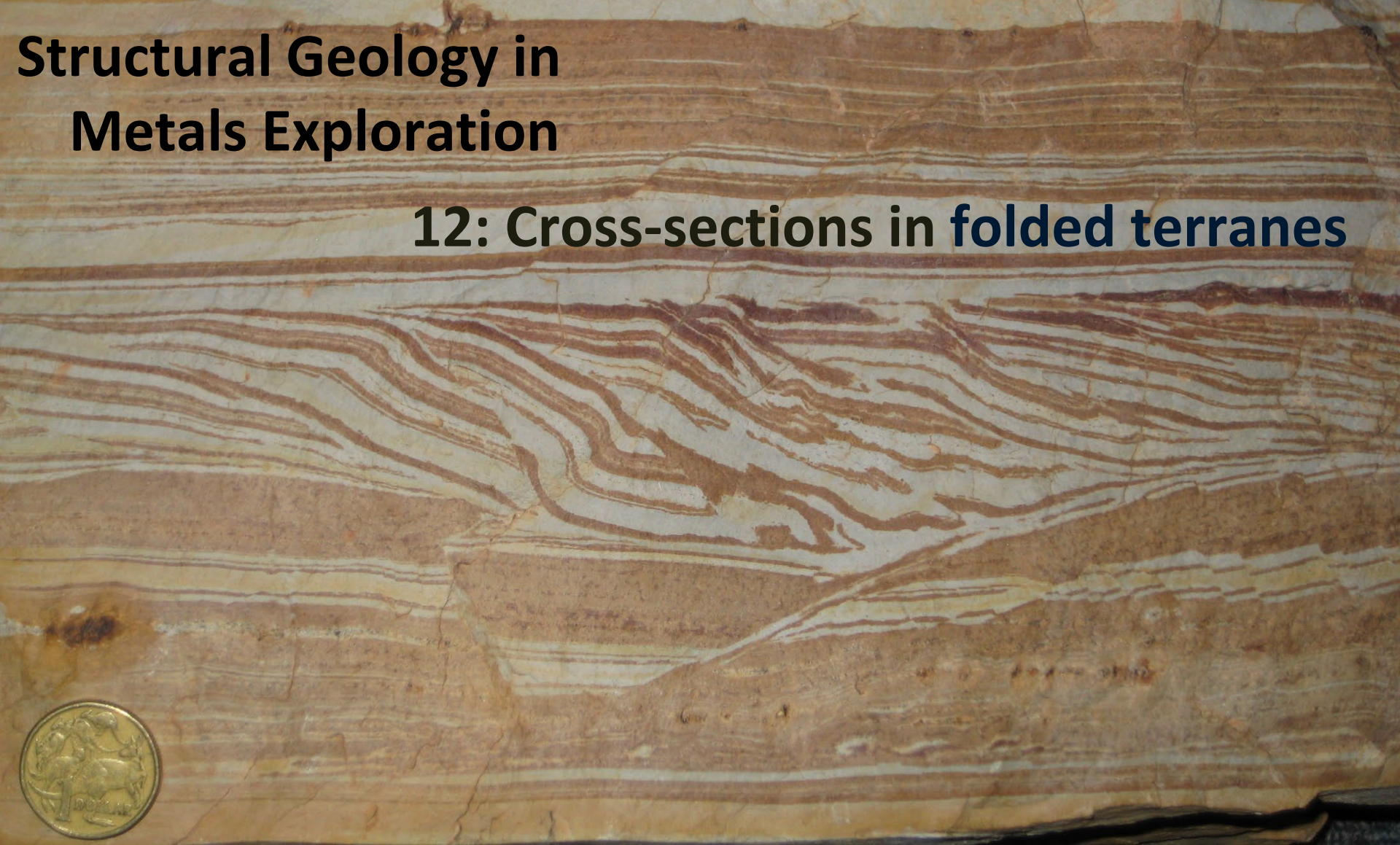


Structural Geology in Metals Exploration

12: Cross-sections in folded terranes



RodHolcombe

rod@holcombe.net.au

Table of Contents

12: Sections in folded terranes

What is in this module?

Fold profiles

Fold map patterns

3D fold and fabric data on maps

Choice of section line

Down-plunge-viewing

Choosing the section line

Sections in reclined folds

Apparent dip

Elementary cross-sections

Assumptions in the elementary method

Fold shape assumption

Fold projection technique

Producing a projection section

Limitations of projection method

Sections across horizontal folds...

Kink method

Tangent-arc (Buskian) method...

Parallel fold problems

Controlled Freehand section construction...

Vertical Exaggeration

Fault extent in section

Igneous bodies in section

Drill sections

Case history: getting the section wrong

Quick and dirty analysis

Drilling implications

Constructing drill sections

Example of projecting drillhole data

Off-section projection

Completed section

3D analysis of oriented core data

3D Form surfaces

Construction of 3D form surfaces...

3D Form surface examples



What is in this module?

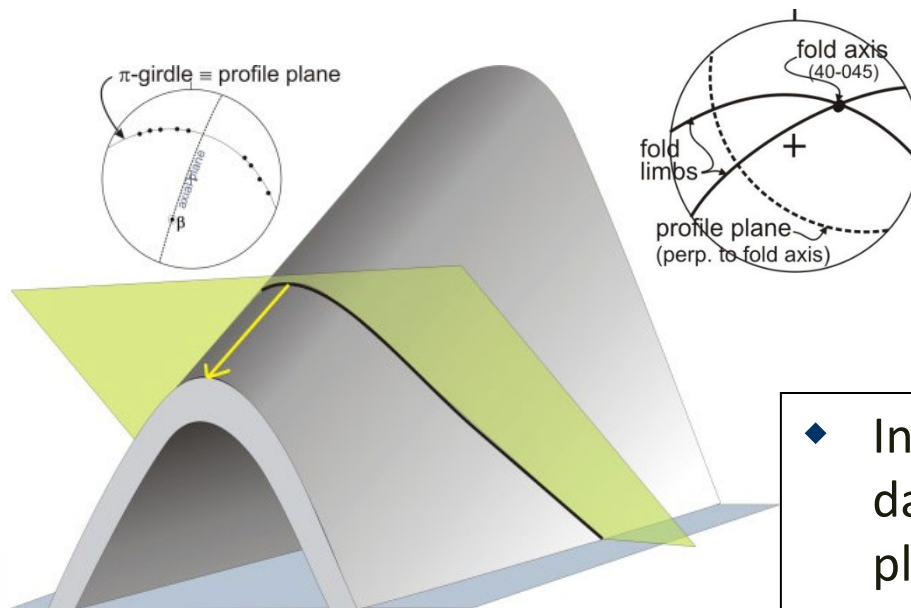
This module covers aspects of constructing 2D and 3D sections in folded terranes. It includes:

1. Choice of section orientation in folded terranes
2. Basic 2-D section techniques depending on the fold style
3. Drill sections, including how to deal with off-section core data
4. Construction of 3D form surfaces



Fold profiles

- ◆ The only true shape of a fold is the fold profile
 - The plane perpendicular to the hinge
 - All other 2D surfaces, such as maps and sections, show distorted views of the fold

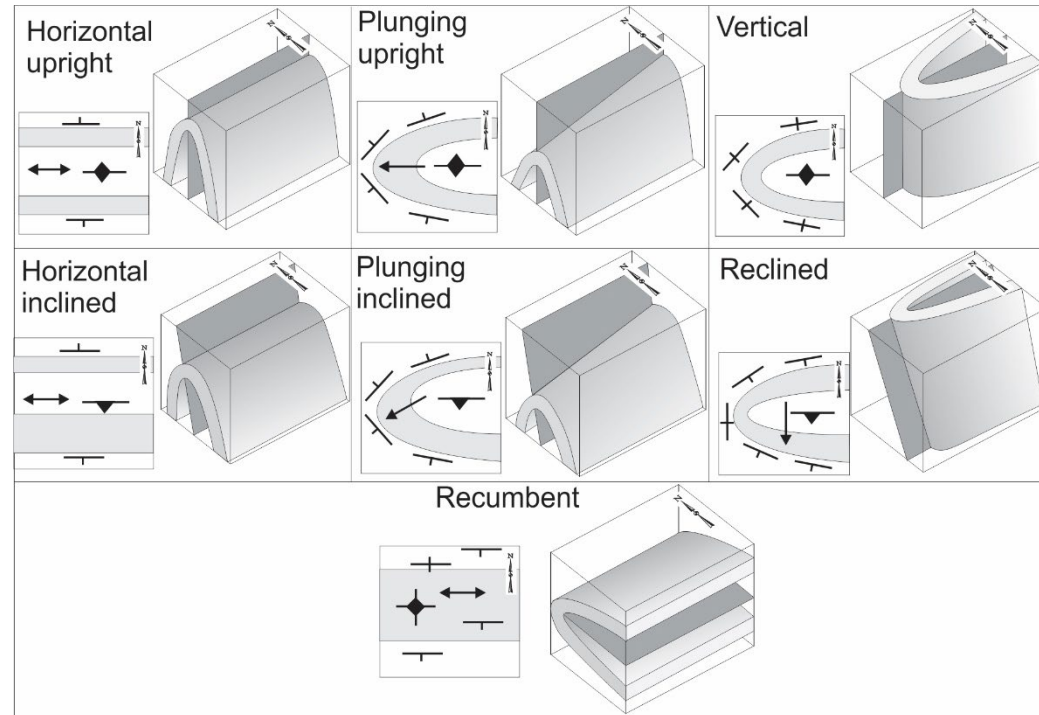


- ◆ In order to successfully convert **any** 2D data in one plane (map) into another plane (section) the 3D orientation of the fold needs to be known



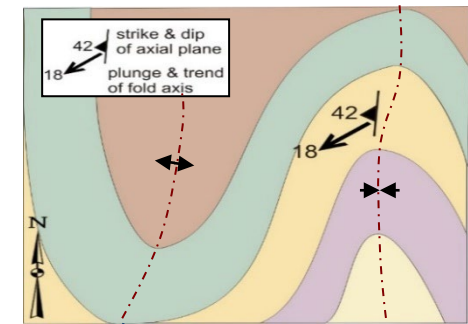
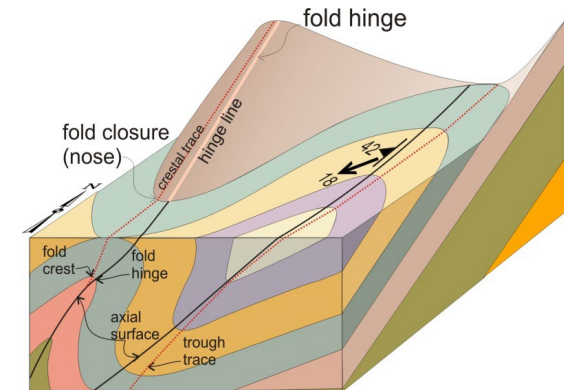
Fold map patterns

- ◆ If the folds are vertical, then the fold profile will only be seen in the horizontal map pattern
- ◆ Vertical sections will only show a profile view horizontal folds
 - And only then if the section plane is perpendicular to the fold hinge
- ◆ For all other fold orientations the shape of the fold seen in both map view and vertical sections will be distorted
- ◆ Note that fold axes are only parallel to the strike of the axial plane in horizontal folds. **This has a major impact on section construction.**



3D fold and fabric data on maps

- ◆ Folds are represented on maps by symbols showing the orientation of the axial plane and fold axis
 - Show fold axes by their true trend
 - Avoid axial plane/axis symbols like this as they disguise the non-parallelism of fold axes and axial planes
 - Use the type of combined symbol shown on the map here, where the arrow shows the true trend of the fold axis
- ◆ Folds on maps are also shown by 'axial traces'
 - generally a line connecting successive fold noses on the map
 - But remember these are really crestral traces, not axial plane traces
 - Not important until requiring precision, such as siting drillholes

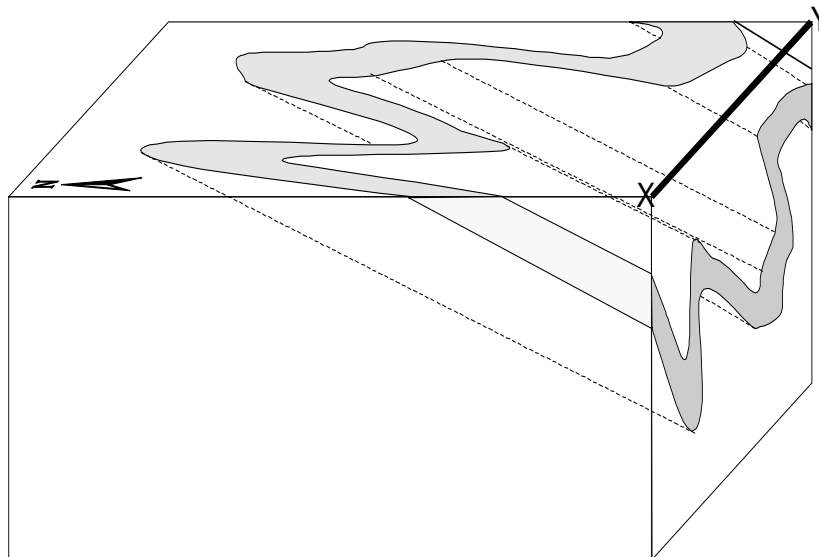


crestal trace



Choice of section line

- ◆ Ideally the best section line is one that is closest in orientation to the profile plane
 - Not always possible in exploration as other factors may dictate the plane of section
- ◆ As profile planes are perpendicular to fold hinges, the best choice of vertical section will in general be the one perpendicular to the fold axes

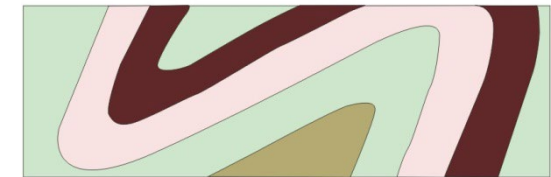
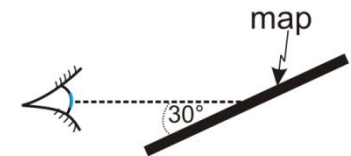
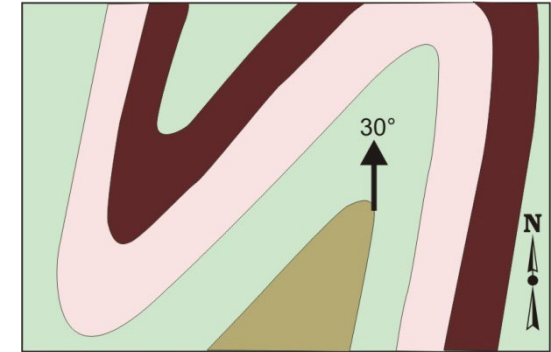


- Fold axes are data projection lines in cylindrical folds
 - and the only direction that can be used to transfer data from one 2D plane to another



Down-plunge-viewing

- ◆ A good trick in maps, and even in outcrop, is to position your eye so that you are looking directly at the 2D plane parallel to the fold axes
- ◆ What you see is a distorted view of the map – but that view is actually the profile of the fold

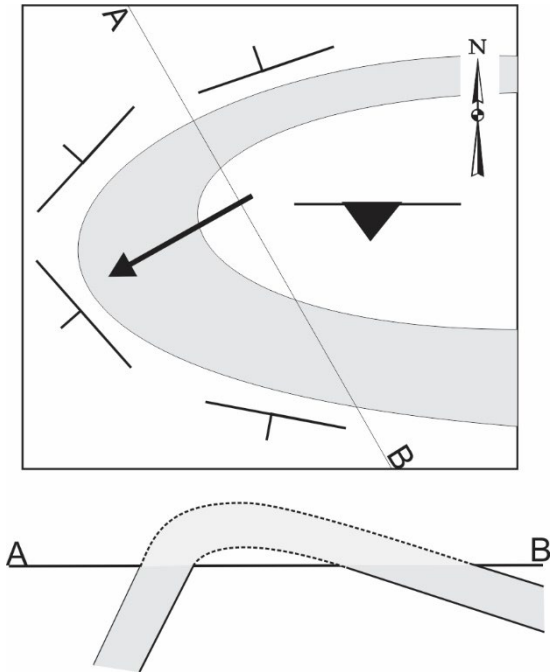


- ◆ It is the same technique used to write instructions on roads for motorists
 - The words look normal size when viewed at low angle



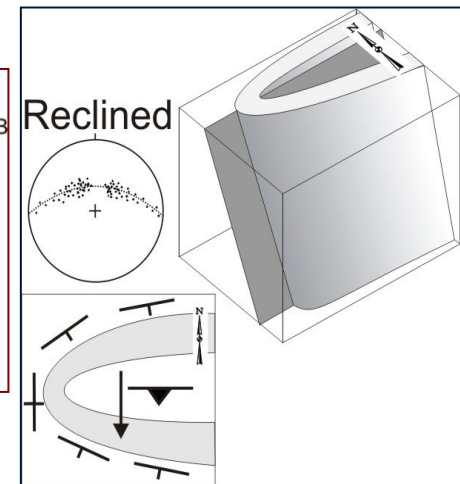
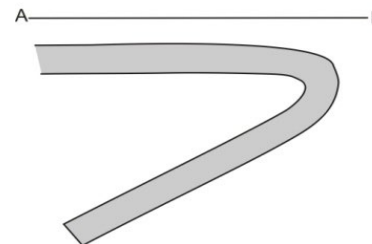
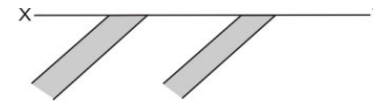
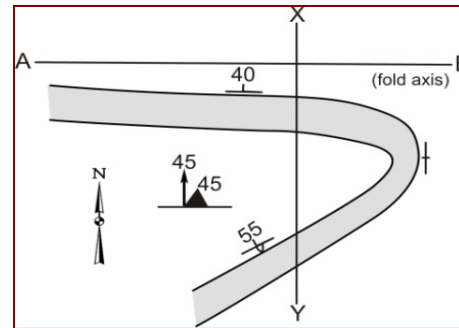
Choosing the section line

- ◆ Check that you have statistically cylindrical folds
- ◆ Choose a section line perpendicular to fold hinge
- ◆ It doesn't matter where the section line is, so choose one that is convenient
 - The shape of the fold will be the same in all sections constructed by projection
 - The only difference will be where the section cuts the ground surface
 - Hence it is common in projected sections to show the entire structure beneath and above the ground surface in the section line



Sections in reclined folds

- ◆ Reclined folds are in an orientation that can create some angst in visualisation and section drawing
- ◆ Consider section lines AB and XY:
 - XY is perpendicular to the trace of the axial plane
 - and shows no fold structure at all!!
 - AB is perpendicular to the fold hinge and at least shows the folded shape
 - albeit distorted



Apparent dip

◆ Calculate apparent dips from:

1. Formula

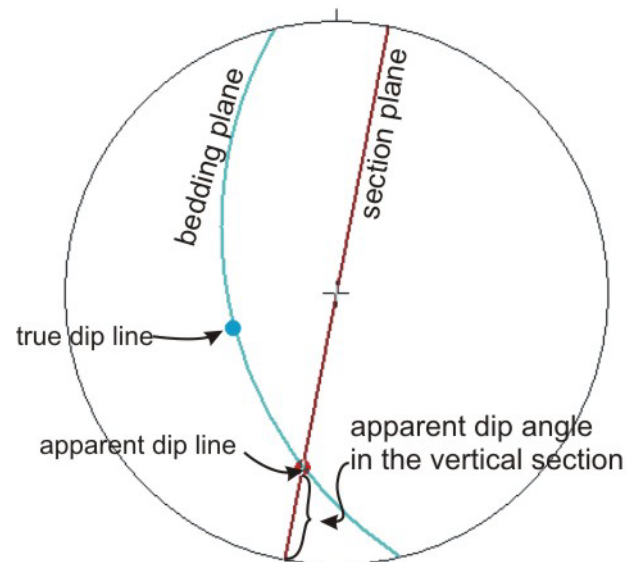
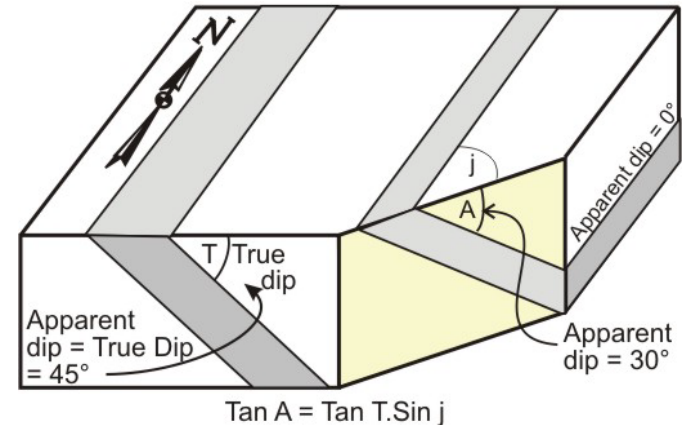
$$\tan (A) = \tan (T) \times \sin(j)$$

2. Stereographic projection

3. Structural calculator application

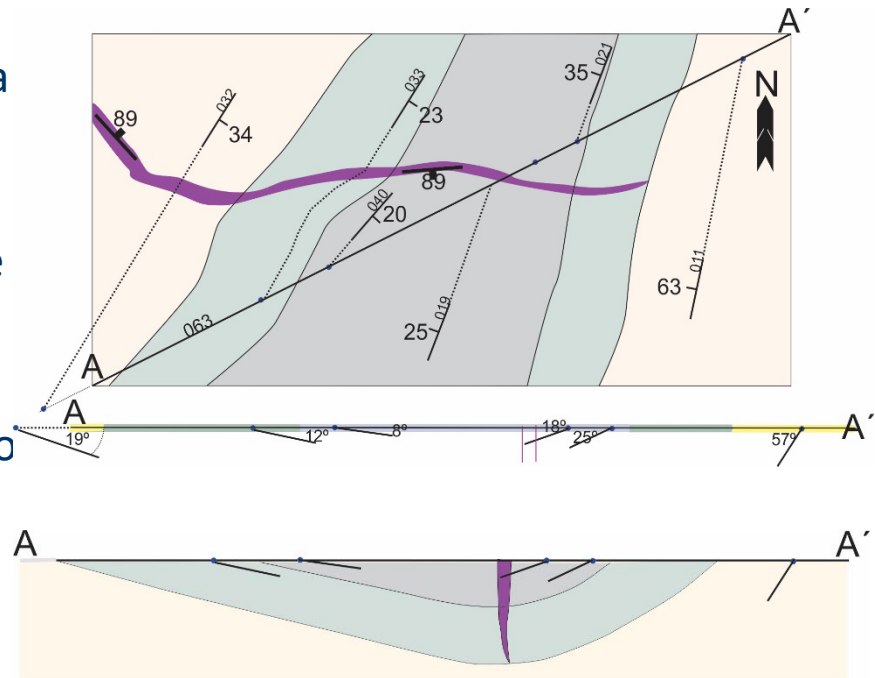
- E.g. GeoCalculator

<https://www.holcombe.net.au/software/geocalculator.html>



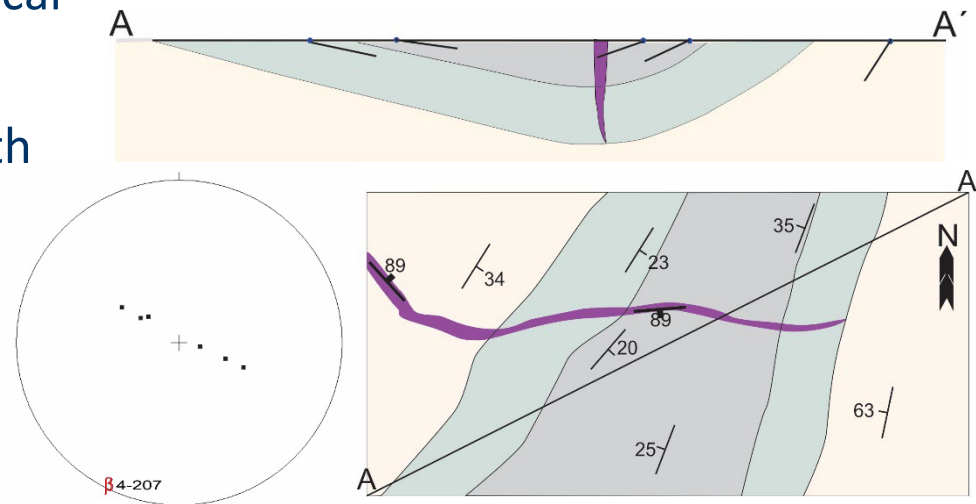
Elementary cross-sections

- ◆ In elementary geology classes you may have been taught to construct cross-sections by:
 - Drawing a section line on a map and marking in the intercepts of each map boundary
 - Locate nearby strike and dip data by subtending on to the section line parallel to the strike
 - Calculate the apparent dip of the data and draw it in
 - Construct the final section by projecting the contacts parallel to the local apparent dip lines



Assumptions in the elementary method

- ◆ The assumptions built in to the elementary technique are not generally spelled out in those classes
- ◆ They are:
 1. The folds must be cylindrical
 2. Horizontal fold axes
 3. Very harmonic folding with no minor folds
- Assumptions that are rarely met in total
 - The fold shape also has to be assumed

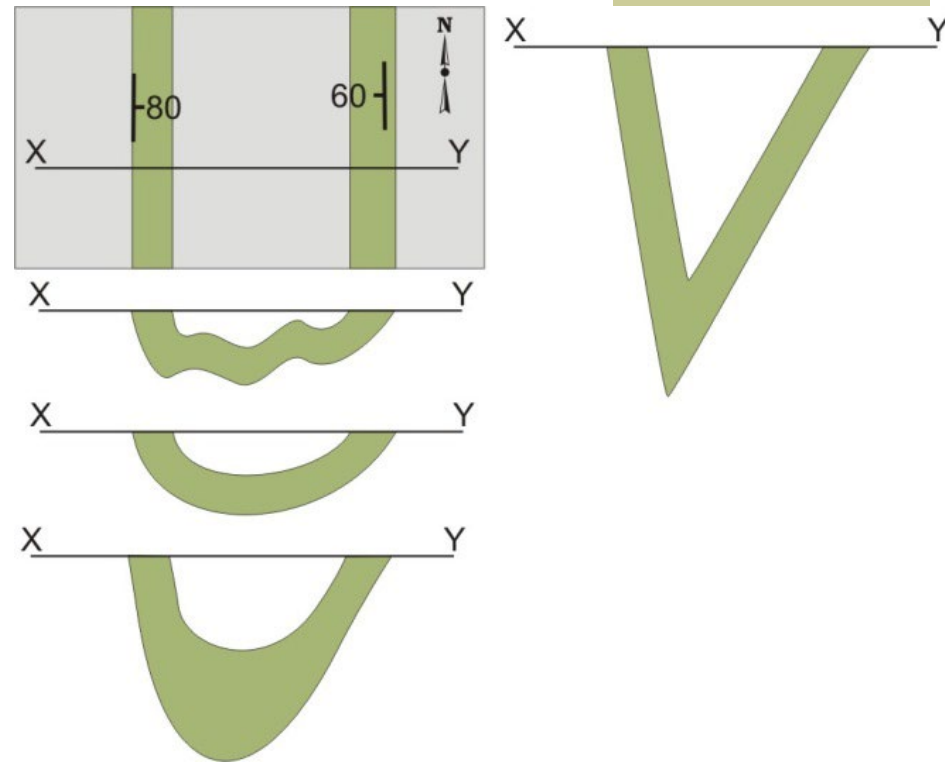


Here the folds are cylindrical and close enough to horizontal for the method to be OK



Fold shape assumption

- ◆ In freeform section construction the depth of the structure in the section is dependent on the assumed shape of the folds
- ◆ All of the assumed fold shapes in the four sections validly fit the map



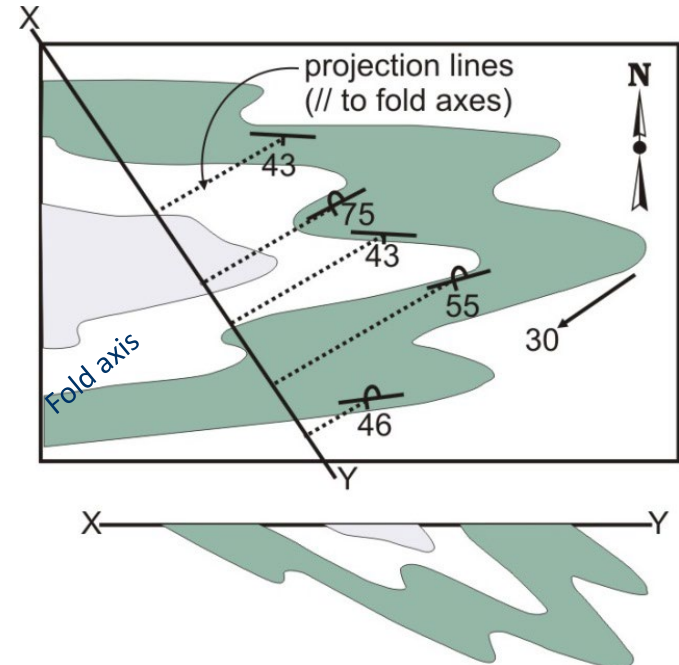
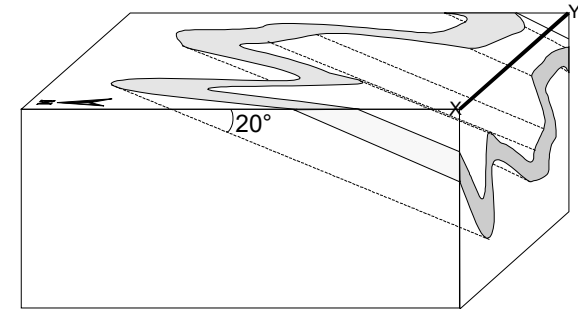
All of these sections are **viable**
Which shape to use depends on your knowledge
of the most likely style of folds in the area



Fold projection technique

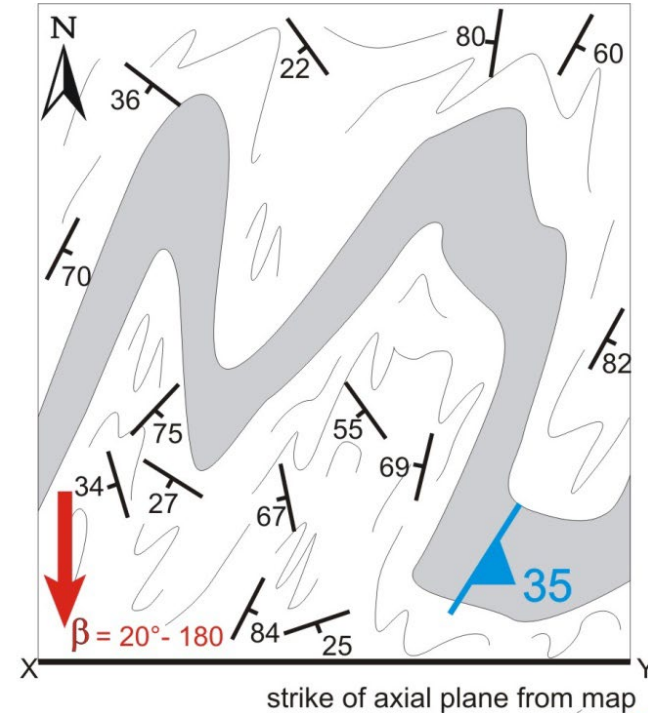
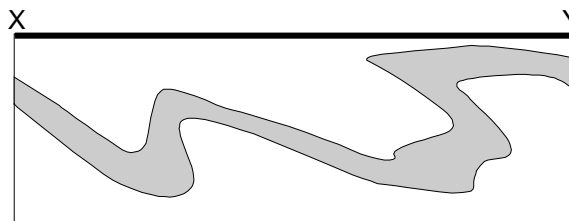
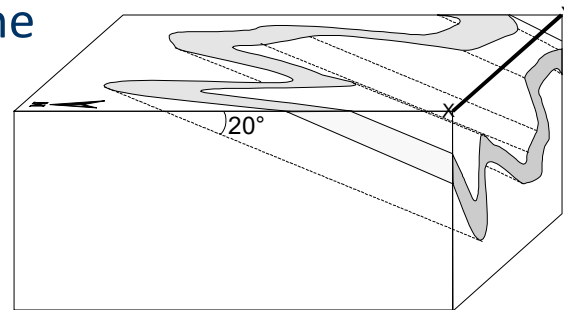
- ◆ No assumption is required about the fold shape
 - except that the folds are cylindrical
- ◆ Any section line can be used
 - even those not perpendicular to the fold plunge
- ◆ All of the bedding data is used, not just those near the section line

But this technique can only be used with plunging folds



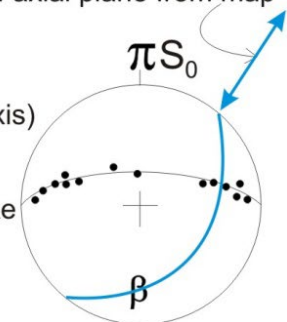
Producing a projection section

1. Plot map data on stereo and determine:
 - a) Whether the folds are statistically cylindrical
 - b) The fold axis from the beta axis on the plot
2. Select section line perpendicular to fold axis trend
3. Project every contact on the map on to the section plane



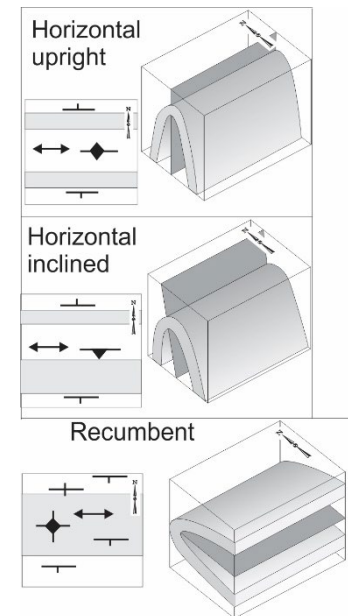
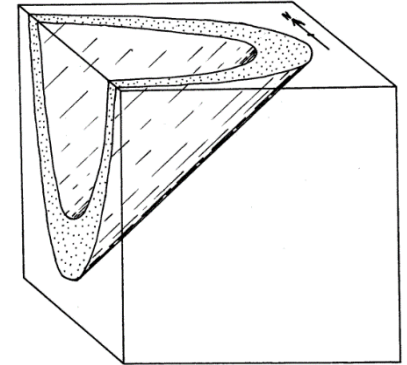
Calculated fold axis = $20^\circ - 180$
(stereographic projection beta axis)

Calculated axial plane: $35 - 120$
(great circle containing map strike
of axial plane and beta axis)



Limitations of projection method

- ◆ When folds plunge steeper than 45° the map is more representative of the profile shape of the fold than any section
 - An inclined profile section should be considered
- ◆ When folds are horizontal and the map surface is flat then there is no map definition of a hinge from which to project
 - But if there is strong topography then the method may still work



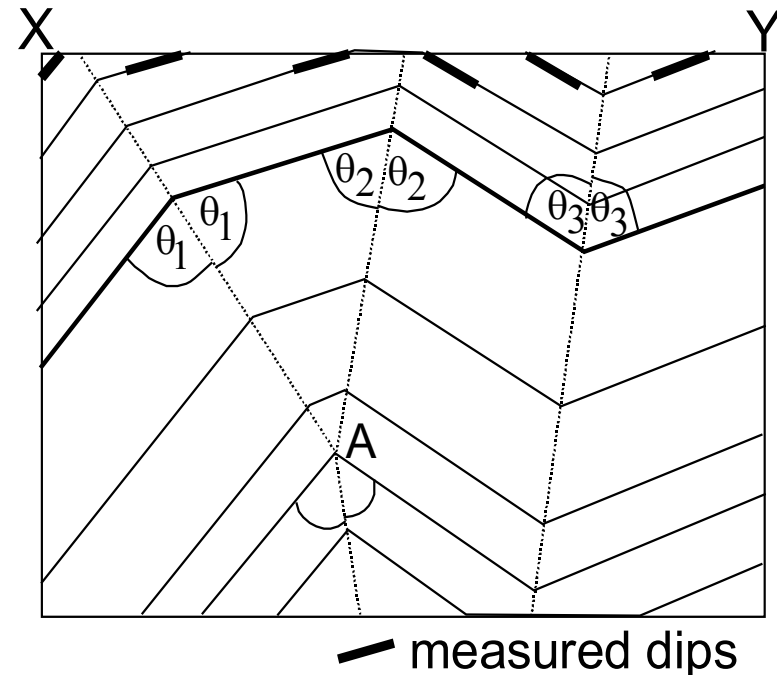
Sections across horizontal folds...

- ◆ There are a variety of techniques to draw sections across horizontal folds
- ◆ Each is valid for its own set of assumptions
 1. Kink method
 - commonly used in fold-thrust belts
 2. Tangent-arc method (also called Buskian method)
 - Useful in low-grade or unmetamorphosed terranes where the folds are parallel, not overturned, and not angular
 3. Controlled freehand construction
 - Useful where the folds may be overturned



Kink method

- ◆ Kink Method:
 - Assumptions
 - horizontal folds; section in profile plane
 - Symmetrical reverse kink folds with domains of constant dip
 - Sufficient dips in each limb domain to not miss a fold
 - The assumptions are commonly met in thrust terranes with fault-bend folds
 - Not applicable to most ductile fold belt terranes



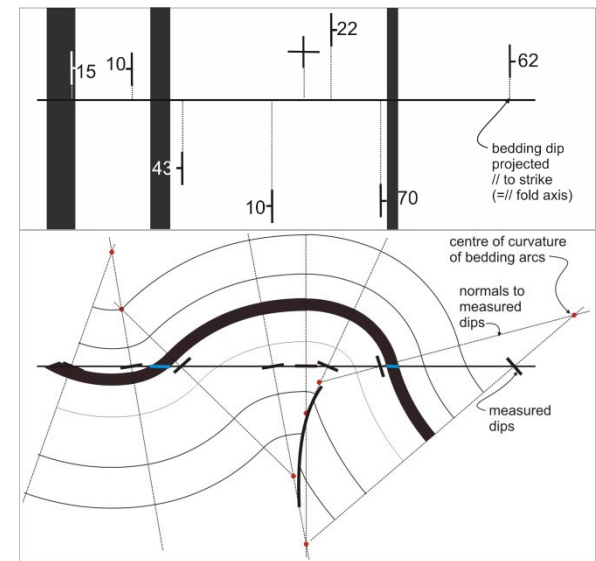
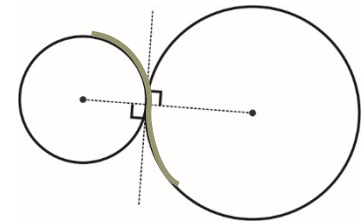
Tangent-arc (Buskian) method...

◆ Assumptions:

- Horizontal folds, section in profile plane
- Parallel concentric folds
 - That is, continuously curved
- Relatively uniform spread of dip data
 - Must define every fold closure

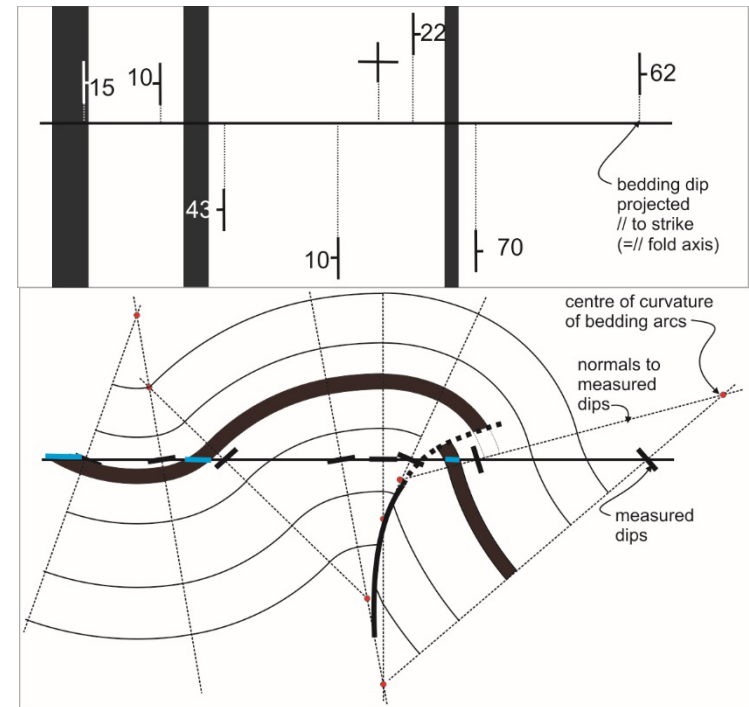
◆ Method:

- Find centres of curvature of each arc segment
- Trace any outcrop contact across the section by joining successive arcs



Tangent-arc method

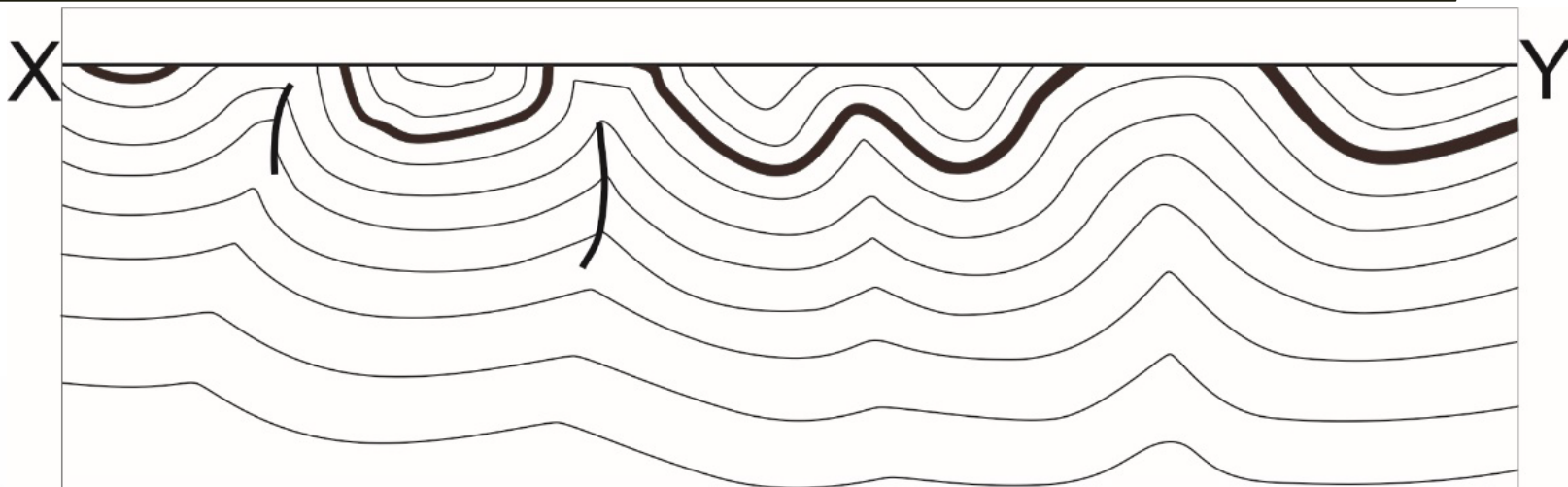
- ◆ Works reasonably well in many non-metamorphic terranes where parallel folds are most common
- ◆ Can be precise enough to pick-up small accommodation faults by mismatches across the section



Parallel fold problems

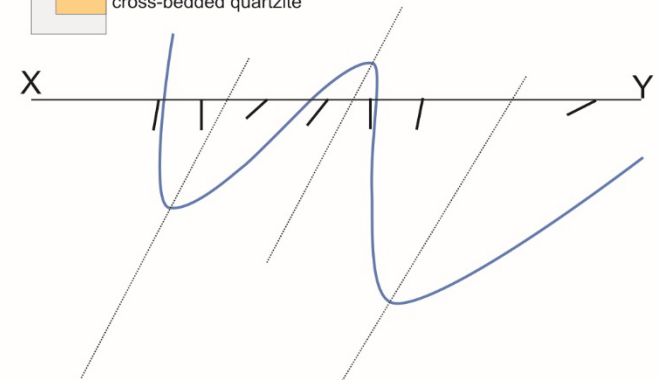
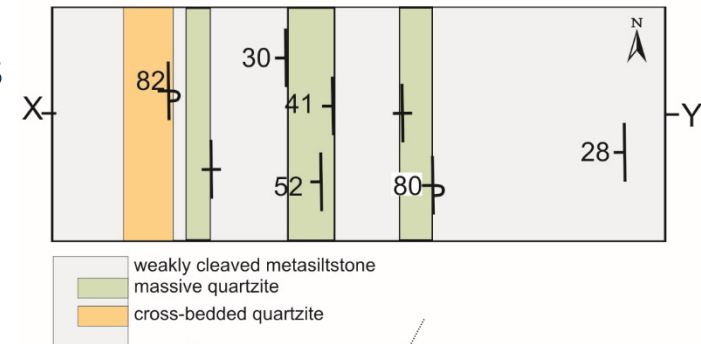
- ◆ Methods that assume parallel folds have two related problems:
- ◆ Parallel folds tighten toward their core, such that eventually the model breaks down and some sort of accommodation structure has to be assumed
- ◆ There is a tendency for such sections to flatten out at depth because the accommodation structures chosen tend to be minimal

Note that many computer-generated sections use this method



Controlled Freehand section construction...

- ◆ Most common method in folded terranes
- ◆ The only assumption that has to be made is the shape of the fold
- ◆ Method:
 - Identify the location of fold closures from the dip data
 - Determine the dip of the axial planes from the dip data or from axial plane field observation or from cleavage
 - Construct the axial plane traces on the section and use these to control the drawing of the structure

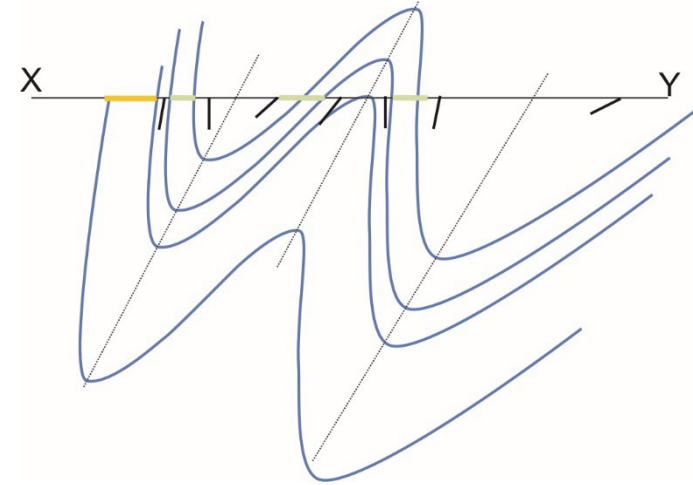


This initial folded trace controls the rest of the section...



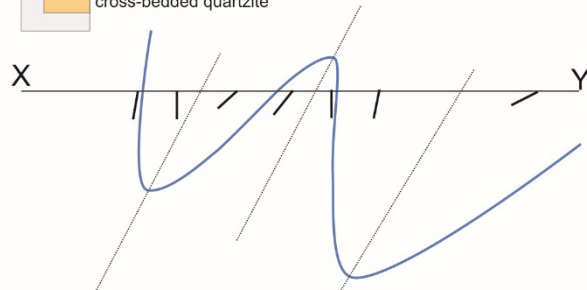
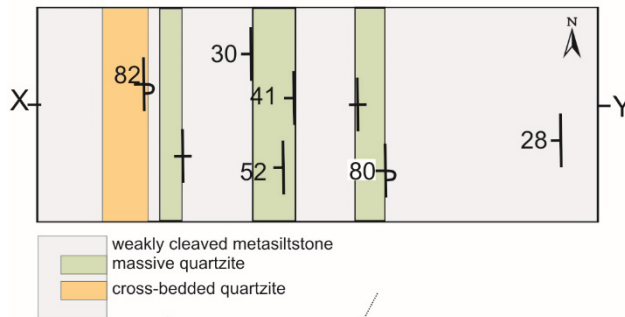
Controlled Freehand section construction

- ◆ It is tempting to complete the section using a similar fold style
 - The only fold shape that can be stacked infinitely
 - Produce sections that go much deeper than expected
 - Truly similar folds are very rare
- ◆ But alternating Class 1b or 1c alternating with Class 3 can also be stacked infinitely
 - And this we do see all the time...



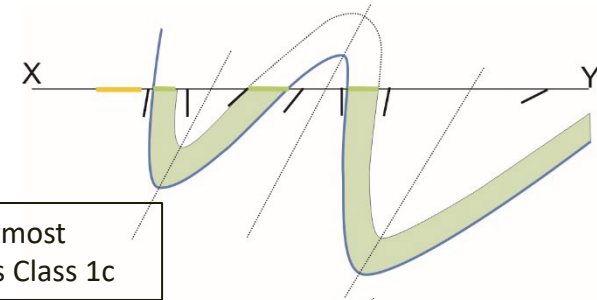
Controlled Freehand section construction

- ◆ Assuming Class 1c for competent units alternating with Class 3
 - But it is still very dependent on the initial surface shape

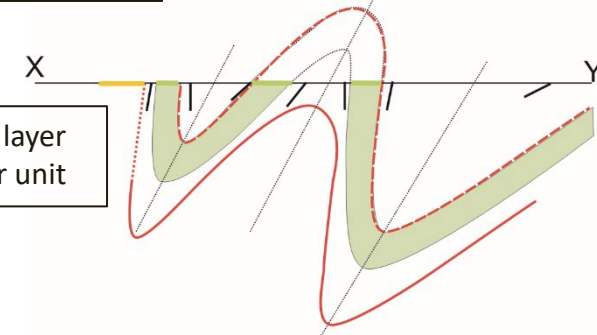


1. Construct initial fold shape in one surface

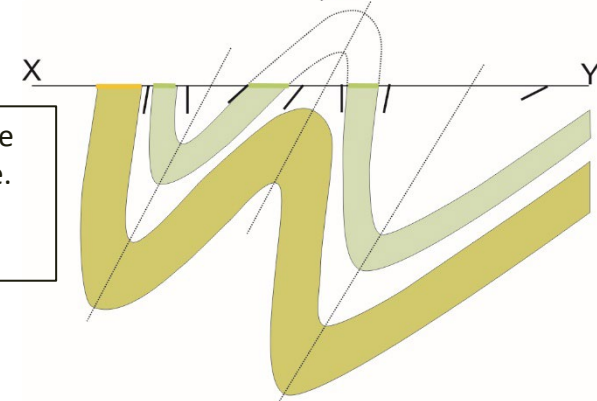
2. Complete uppermost competent layer as Class 1c



3. Copy top of 1st layer to top of lower unit

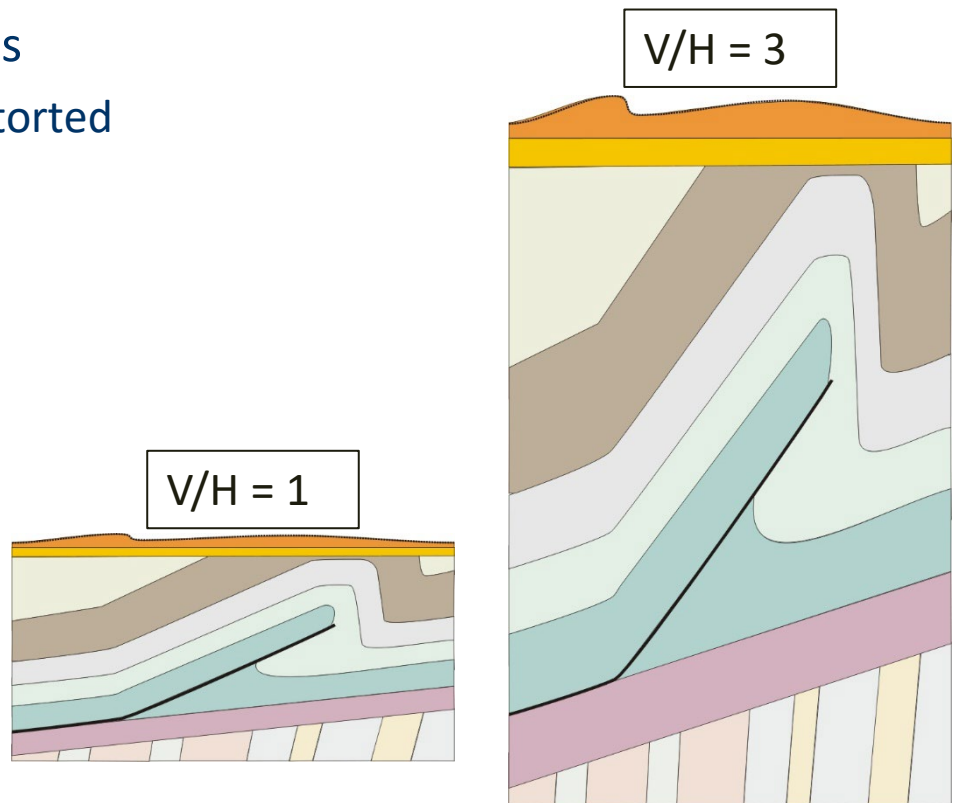


4. Copy base of 1st layer to base of lower unit as an initial guide. Complete layer. ... repeat as necessary



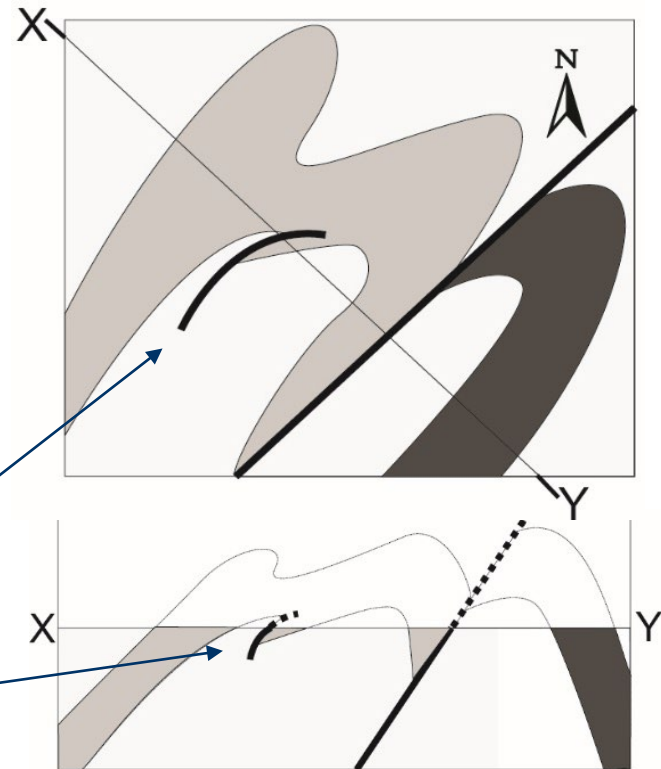
Vertical Exaggeration

- ◆ Avoid vertical exaggeration in folded rocks where possible
 - Additional problems to sections in horizontal strata
- ◆ Dips are steepened
- ◆ Apparent shape change in folds
 - e.g. parallel folds become distorted



Fault extent in section

- ◆ Use the map signature of faults to control how they are shown in section
- ◆ Large faults are shown to full depth in the section
- ◆ Local accommodation faults should only be shown in section to the same extent (depth) that they have in a map



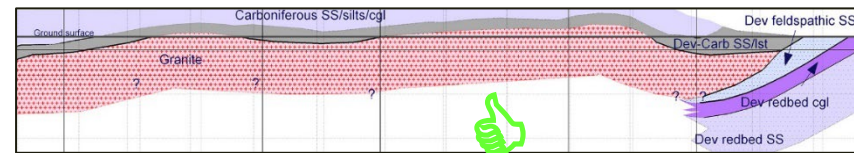
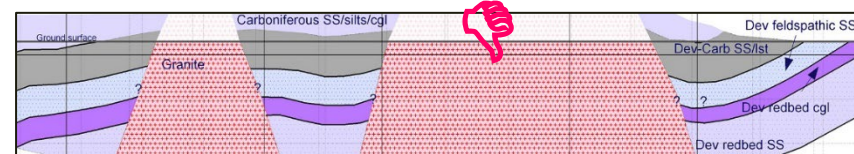
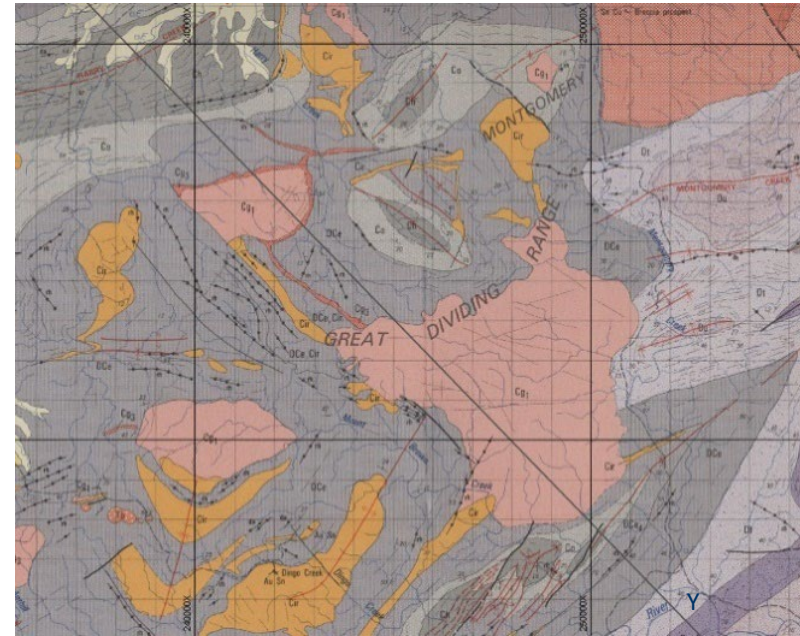
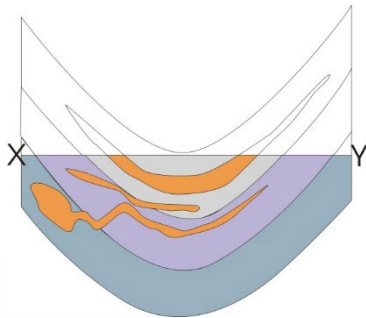
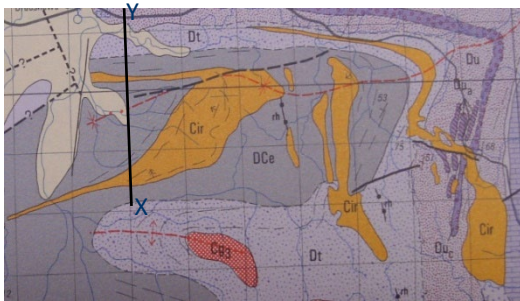
This small fault only cuts one boundary on the map

So show it the same way in the section



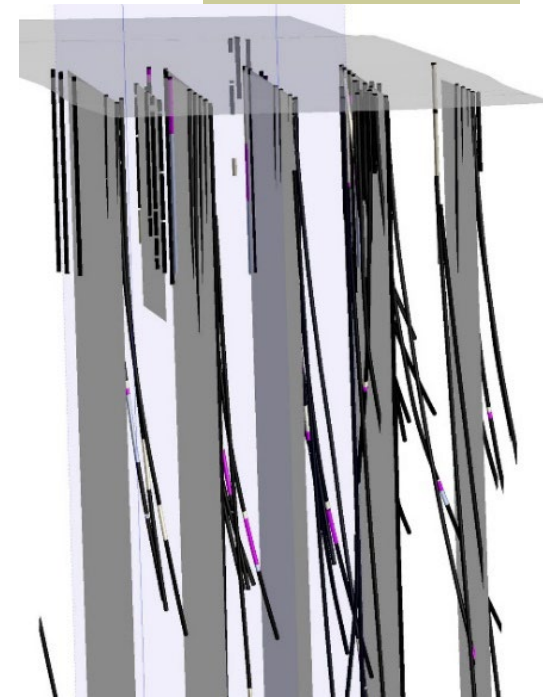
Igneous bodies in section

- ◆ If igneous contacts show strong parallelism with local bedding then show these parts of the contact as sill-like
 - unless there is evidence otherwise



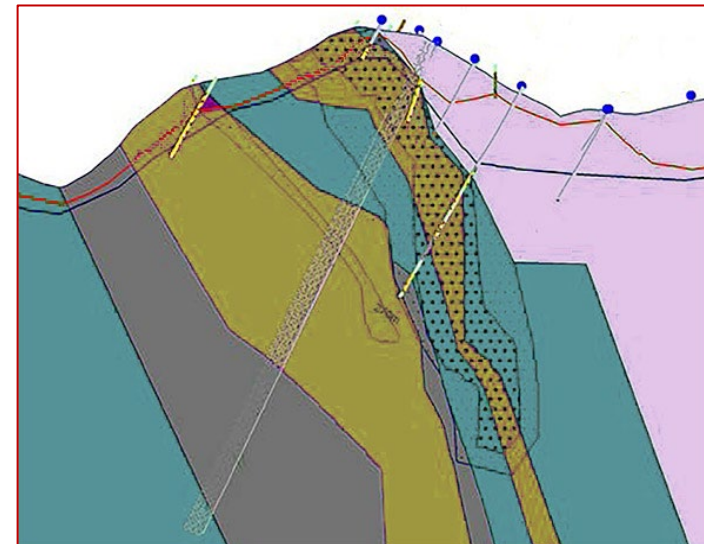
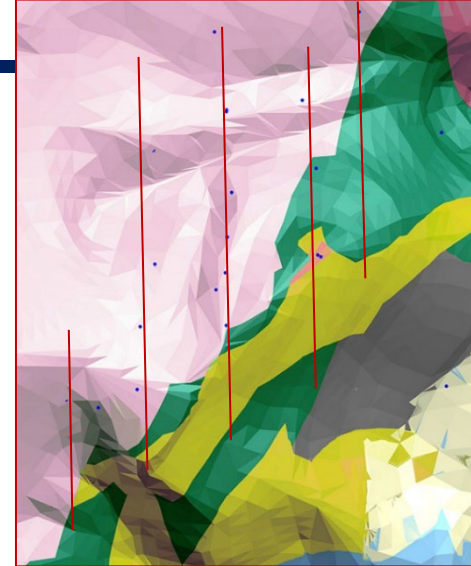
Drill sections

- ◆ Drill sections are simply vertical cross-sections
- ◆ So the selection of an appropriate section line is driven by the same considerations
- ◆ Unless constrained by other factors, design the section perpendicular to the fold hinge
- ◆ Do NOT choose a section that is perpendicular to the axial plane **unless the folds are horizontal**



Case history: getting the section wrong

- ◆ Au prospect, mountainous terrain in Laos
 - N-S drilling sections perpendicular to strike of cleavage and to most common strike of bedding
 - Au in multiple felsic volcanic units (yellow) intercalated with black slate
 - i.e. appears to be multiple potential orebody hosts
- ◆ Problem:
 - Number of felsic units varied between drill sections
 - Could not correlate at all between drill sections
 - Therefore could not estimate a resource

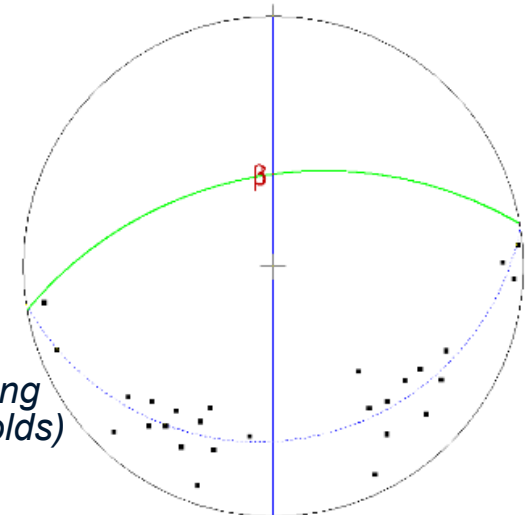


The half-day solution

- ◆ Quick look at drillcore:
 - Units of well-bedded slaty turbidite with abundant younging
 - Younging reverses – therefore folded
- ◆ So what are the fold axes?
 - Measure bedding and plot on stereo
- ◆ Uh Oh! Looks like we have reclined folds
- ◆ Even worse – the fold axes are parallel to the drill sections!
- ◆ Even worse – the folds plunge moderately steeply!

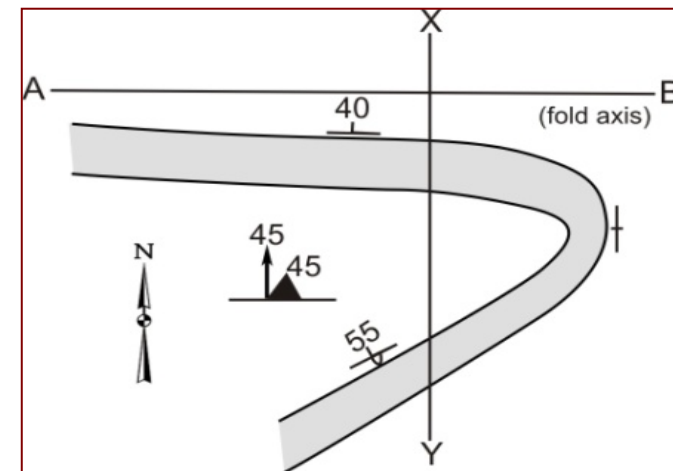
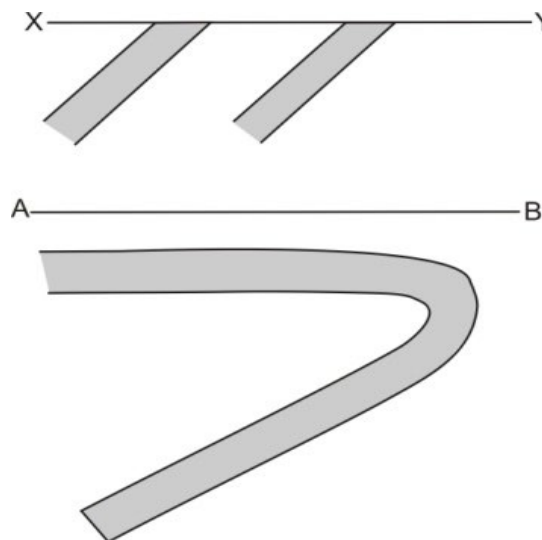
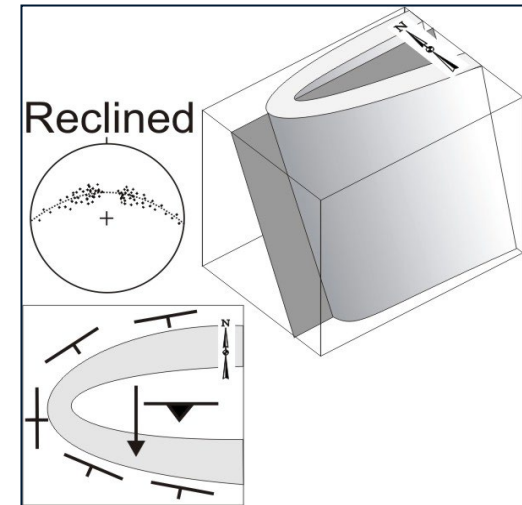


- poles to bedding
- β beta axis (fold axis)
- great circle girdle to bedding
- cleavage (axial plane of folds)
- vertical section plane



A Quick Recap of Reclined folds

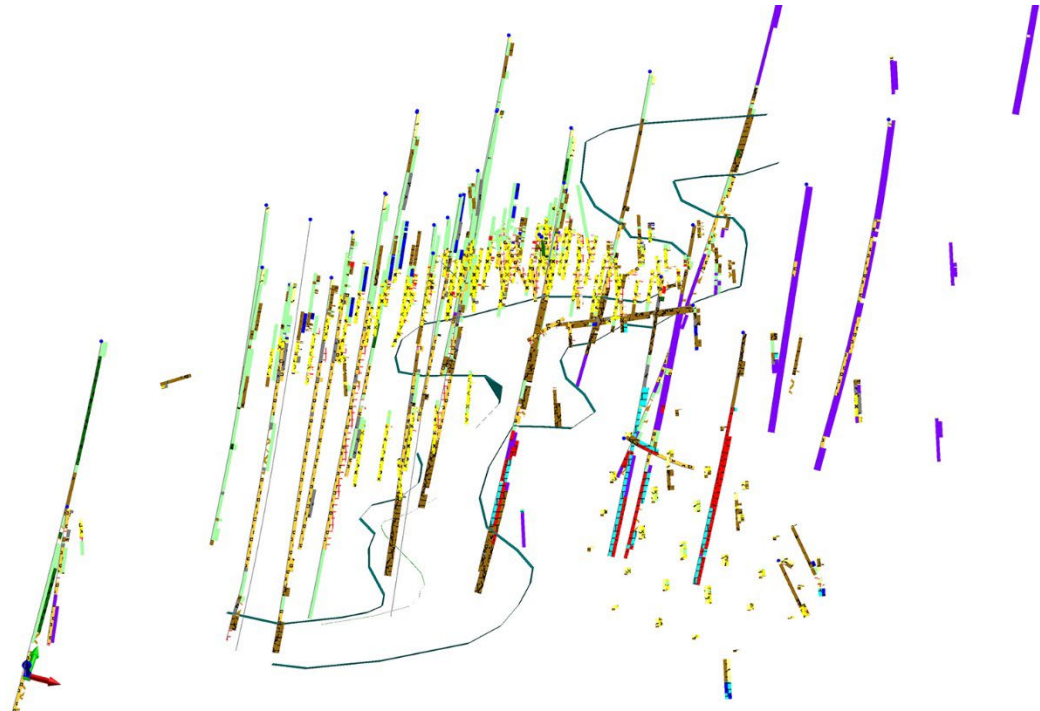
- ◆ Fold hinges plunge parallel to the dip of the axial plane
 - Therefore axes trend perpendicular to strike of axial plane
- ◆ Vertical sections drawn perp to axial plane see no fold closure – just multiple limb intersections
- ◆ Vertical sections drawn parallel to trace of axial plane do see a closure – but are still a distorted view
 - The steeper the plunge the more distorted is the apparent fold shape



Quick and dirty analysis

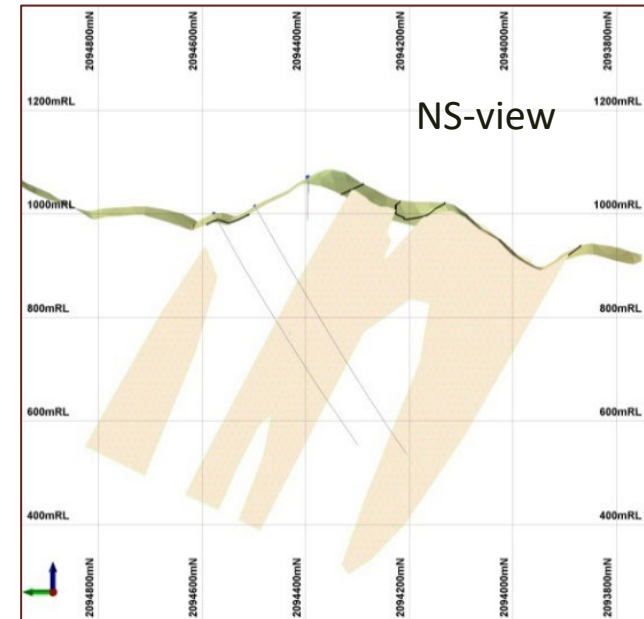
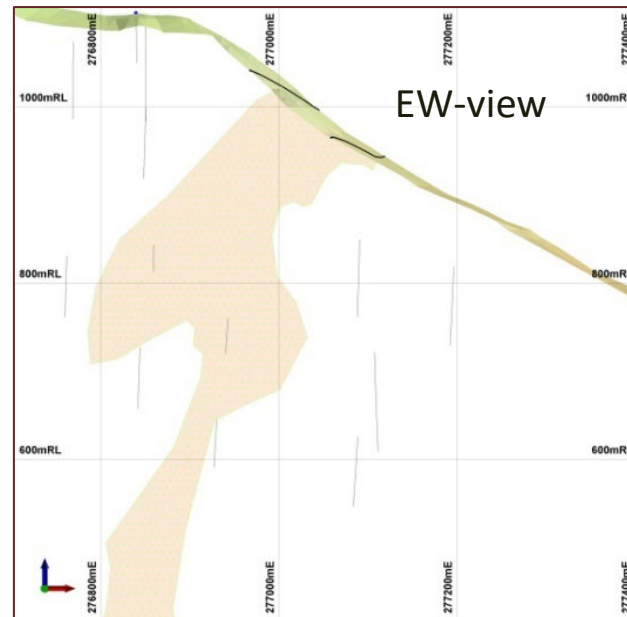
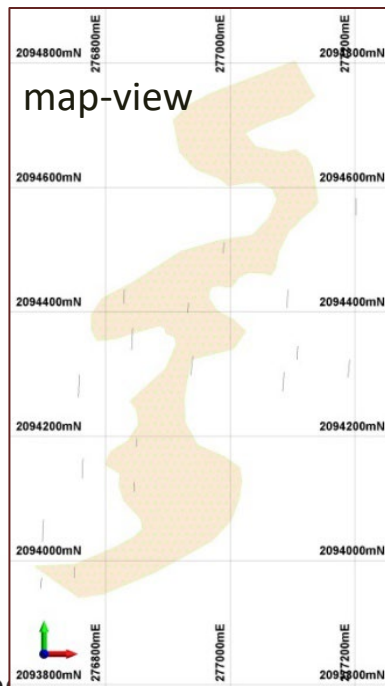
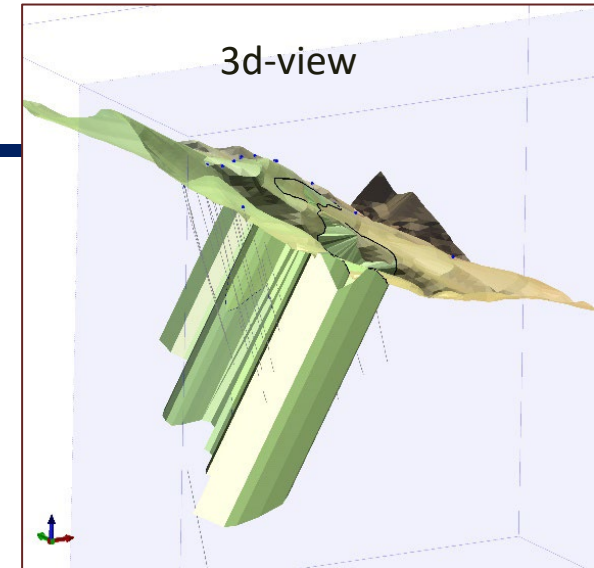
- ◆ Using a 3D modelling package (here it is Micromine), view all of the drillholes parallel to the fold axes
 - i.e. looking at a theoretical profile view of any folds
- ◆ Instead of multiple felsic and slate units there is only one of each
- ◆ Suddenly the potential resource may have been reduced in size

An example of
down-plunge
viewing



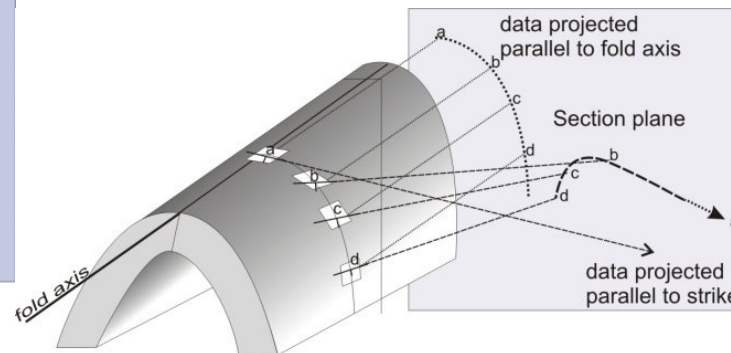
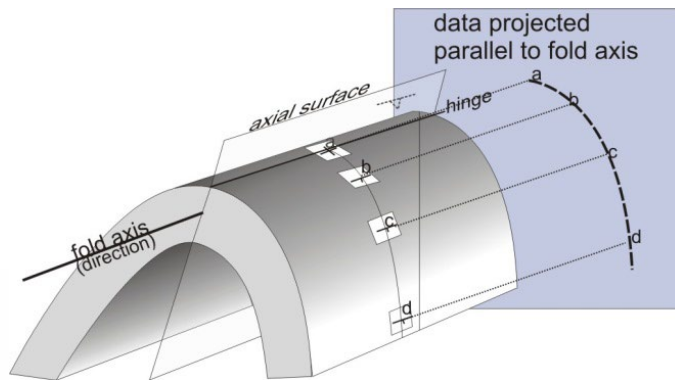
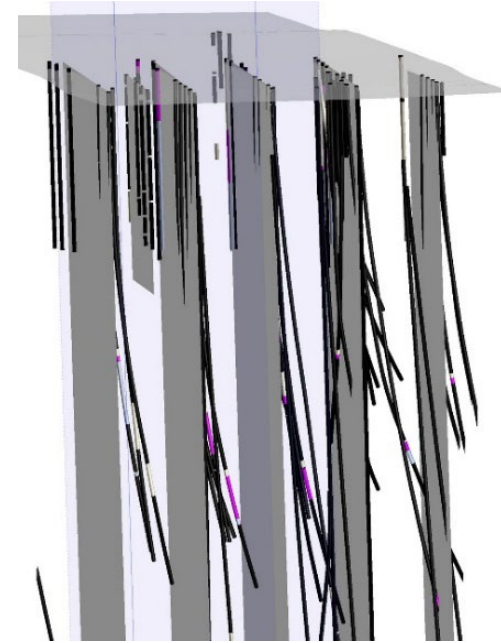
Drilling implications

- ◆ N-S drill sections are the worst option for designing the drill patterns here
- ◆ E-W is better – but not by much
- ◆ Best to combine N-S with E-W
- ◆ Constructing serial horizontal sections is the best strategy for Resource Modelling



Constructing drill sections

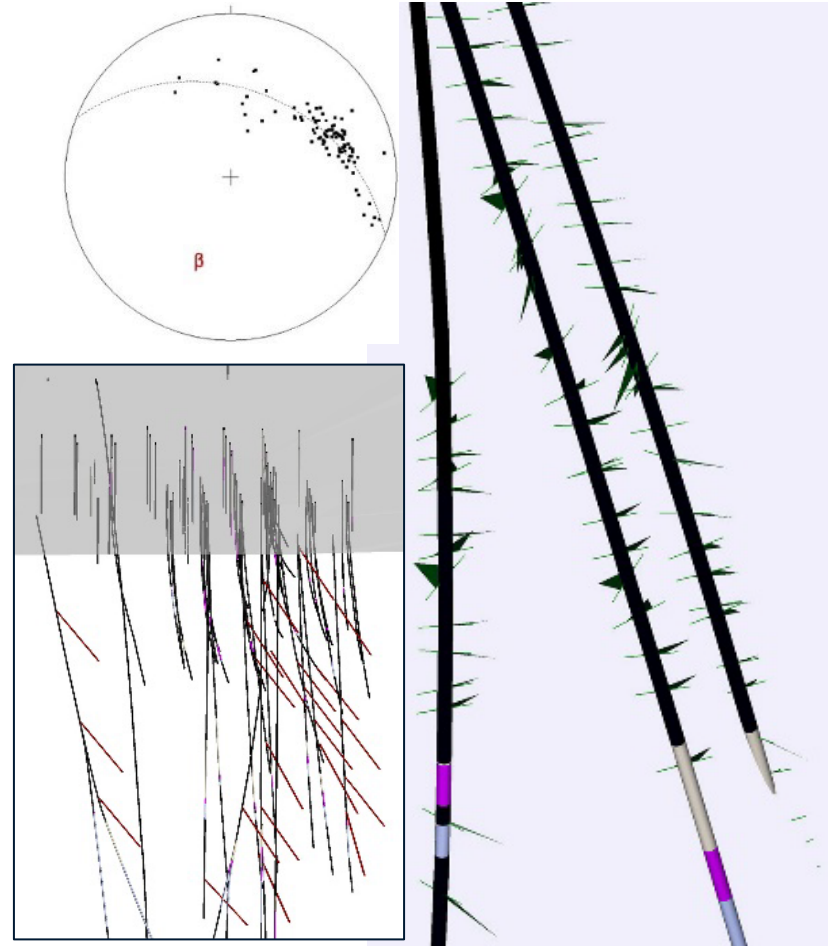
- ◆ Drillholes rarely lie exactly within the section plane and data from the drillhole must be transferred some distance to the section plane
- ◆ Only use strike projection in folded areas if the beds are perfectly planar, or you know the fold axes are horizontal and perpendicular to the section plane
- ◆ **In all other cases project parallel to fold axes**



Example of projecting drillhole data

- ◆ Bedding data on drill strings show statistically cylindrical fold pattern in bedding
 - (Found here by selecting and copying data on drill strings, and pasting into GEOrient)
 - Fold axes lie about 45° from the E-W drill section planes!
 - MUST use fold axis projection here for off-section data

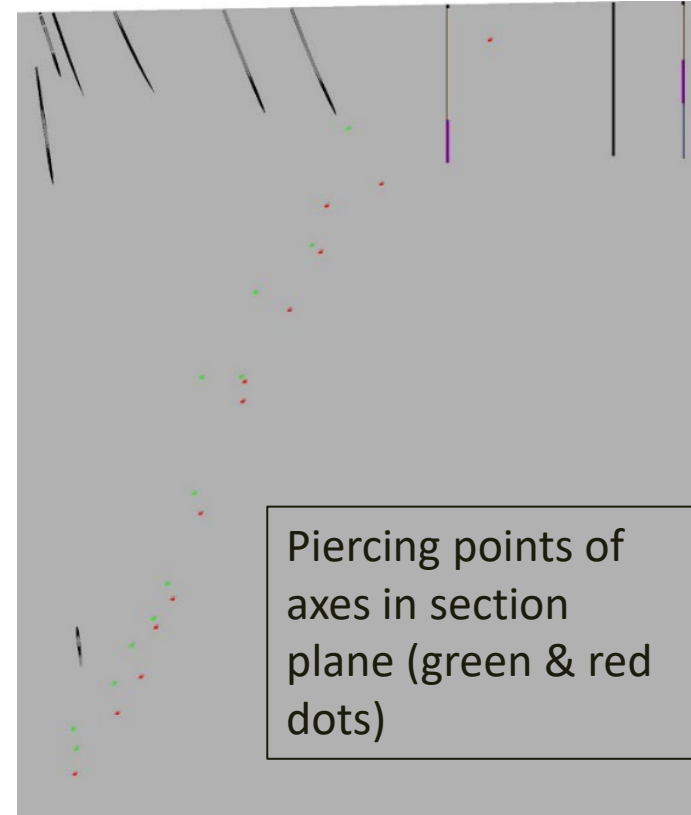
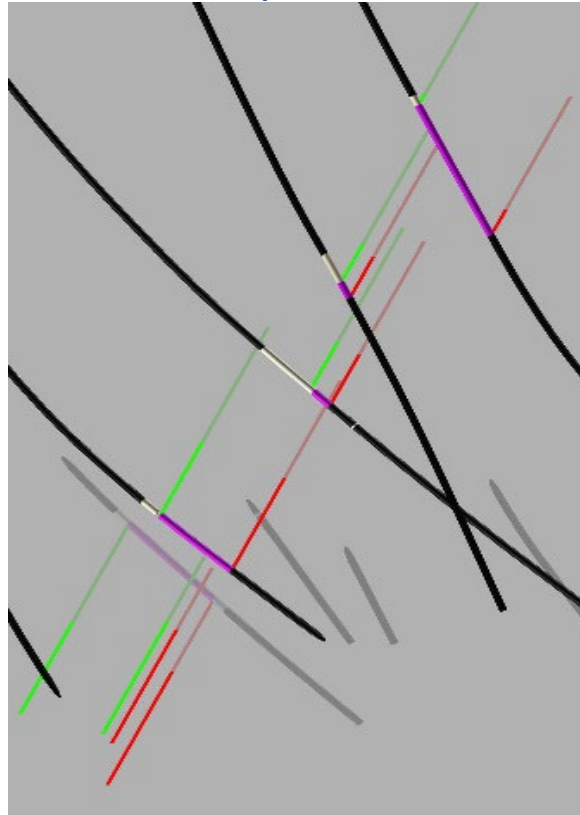
Fold axes calculated from different drillholes and plotted as axes back onto drill strings in 3D modelling package



Off-section projection

- ◆ Subtend the calculated fold axis from each contact (or structural data of interest) on each off-section drill string
- ◆ Where it pierces the section plane is its on-section location

3D modelling package used to project fold axes upper (green) and lower (red) contacts of a unit (pink) in drill strings



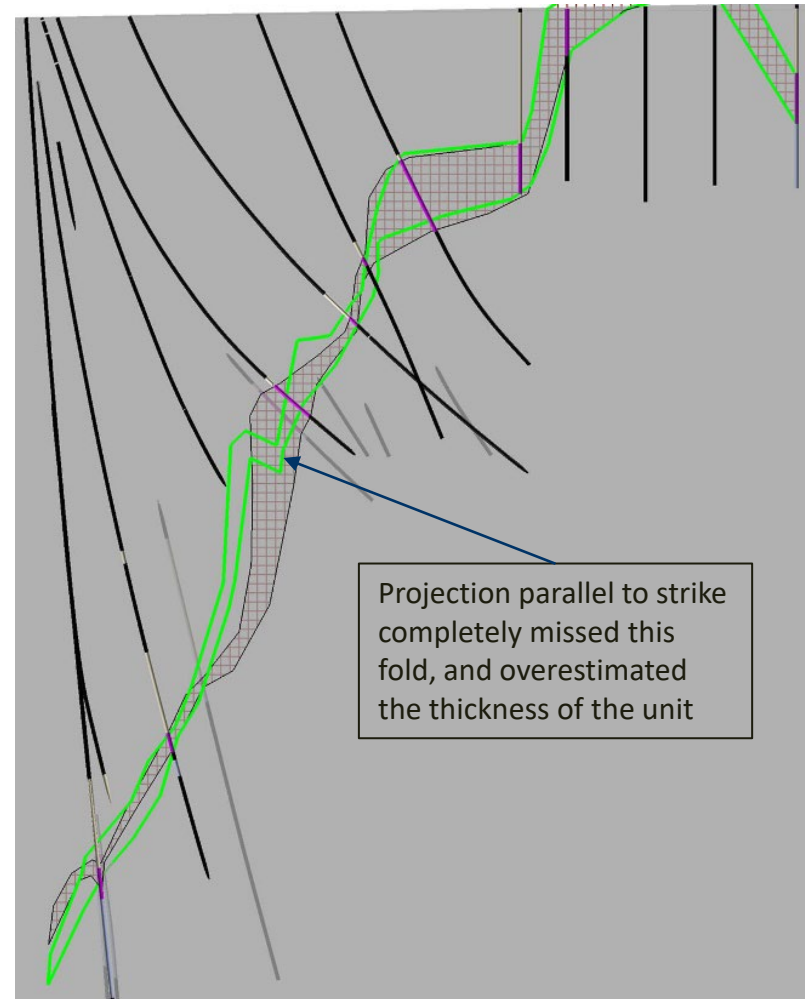
Piercing points of axes in section plane (green & red dots)



Completed section

- ◆ Green: section using projected data
- ◆ Red hatched: section using orthogonal projection
 - i.e. all intervals within a narrow window are viewed and plotted on to the section plane by projection normal to the plane
 - This the common method and inherent in most mining software
 - **BUT it is wrong if the folds plunge**

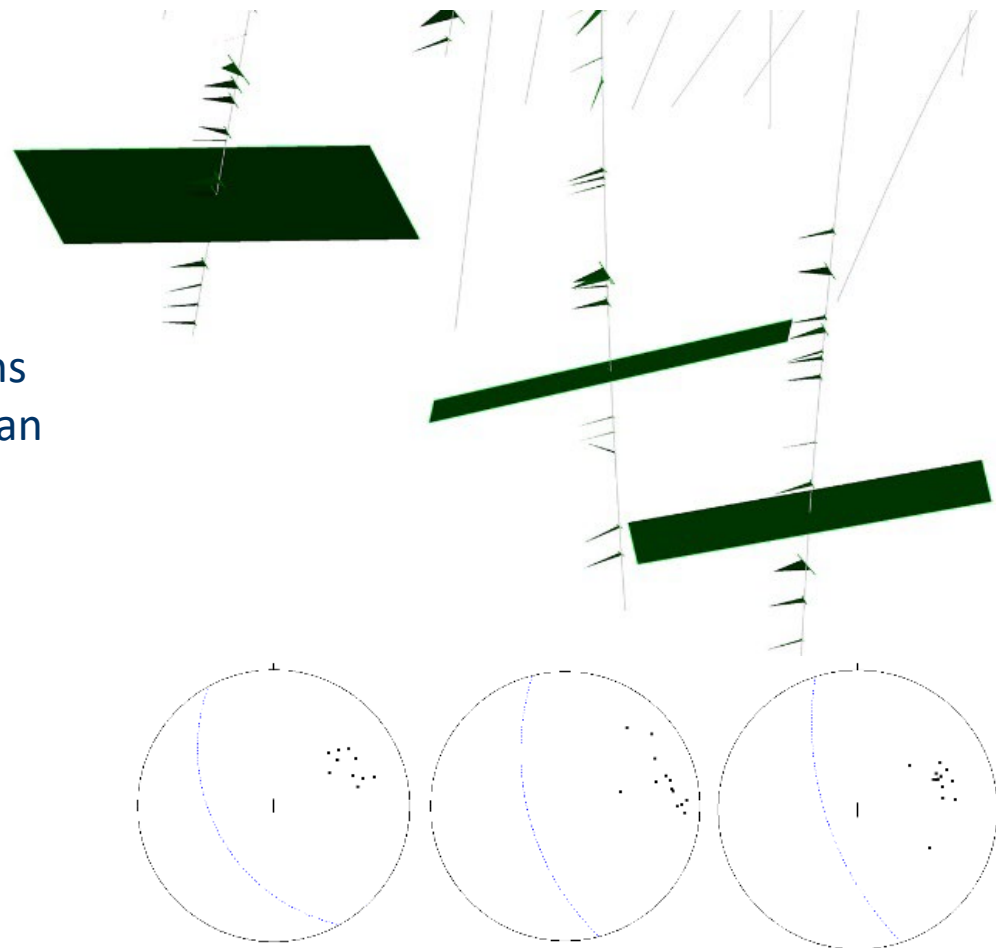
The difference may appear minor in this example, but could make the difference between hitting and missing a target at depth



3D analysis of oriented core data

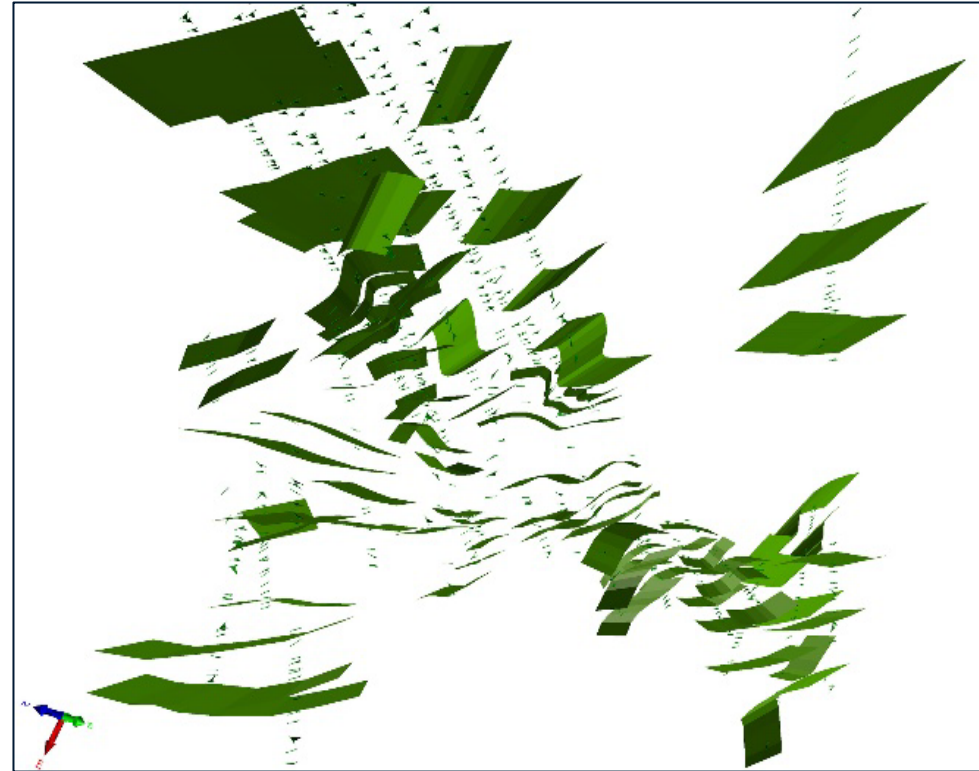
1. Mean orientation from surfaces

- Oriented core data is notoriously imprecise
- Best to treat it statistically
- One way is to group subparallel data from sections of core and calculate the mean orientation
- These means can be represented by larger 3D platelets on the drill strings
 - Essentially they provide an exaggerated view of the orientation relationships



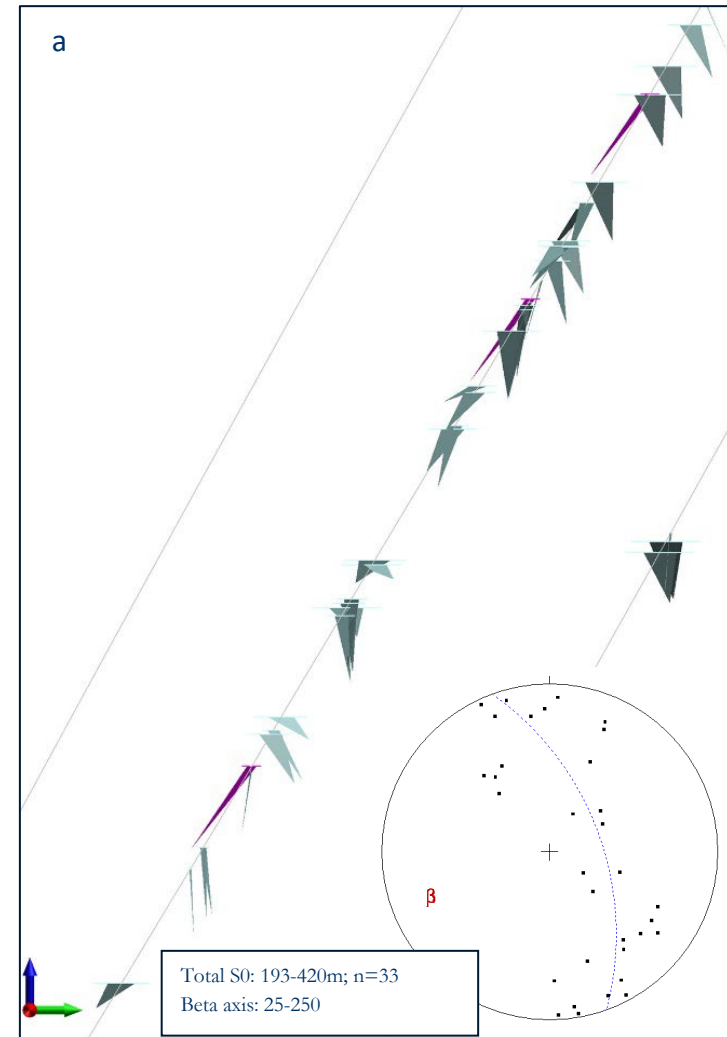
3D Form surfaces

- ◆ An extension of the last method in folded areas is to construct 3D form surfaces
 - An exaggerated view of the local data
 - Provide a simple way to look at larger structures through the data
 - Requires abundant, and reliable, oriented core data



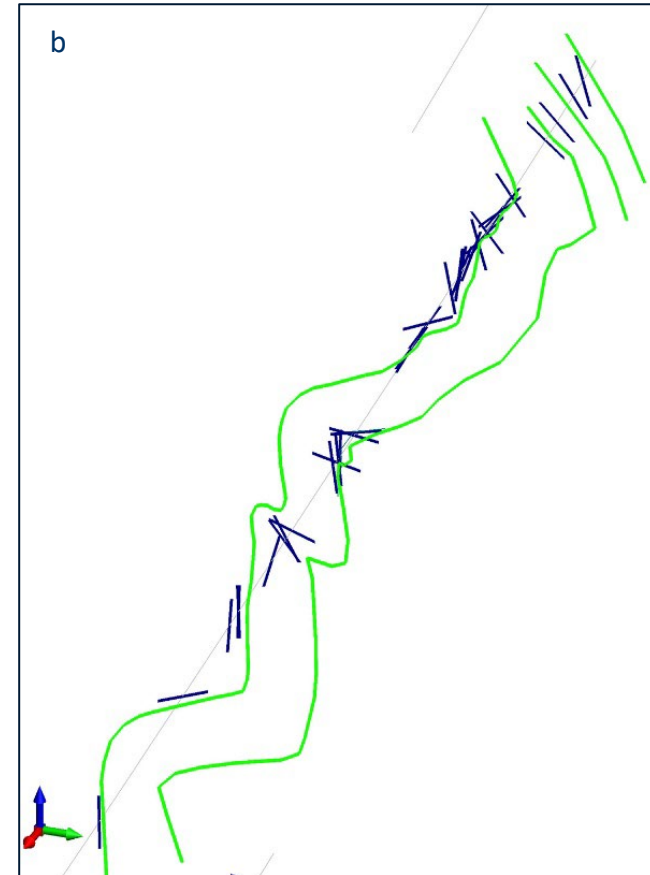
Construction of 3D form surfaces (1)

1. Fold axes are identified for cylindrically folded domains from stereographic projection plots
 - A domain may be part of a single drill hole, or may include several drillholes
2. The calculated fold axis is subtended off the drill string (long pink triangles) within each domain



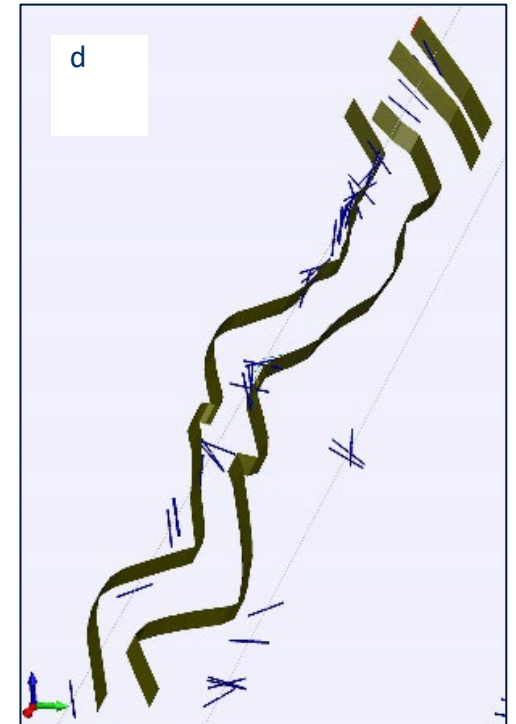
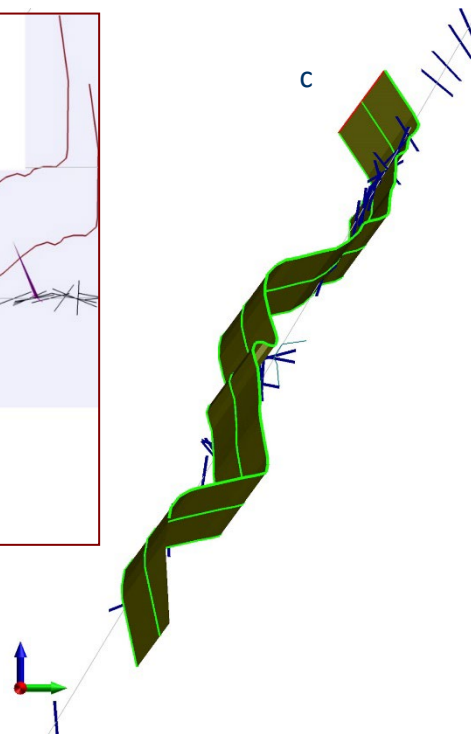
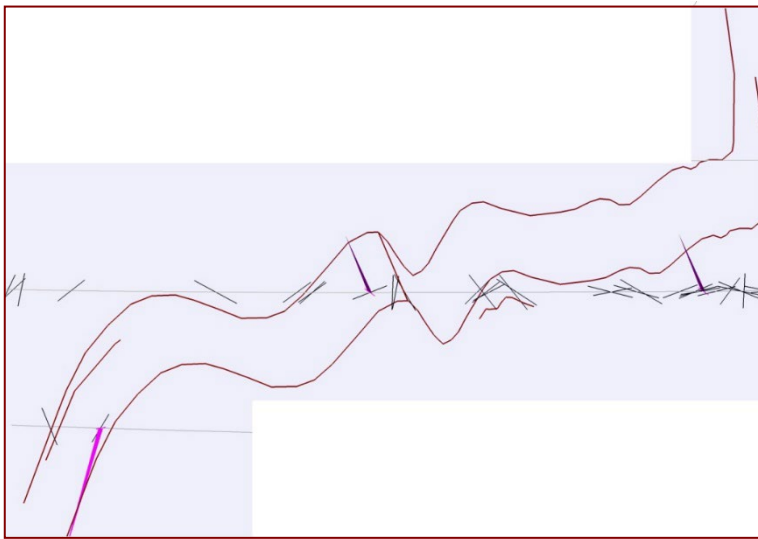
Construction of 3D form surfaces (2)

3. The view is rotated until it is perfectly perpendicular to the fold axes
 - Change the view of the structural data to apparent dip format
4. Set the drawing plane to one of the data points on a drillhole
5. Construct a set of 2D form lines as you would do on a map using the apparent dips as a guide
 - Note that these form lines do not lie in the drill section plane, but in a plane oblique to the section



Construction of 3D form surfaces (3)

- Complete the 3D wireframe by moving a copy of the form line parallel to fold axis line and fitting a surface
 - Choose a distance that is reasonable for the amount of data
- Repeat for any other form lines



3D Form surface examples

