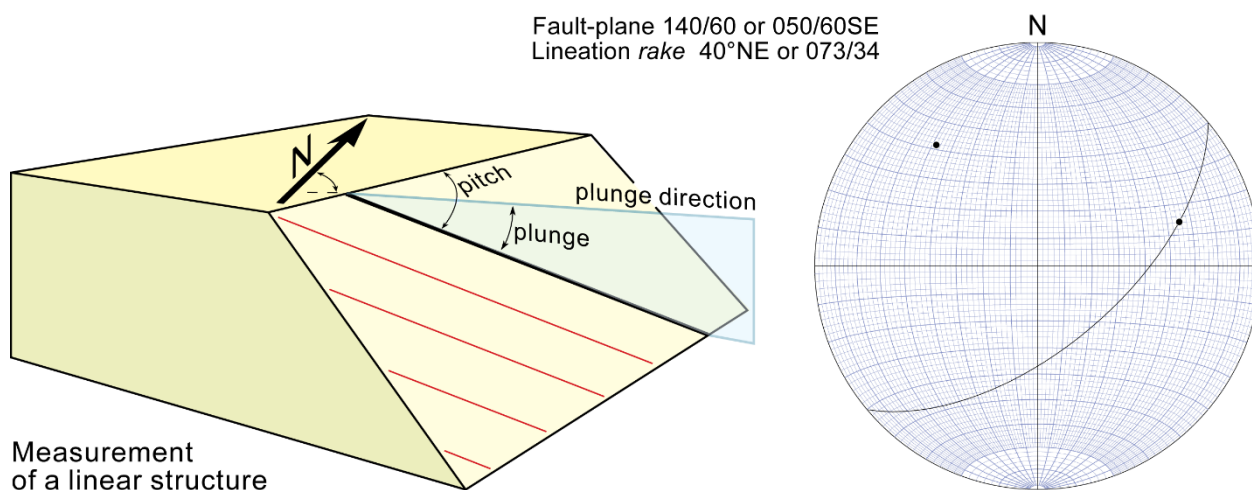
Calculation of the true thickness of a layer from field measurements

Linear elements

The attitude of a linear structure is described by its trend and its plunge.

Remember: Lecture Lination

- The trend is the compass direction of the projection of the linear structure on a horizontal plane, read towards the down-line direction.
- The plunge is the angle made by the linear structure with the horizontal, in the vertical plane parallel to the trend.
- The rake (or pitch) is the angle between lines lying in a plane with the horizontal, strike line of that plane. Therefore, it is an angle measured in the plane that contains the linear structure. This angle is generally used to measure slicken side striations on a fault plane. Like for planes, azimuth is indicated by a three-figure number (000 to 360°), and plunge by a two-figure number (00 to 90°).



Complex structures

The complete orientation of a fold is given by both the attitudes of its axis, which is a line, and axial surface, which is a plane.

Direct measurement of the direction and the angle of plunge of mesoscopic folds and/or the associated intersection lination provides a good idea of the regional trend of fold axes in simple areas. A similarly accurate result can be obtained by plotting the bedding orientation data on a stereographic projection. It is useful to remember that in areas of cylindrical folding the trend of the hinge line is parallel to the strike of any vertical beds that may be present and the plunge of the hinge line is equal to, or less than, the shallowest dip.

Bedding orientation

The dip and strike of bedding measurements may be used to determine the shapes of the folds.

- Downward-converging dips, for example, indicate that the fold between the two measurement localities is a synform.
- Conversely, upward-converging dips indicate that the fold between the two measurement localities is an antiform.
- The angle between the dips suggests whether the fold is open, tight or isoclinal.
- Northward-converging strikes suggest that lithological boundaries connect, i.e. "close" north rather than south of the outcrops and that the plunge of the antiform between these exposures is toward the north; the hinge plunges southward if it is a synform.

Angular relationship between bedding and axial plane cleavage

The relationship between bedding and any axial plane foliation, in macroscopic folds, is assumed to be the same as that generally observed in mesoscopic folds.

- If bedding and foliation are perpendicular to one another, the outcrop is on the hinge of a fold.
- If bedding and foliation make a small angle with one another, the outcrop is on the limb of a fold.

- If bedding and foliation dip in the same direction with bedding dipping steeper than the foliation the beds are probably pertaining to an inverted limb.
- If bedding and foliation dip in the same direction with the foliation dipping steeper than bedding the beds are probably pertaining to a normal limb.
- The intersection line of bedding and cleavage adequately approximates the orientation of local hinge lines.

Stereonet projection

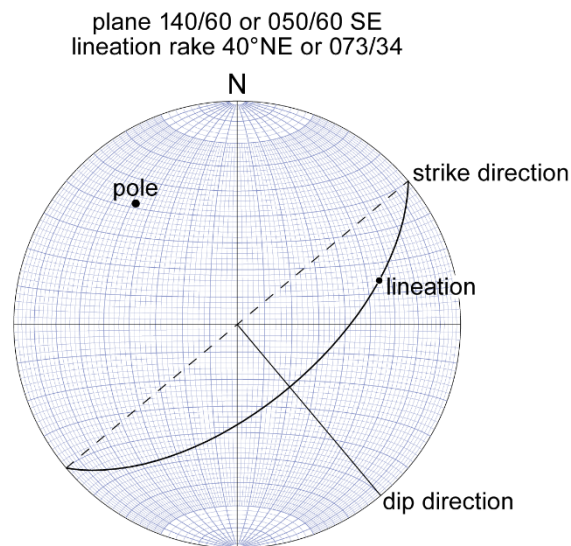
Stereographic projections are techniques (complementary and not alternative to maps) to display and record orientation data. These projections are based on the principle that points on the surface of a sphere can be projected onto the horizontal equatorial plane. Taking the pole axis vertical, the sphere has lines of latitudes and longitudes. Any circle on the surface of the sphere whose centre lies at the centre of the sphere is a great circle. Thus, the equator and lines of longitude are **great circles**. Lines of latitudes are **small circles**. International tradition considers intersections on the lower hemisphere only, because dips are measured below the horizontal.

Two types of projections are common in structural geology. In both, the strike or azimuth is plotted around the circumference of the plot and the distance d from the center of the plot represents distance (i.e. the angle $(90^\circ - \text{dip})$ from the pole of the sphere. Projection types differ in the manner d is calculated in function of r , the plot radius.

- **Equal area projections** (so-called Schmidt nets) are the most common. In this case:

$$d = \sqrt{2} \cdot r \cdot \sin\left[\frac{(90 - \text{dip})}{2}\right]$$

Equal areas on the sphere have equal areas on the plot. The projection is important for a density appraisal of the orientation of structural elements. However, angular relationships are distorted, particularly at the edge of the projection.



Stereographic projection of a plane bearing a lineation
in a Schmidt net (equal area, lower hemisphere)

- **Equal angle projections** (so-called Wulff nets) in which angles on the projection are the same as angles on the surface of the sphere. In this case:

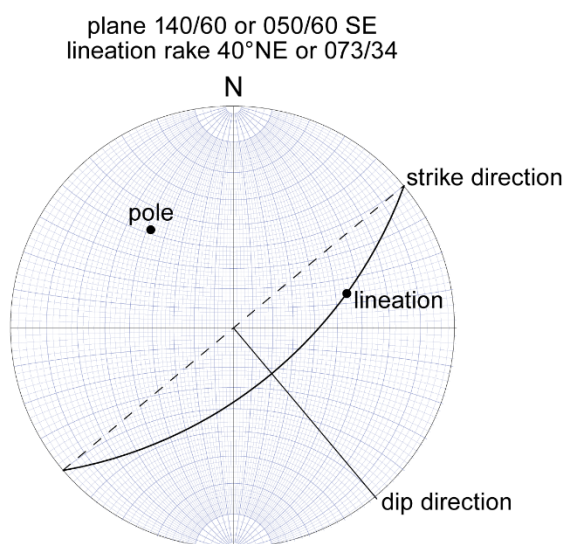
$$d = r \cdot \tan\left[\frac{(90 - \text{dip})}{2}\right]$$

Angular relationships are not distorted. In particular, circles on the sphere project as circles but their areas are not respected.

Planar and linear elements are the main geological structures measured. The plotting procedure is as follows:

- 1) An equatorial net is mounted on a board with a pin through its centre and into a sheet of tracing paper placed over the net.
- 2) The tracing paper on which an equatorial circle with its north-mark is drawn is rotated to place the strike of the plane or azimuth of the line on the net north.
- 3) The dip of the plane is measured along the net E-W axis from the border to identify the plane traces; the plunge of the line is measured from the border along the N-S axis.

Linear structures are plotted as points and surfaces are represented by their cyclographic trace (great circle or small circle) or, more commonly, by their **polar projection** (impingement of the normal to the plane on the sphere). Each fabric element is normally plotted on a separate diagram and points are commonly contoured in terms of the percentage of points per 1% area of the surface of the projection sphere. The advantage of these projections is manipulation of the data, such as rotations about tilt or fold axes that may have affected the original geometrical distribution.



Stereographic projection of a plane bearing a lineation
in a Wulff net (equal angle, lower hemisphere)

In an area in which a given surface S is cylindrically folded the poles to S spread along or about the same great circle. Thus by plotting poles to a given surface the axis about which it is folded is readily determined as the pole to this great circle. The axial orientation of the large folds can then be compared with that of mesoscopic folds and lineations and a basis thereby established for interpretation of the relationship between mesoscopic and macroscopic structures.

An early lineation folded around a flexural flow fold will plot on a small circle etc and in practice the superposition of structures can be identified through characteristic figures on stereographic projections. But such studies are unlikely to provide definitive information regarding the types of deformation the rocks have experienced.

Polyphase folding is indicated by a wide distribution of bedding attitudes, away from simple great circles or conical patterns on the stereographic projection.

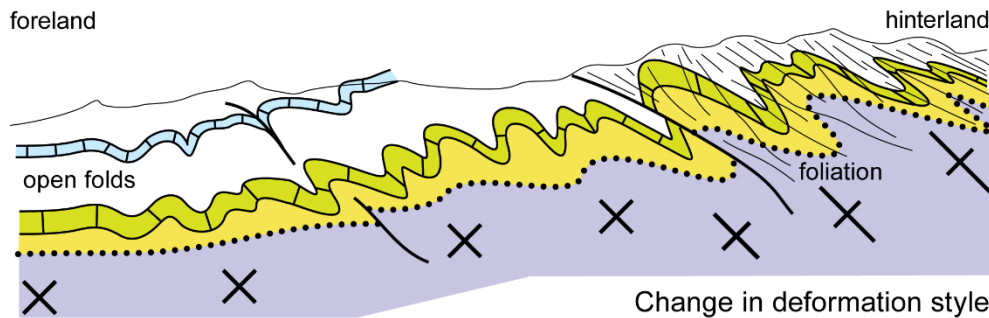
Style - Fold geometry

Style refers to a combination of distinctive geometric characteristics seen on outcrops, in map and cross-sections. It is used mainly in describing folds, less often fracture populations. It is concerned with all morphological features as the shape of the fold in profile, the presence or absence of an axial plane foliation, the type and dip of axial plane foliation (is the fold upright, inclined, recumbent?), and whether the fold is cylindrical. Other important aspects of style are the nature of related or deformed lineations and the related metamorphic assemblages and microstructures. More quantitatively, the aspect ratio, tightness and bluntness are meaningful to identify groups of folds of a given style.

Reminder: Lecture on Folds

The aspect ratio is the ratio of the amplitude of a fold, measured along the axial surface, to the distance between the adjacent inflection points that bound the fold. The tightness is defined by the interlimb angle. The bluntness measures the relative curvature of the fold at its closure.

Folds of an area can usually be assigned to a small number of style groups. For example, in orogenic zones, tight to isoclinal recumbent folds with axial plane foliation are ordinarily accompanied (and likely deformed) by upright, more open folds that have no or alternatively one crenulation, axial plane foliation. All of these folds can be ascribed to two fold-style groups.



Style is governed by physical conditions but also varies with rock type. For example, a given fold in mica-rich layers may have an angular hinge in profile, but appears rounded in a more competent, sandy interlayer. In addition, this fold may have an axial plane foliation in the mica-rich layers but not in the competent layers. Furthermore, fold styles may regionally vary noticeably, but in a continuous manner, with respect to one prominent feature such as the interlimb angle, which commonly becomes tighter from foreland to hinterland. Therefore, style may be compared only between folds in the same lithological type. An efficient approach considers first structures in massive, competent lithologies that only responded to the major tectonic pulses and, secondly, the more complex array of structures formed in the less competent horizons, which responded to the slightest and local deformation.

Use of small-scale structures in structural analysis

Geometrical extrapolation

The profile and local vergence of mesoscopic folds are used to determine the position of each exposure relative to nearby larger folds whose profile and orientation are assumed to be similar to those of the mesoscopic folds. For example, S-type mesoscopic folds indicate a position on the east limb of an anticline or the west limb of a syncline, it is the contrary for Z-type mesoscopic folds. Where the mesoscopic folds are symmetrical M-types, the outcrop should be near the hinge of a larger fold.

Principle of superposed structures

Deformation structures range in size from fractions of millimetres to kilometres. It is almost axiomatic that small structures reflect the orientation and character of larger structures of same generation. In other words, deformation structures are homothetic and share the same style and orientation at every scale. Accordingly, structural geologists study small-scale structures as a powerful tool to resolve the geometry and orientation of regional structures and to unravel the sequence of tectonic events that has affected the study area.

The safest indication of multi-phase deformation is direct observation of superposed structures and fabrics during fieldwork. The various structures are ascribed to style groups. Crosscutting and overprinting relationships allow inferring a temporal succession of the various deformation style

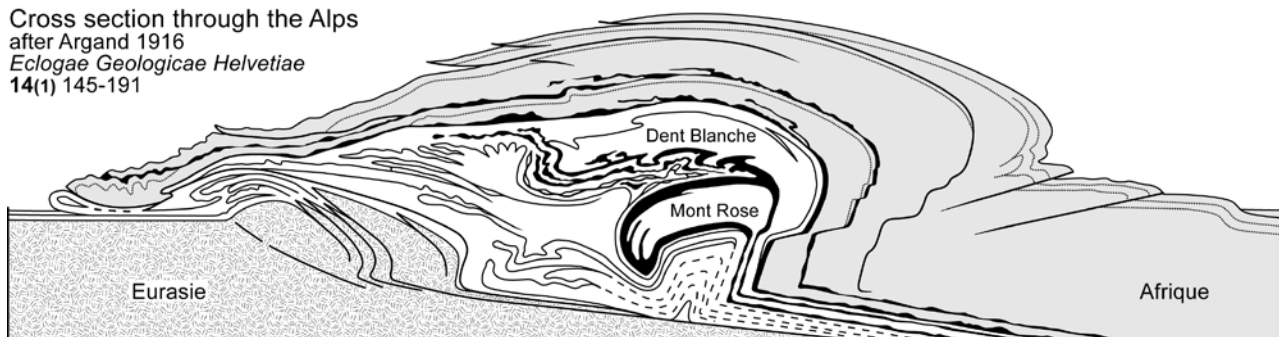
groups, which are ascribed to **generations**. From this sequence of structure generations one can anticipate the kind of large structures that portrays the study area. For example, if interference of two of fold groups produces mesoscopic dome and basin structures, then it is most probable that dome and basin structures exist on a larger scale.

The underlying principle is that each phase of deformation has left an imprint on the rocks such that small samples ultimately yield a complete record of the deformation and, in principle, provide all the information required to determine the sequence of events. This is readily substantiated by observation, although it is generally essential to look at more than one sample to determine the complete history of the area. Nevertheless, in retrospect, one is able to see details of the complete history of an area in few, well-chosen hand specimens. In strongly deformed areas, however, early fabrics may be completely obscured by later deformation.

Cross-sections

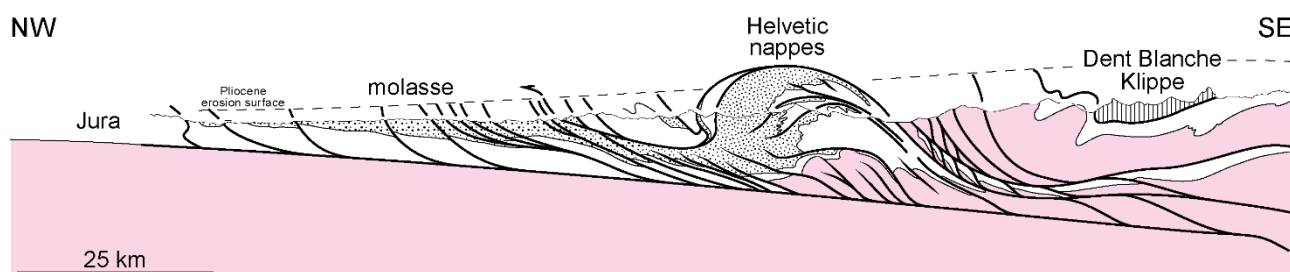
As in other disciplines, the graphical display of data is often the best guide to solve a geological problem. Maps are a two-dimensional horizontal graphic of surface features. Vertical cross-sections, preferably perpendicular to the regional trend, illustrate the structural interpretation. They show the shape, the attitude and the arrangement of rock units in a vertical plane, below and above the earth's surface. The accuracy of profile interpretation is much enhanced if subsurface information (from drill holes, mine openings, seismic profiles) is available.

Cross section through the Alps
after Argand 1916
Eclogae Geologicae Helvetiae
14(1) 145-191



Several adjacent **serial sections** combined with the corresponding map help building a **block diagram**, which pictures the three-dimensional structure of an area. Owing to perspective angles, block diagrams are excellent for illustrative purposes, but display distorted surfaces. Therefore, two-dimensional maps and profiles display a more accurate solution.

In mathematics, an important solution to problems is sought from the behaviour of a function over a limited range. **Balancing** and **restoration** are tools used by structural geologists to explore the behaviour of their sections.



Thin-skin tectonics interpretation - balanced profile through the Alps
after Boyer & Elliott 1982 *Am. Ass. Petrol. Geol. Bull.* 66(9), 1196-1230

Overprinting - Outcrop patterns of superposed folds

Overprinting criteria form the basis for dating structures relative to one another, even though the interval of time between formations of them may have been very small. Two aspects are the rule:

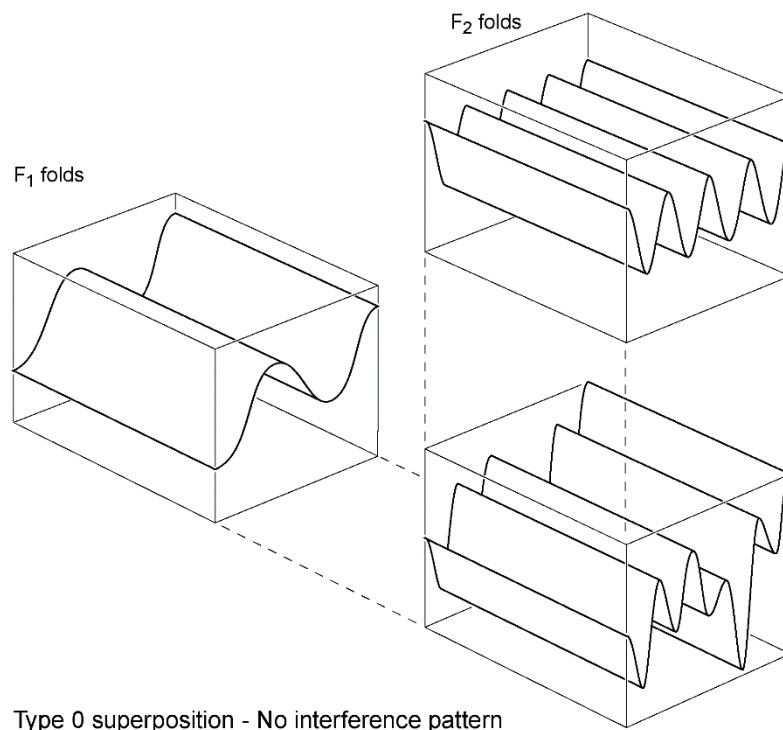
- Intersected structures are older than those that cut them (which applies in particular to veins, dykes and foliations).
- The fold that deforms the hinge or the axial surface and associated lineations of another fold is the younger.

The resulting complexity of geometry is reflected in the **interference patterns** that refolded folds form on outcrop surface. For example, F_1 folds may have changed shape during the development of F_2 folds but they must, at least, have been initiated before the F_2 folds began to develop. By the same token if both fold generations have an axial plane foliation, then S_2 will overprint S_1 .

Patterns vary according to the scale, the number, the angular relationship and the shape of the folds. When later folds are smaller than earlier folds, minor fold patterns are incongruous with the major folds. When both generations are on the same scale, the shape of interference patterns depends on the angular relationships between folds. When later folds are larger than earlier folds, the pattern of early folds is preserved but later folds determine orientations.

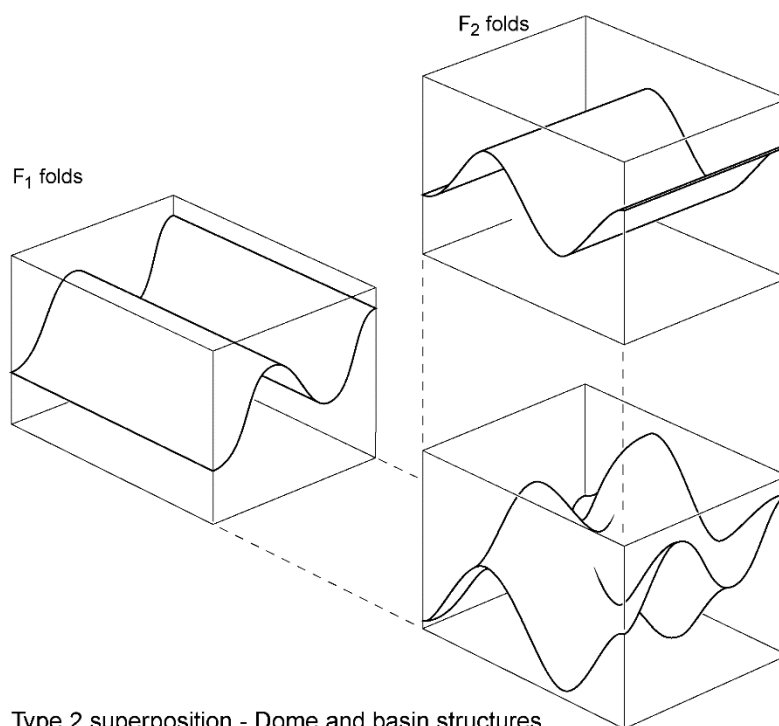
Interference patterns resulting from the intersection of two sets of folds, upright F_2 folds on F_1 folds of variable attitudes, are classified into four characteristic types that are end-members in a continuous series of interference shapes:

Type 0) no interference pattern: axial planes and axes of both fold generations are parallel,



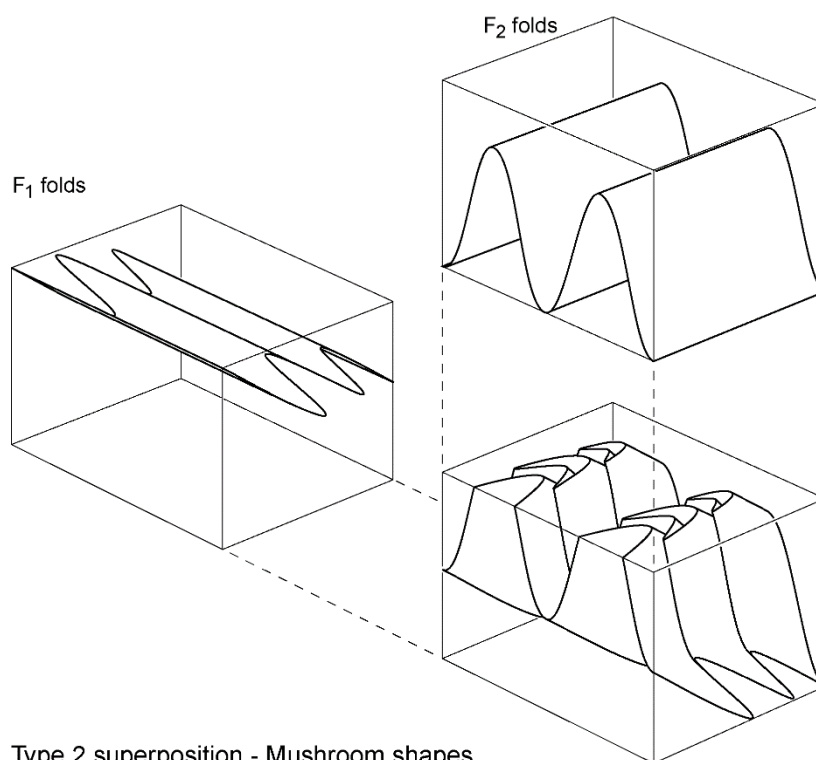
Type 0 superposition - No interference pattern

Type 1) closed **dome and basin** (egg-box) structures are oval, somewhat lozenge-shaped patterns. They arise when both the axial planes and axes of upright F_2 are nearly perpendicular to those of F_1 . Both fold generations have the same style and both axial surfaces dip steeply. Domes result where antiformal axes cross and basins form where synformal axes cross. Note that F_1 axial planes remain unfolded.



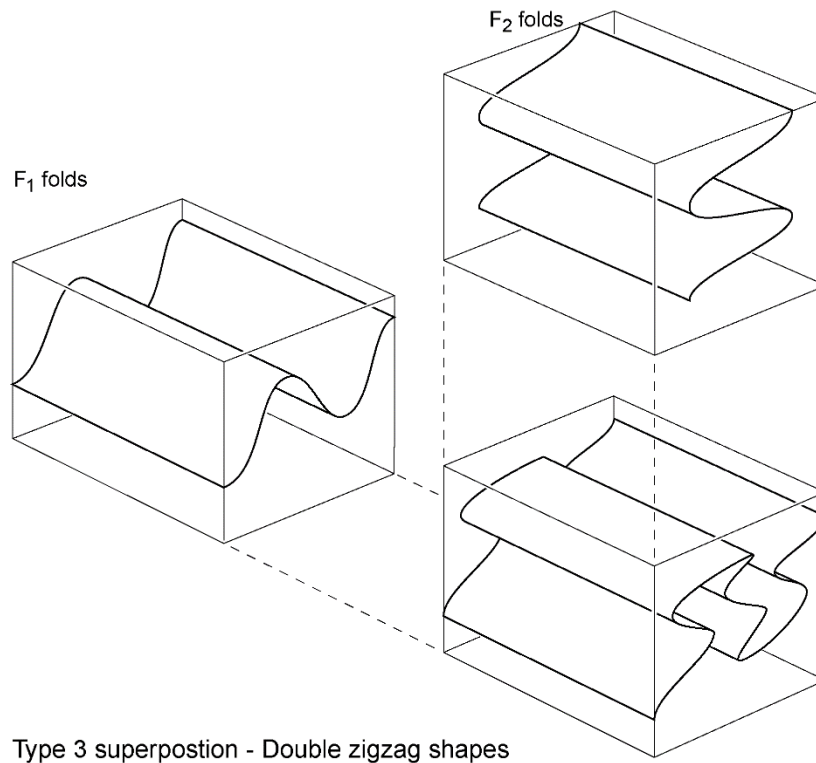
Type 2 superposition - Dome and basin structures

Type 2) **crescent** or **mushroom** (boomerang) shapes develop when the axial planes and axes of upright F_2 are at a high angle to those of earlier inclined or recumbent F_1 of any size (i.e. non-coaxial generations of folds). The tips of the crescents are F_1 closures and the F_1 fold axis runs parallel to a folded line joining the tips.



Type 2 superposition - Mushroom shapes

Type 3) **double zigzag** or **refolded** shapes are produced when the axial planes of F_2 are nearly perpendicular to those of earlier recumbent F_1 , but the F_1 and F_2 fold axes are sub-parallel (i.e. coaxial fold generations).



Structural element	Orientation → Interference type		
	Vertical		
S ₂	Vertical		
S ₁	Vertical	Horizontal	
F ₁ ⊥F ₂	Type 1	Type 2	
F ₁ //F ₂			Type 3

One must be aware, however, that overprinting of one structure by another may result in annihilation of the earlier structure and this is particularly true when one foliation overprints another. Additional factors may also be involved in the generation of some ‘eyed’ or circular fold patterns (e.g. sheath folds), which indicates that the occurrence of interference patterns, especially dome and basins, does not necessarily imply that two separate deformation phases have taken place. Fold interference may take place synchronously when the deformation is of constriction type and the layers are shortened in nearly all directions but the extension direction.

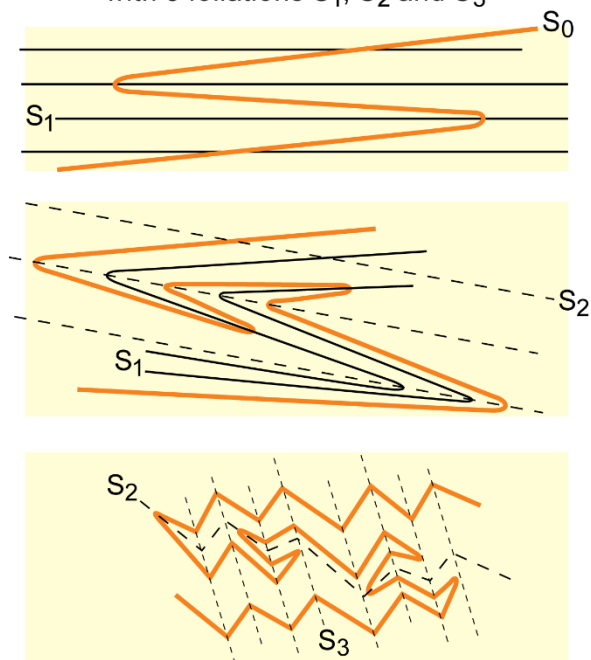
Generation

The ideal structural analysis aims at ascribing each structure to its position in both a succession of events and in the absolute time scale. Ascribing structures to a given generation with some relative dating is an attempt to achieve this end.

The proposition is that a **generation** comprises a group of folds and related structures believed to have formed at the same relative time interval. Two steps are necessary to establish a generation:

- (i) Grouping of structures uses geometrical features such as orientation and style, assuming that structures similar in orientation and style belong to the same group.
- (ii) Although structures of similar style are usually seen in isolated outcrops, they are assumed to have formed at the same time. Overprinting relationships between representatives of the different groups positions the various style groups in relative chronological order.

Example of 3 superposed fold generations with 3 foliations S_1 , S_2 and S_3



This way, overprinting criteria allow deciphering a narrative sequence of separated and successive deformation **phases** that gather as many sets of contemporaneous structures. If the grouping is valid, the structures in one group occupy the same niche in the relative time scale and occupy a different niche than all other structures. In practice, a series of numerically higher subscripts is assigned to the various structures in chronological order. Fold generations are generally labelled F_1 , F_2 , etc., foliations S_1 , S_2 , etc. and lineations L_1 , L_2 , etc. But numbering structures can lead to confusing or even erroneous interpretations. For example, the oldest foliation S_1 seen in an outcrop is not necessarily associated with the oldest folds F_1 in the studied region. The first folds may have occurred without axial planar foliation, and the locally oldest S_1 foliation may have developed during a later F_n fold generation. Therefore, it is critical to verify that the successive foliation generations of S_1 , S_2 , etc. are systematically and consistently axial planar to the successive fold generations F_1 , F_2 , etc. on a regional scale before inferring a stream of regional deformation phases D_1 , D_2 etc...

However, a consistent overprinting does not prove that the grouping is valid. Folds having the same style can belong to more than one generation. Therefore, grouping structures from style characteristics is not final, but there is no better field technique to make use of discontinuous outcrop and the method has been successful in many geological environments.

In addition, two generations of folds may have formed

- (i) during a single, progressive or protracted deformation event with changing orientations of the strain (stress) axes or
- (ii) may have formed during two periods of deformation separated by hundreds of millions of years or
- (iii) in the course of a single, continuous orogeny where separate deformation events, whose durations are also unknown, were superimposed with different orientations of strain axes.

These possibilities cannot be distinguished without neat unconformity between structure generations, clearly different mineral assemblages formed during deformation and/or absolute dating.

Furthermore, an identical sequence of structure generations in every individual outcrops may indicate that there is regional **diachronism**, the same structural sequence progressing geographically (likely forelandward) through time. Besides, irregular distribution of strain (**strain partitioning**) may flaw uncritical correlation.

Limitations of structural analysis

The interpretation of multiply deformed areas, in practice, commonly rests very heavily on the assumption that the members of a style group all belong in the same niche in the deformational sequence of events. Unfortunately it can be shown that this is not always true.

In some areas outcrop is sufficiently continuous to allow the overprinting relationships of all or most of the folds to be determined. In such areas the folds can thus be ascribed to generations, without recourse to style, so that style variation within a generation can then be studied. In some areas where this has been done it has been found that there is no simple one-to-one correlation between style groups and generations. Thus style is unsatisfactory as a means of grouping structures. Unfortunately, except in areas of unusually good outcrop there is no better basis; overprinting relationships are generally too few and far between and orientation can be completely unreliable.

Another limitation of structural analysis is that it does not always provide a means of interpreting the macroscopic structure of areas in which the layering has undergone transposition.

Major phases of deformation are sometimes associated with a group of small-scale structures, some of which may be deformed by structures which develop slightly later, but which are related to the same deformation phase. If such groups of structures can be recognised in the field, the major phases of tectonism that have affected an area can be discussed without recourse to the listing of countless minor deformation episodes that characterise and confuse many structural descriptions of areas of multiple deformation. Each group of structure can be considered separately and a detailed picture of the major deformation phases deduced. In addition, the relative importance of each major phase can be determined by using criteria such as regional extent and intensity of the deformation.

Superposed faulting

The precise mechanics of fault reactivation are still unconstrained in details. Fault reactivation occurs in a wide range of tectonic settings. There are two possibilities:

- The fault keeps its relative sense of movement throughout the geological history.
- The relative sense of movement is changed.

Normal faults inherited from an early phase of crustal extension can be reactivated in compression during **positive basin inversion**.

Summary

Exposures display the end results of a succession of events: deposition, deformation, erosion, and so forth. With experience, observant field geologists learn to recognize critical exposures with relationships between rock units or other significant features that provide unmistakable clues to sedimentary, igneous, and metamorphic processes. Geologists deduce the deformational history of a region by identifying and fixing the ages of the rock layers, recording the geometric orientation of the beds on maps, mapping folds and faults, determining the geometry of major structures from smaller scale structures, ascertaining their spatial and temporal relationships, and reconstructing cross sections of the subsurface consistent with the surface observations. The superposition of small-scale structures can occur either by the sequential development of structures with progressive deformation during a single major phase of deformation, or as the result of two or more widely separate tectonic events. Geologists can ascertain the relative age of a deformation by finding a younger undeformed formation lying unconformably on an older deformed bed. The ability to read exposures, a skill that is critical to field observations, provides an opportunity for developing working hypotheses to be tested by closer field examination and enables geologists to plan subsequent field and laboratory work effectively. Those hypotheses may then be developed into computer-based theoretical models, but to carry conviction they must be testable and compatible with field evidence, or ground truth, as the remote-sensing specialists call it.

In orogenic zones, that is to say regions where mountains have been built, rocks have typically been deformed by several 'phases' of deformation, which means that sets of geometrically superimposed structures are attributed to a succession of distinct episodes of regional deformation. To know these phases, actual sets of associated folds, foliations and lineations or any other structure are assigned to

as many deformation episodes, but the time intervals between successive events may range from infinitesimally short (geologically) to several hundred millions of years. Therefore, the time delays between structural (i.e. geometric) phases, and strain rates, are crucial parameters in the study of rock deformation.

Recommended literature

All books with structural geology in their title, and more