Ivo Vos, Ph.D., P.Geo., is a Senior Consultant (Structural Geology) with SRK, based in the Toronto office. Ivo has over 10 years of experience in the regional and local structural analysis of mineral deposits and has successfully applied his knowledge to the discovery of new gold deposits in East Africa. He is an expert in deciphering structural controls on the distribution of mineralization for a variety of deposit styles, including mesothermal and epithermal precious metal deposits, nickel sulphide deposits, iron-oxide copper-gold deposits, porphyry-copper deposits and unconformity-related uranium deposits.

Ivo combines his field skills with deposit-scale 3D modelling, structural and geological interpretation of geophysical data, and has a special interest in (multi-commodity) regional exploration targeting studies. He has been involved in exploration and deposit-scale studies for a variety of commodities in Canada, East and West Africa, Australia, South America and the Middle East. Furthermore, Ivo has been actively teaching the Applied Structural Geology Courses with SRK.

ivovos@srk.com
WORKSHOP SCHEDULE

Saturday, March 22, 2014

0800-0815 Welcome and Introduction.
0815-0930 General concepts of structural geology and their application to mineral systems.
0930-1100 Structural mapping, core logging and 3D modelling techniques for exploration and mining geologists.
1000-1030 Coffee Break
1100-1200 Structural analysis of faults and vein systems – Part 1.
1200-1300 Lunch Break
1300-1500 Structural analysis of faults and vein systems – Part 2.
1500-1530 Coffee Break
1530-1700 Structural analysis of folds and fold systems.
Applied Structural Geology in Exploration and Mining

CM1 – General concepts of structural geology and their application to mineral systems
Applied Structural Geology in Exploration and Mining

Welcome and Introduction

Housekeeping Notes
- Emergency Exits;
- Bathrooms.
Aims of Course

• Demonstrate why so many ore deposits are strongly structurally controlled;

• Define the simple principles of “structural control”;

• Give you the tools you require to do structural geology in the mining and exploration environment; and

• Give you the confidence to apply these tools, and therefore to make a real difference!

What is SRK?

• SRK Consulting is an independent, international consulting practice that offers services from exploration through feasibility, mine planning, and production to mine closure.

• Formed in 1974, SRK now employs more than 1600 professionals internationally in over 50 offices on 6 continents.
SRK’s Services

• Approximately 15 professionals based in UK, Canada, Australia and UK.

• Qualified to MSc or PhD level in structural geology and mineralisation processes.

• Experienced in the issues in mining and exploration where structural geology impinges.

• Commissioned to conduct structural evaluations on projects at all stages (grassroots to advanced exploration; feasibility studies and production).

• Types of commission: assisting exploration, resource modelling and definition, geotechnical and hydrogeological evaluations and due diligence.
Course Presenters

- Senior Consultant - Structural Geology, SRK Canada
- Principal areas of expertise:
  - Regional and local structural analysis of mineral deposits
  - Deciphering structural controls on the distribution of mineralization
  - Multi-commodity regional exploration targeting studies
- Au-Ag (epi- and mesothermal), Ni-sulphide, IOCG, porphyry-copper, unconformity-related U.
- Canada, East and West Africa, Australia, South America and the Middle East
- Professional Geologist (PGeo)

Course Schedule

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1530-1700  Structural analysis of folds and fold systems
CM1 - General concepts of structural geology and their application to mineral systems
Structural mapping - why bother?

Applied Structural Geology in Exploration and Mining

A Risky Situation?

A man floating along in a hot air balloon began to realise he was lost. He reduced his altitude and spotted a person below. He descended a little more and shouted:

"Excuse me, can you help me? I promised a friend I would meet him an hour ago, but I don't know where I am".

The stranger replied,

"You are in a hot air balloon hovering approximately 10 metres above the Bayan Obo mine in Inner Mongolia."
A Risky Situation?

"You must be a geologist", said the balloonist.

"I am" replied the stranger, "How did you know?"

"Well", answered the balloonist, "everything you told me is technically correct, but I have no idea what to make of your information, and the fact is I am still lost. Frankly, you've not been much help so far".

The stranger below responded,

"You must be a engineer".

"I am," replied the balloonist, "but how did you know?"

A Risky Situation?

"Well," said the geologist,

"you don't know where you are or where you are going."

"You have risen to where you are through a large quantity of hot air."

"You made a promise to someone that you have no idea how to keep, and you expect me to solve your problem, but you really aren't interested in the information I'm providing."

"The fact is you are in exactly the same situation you were before we met, but now, somehow, it's my fault".
Most operations do not maximize the value of continued geological input.

Many mining companies have not effectively implemented information visibility inside or outside their organizations, limiting the amount and quality of information required to evaluate risks and make decisions on appropriate mitigation strategies.

Deloitte: How secure is your supply?

Geology underpins every aspect of the mining process.
How Does Structural Geology Make a Difference?

- Direct input on the limits, size and shape of ore bodies;
- Elevates confidence in predictability of ore behavior:
  - Geometrical – grade control, dilution, targeting;
  - Geochemical – grade control, ore quality/metallurgy; and
  - Geotechnical – ground control, dilution.
- Definition of hydrogeological pathways, geotechnical domains, etc.

The Conceptual Basis of Structural Control in Mineral Deposits

- All hydrothermal ore deposits require transport of large quantities of relatively insoluble metals in solution from some source region to the site of deposition;
- Metal transport takes place principally by percolation of the fluid through the rock, and the low solubility of the metals means that very large fluid fluxes are required.
## Metals Abundance in Various Rock Types

<table>
<thead>
<tr>
<th>Element</th>
<th>Ultramafic</th>
<th>Mafic</th>
<th>Felsic</th>
<th>Greywacke</th>
<th>Cont. Crust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu ppm</td>
<td>10</td>
<td>87</td>
<td>30</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Zn ppm</td>
<td>50</td>
<td>105</td>
<td>60</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Pb ppm</td>
<td>1</td>
<td>6</td>
<td>15</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Au ppm</td>
<td>0.0008</td>
<td>0.0017</td>
<td>0.002</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>Ag ppm</td>
<td>0.06</td>
<td>0.11</td>
<td>0.051</td>
<td>0.08</td>
<td>0.08</td>
</tr>
</tbody>
</table>

## Solubility of Metals

- **Cu, Zn** = not constrained by solubility in saline solutions, therefore approximate abundance in rocks.
- **Au** = not constrained by solubility in hydrothermal solutions, especially those containing S, therefore approximate abundance in rocks.

## Exercise 1:
**Fluids and Plumbing**
Exercise on Fluids and Plumbing

• Assume:
  • Solubility of Au in hydrothermal solution = 0.03 ppm;
  • 1 oz = 31g; and
  • 1 litre of hydrothermal fluid = 1 kg.

• How much fluid required for a 5 Moz Au deposit?
Fluid Required

<table>
<thead>
<tr>
<th>Deposit Size</th>
<th>Grams</th>
<th>Solubility (ppm)</th>
<th>Fluid (tonnes)</th>
<th>Fluid (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au (Moz)</td>
<td>5</td>
<td>0.03</td>
<td>5166666667</td>
<td>516666666667</td>
</tr>
</tbody>
</table>

Remember, these calculations assume 100% efficiency in depositing the metal at the deposit site!

5E+12 litres = 5 km³

Fluid Required

Toronto Skydome (Rogers Centre):
Volume roof closed: 1,600,000 m³
1.6 x 10⁹ litres

5Moz Au deposit:
Minimum fluids: 5.0 x 10¹² litres
3,125 Skydomes

Another way of looking at this problem is that 1oz of gold will saturate an Olympic swimming pool full of a typical hydrothermal fluid!
Basis for Structural Control

- Getting the metal to the deposit is first and foremost a severe hydrodynamic problem;

- A simple analysis of this hydrodynamic problem provides the foundation for the principles of structural control; and

- It also leads to a set of simple, practical structural geological tools for aiding the discovery, delineation and efficient exploitation of mineral deposits.

The Basic Hydrodynamic Problem

- So how does the earth manage to channel several millions of Olympic swimming pools of fluid through the relatively small rock volume that is to be the mineral deposit?

Bayan Obo deposit – the world’s largest known REE deposit containing >40Mt REE grading 3.5-4% REE; 1 Mt of Nb2O5, 470 Mt Fe and 130 Mt of fluorite
A Simple Hydrodynamic Analysis

- The migration of fluid through a porous and permeable rock mass is described macroscopically by Darcy’s Law;

\[
\text{Fluid flux} = \frac{\text{Pressure head} \times \text{Rock permeability}}{\text{Fluid viscosity}}
\]

- Pressure heads have a limited range in the earth - e.g., \( P_{\text{lith}} - P_{\text{hyd}} \);

- Hydrothermal aqueous fluids have approx constant viscosities at upper to mid-crustal conditions.

Driving Forces for Fluid Flow

- Pressure gradients factor of \(~3\) (lithostatic versus hydrostatic):
  - Topography;
  - Seismic pumping;
  - Metamorphic dehydration;
  - Magmas emplaced in fluid-saturated rocks;
  - Fluids expelled from crystallising magmas;

- Buoyancy:
  - Temperature (thermal expansion);
  - Salinity;
- Viscosity - range of 1 order of magnitude:
  - 40-400 \( \mu \text{Pa}s \) at \( T = 100-800^\circ\text{C} \) and 50-300 Mpa.
Driving Forces for Fluid Flow

- Permeability:
  - Porous sandstone (Ø>15%) = 1 darcy (10^-12 m^2);
  - Crystalline granite = 10^-10 darcies (10^-22 m^2);
  - Fault at mid-crustal depth = 1 darcy (10^-12 m^2);

- 10 orders of magnitude!

- Therefore only permeability can vary sufficiently to permit the large fluid fluxes required to form ore deposits.

The Principles of Structural Control

- Only abnormally permeable rocks will permit the fluid fluxes necessary to form ore deposits;
- Fractured rocks (i.e. fault zones) are the most likely conduits for transport of large fluid volumes;
- But there is a built-in negative feedback in the system which will reduce the effectiveness of the fault zone to pass the fluid (and metal) volumes required.
The Principles of Structural Control

• The evidence for this is ubiquitous in paleo-fault zones - fractures are vein-filled, wall rocks are often highly altered, gouge zones are tight and cemented - all of which dramatically reduce the hydrodynamic efficiency of the zone.

Therefore, in order to transport the required metal volumes, the permeability of the fault zone must be continuously regenerated – (permeability of an active fault at mid crustal depth ~4 darcies, or $10^{-8}$ m²);

• This leads to the important conclusion that hydrothermal ore deposits are localised on faults that were (repeatedly / continuously) active at the same time the hydrothermal system was active and metal-pregnant;

• Therefore, the concept of “structural preparation”, whereby the fault sits around waiting for the mineralising fluid to come by is flawed.
The Importance of Getting Timing Right

- Application of structural control principles requires that the timing of mineralisation must be carefully matched with the history of activity on a fault system.
The Principles of Structural Control

- Most (all?) hydrothermal ore deposits form on or adjacent to active faults/shear zones;

- Especially in gold deposits, economic grade is broadly correlated with vein/fracture concentration, which in turn is a measure of dilatancy in the controlling structure; and

- A key component of mineral exploration is identifying and locating sites of dilation in structures that were active at the time of ore formation.

Sulphide filled dilational jog, Sudbury, Ontario

The Principles of Structural Control

- Permeability is unlikely to be the same everywhere on an active fault zone;

- Permeability will generally be highest where damage within and around the fault zone is highest;

- This will depend to some extent on host rock type, but will principally be localised by irregularities (e.g. bends, branches, steps, jogs) along the fault.

Damage zones around irregularities along fault zone are zones of enhanced permeability
The Principles of Structural Control

- Fluid flow is therefore maximized, and ore deposits are generally localized on irregularities (i.e., bends, bumps, branches and jogs) in fault zones;
- Irregularities commonly extend beyond or sit off the main fault strand, which explains why deposits commonly occur on second- or third-order structures rather than on the main fault;
- Aside from fluid flow, this concept applies to magma as well. Therefore, intrusions and breccia pipes and associated mineral deposits also commonly occur along irregularities.

The Principles of Structural Control

- Zones of local damage and permeability enhancement in active fault zones have another key influence on fluid flow and deposit localization;
- The damage zone undergoes (fracture) porosity enhancement during each episode of fault movement. This increase in local porosity causes a transient reduction in local pore fluid pressure, which will suck fluid towards the damaged zone.
The Principles of Structural Control

There are two other important consequences of this local pressure drop:

- It encourages mixing of fluids sucked from the surrounding wall rock and along the fault zone;
- It can drastically alter the solubility of metals in the fluid;
- Both of these processes can lead directly to metal precipitation in the zone of maximum fluid flux.

In summary, irregularities on active fault zones:

- Provide the very high-permeability fluid pathways that have the capacity to transport large volumes of metal to a local site of deposition;
- Are fluid pumps which suck fluids into the zones of enhanced permeability; and
- Encourage mixing of locally derived and equilibrated fluids with (hotter and metal-saturated) fluids travelling along the fault zone.
Applied Structural Control Principles

There are three basic steps to applying these principles at regional to local scales:

1. Determine the **timing** of mineralization relative to structural events, and identifying the event(s) that produced the mineralization;

2. Mapping/logging/interpreting in **3 dimensions**, to determine the structural setting and **pattern** of active structures during mineralization; and

3. Determine the likely **shapes**, **orientations**, and **locations** of dilational sites on the active structures.

• Determine the **timing** of mineralization in the event history and match it to the history of movement on the fault/shear zones in the region.
Applied Structural Control Principles

• Carefully map in 3 dimensions those faults considered to have been active at the time of mineralization, paying particular attention to even the subtlest variation in strike, dip or continuity.

Applied Structural Control Principles

• Determine the direction and sense of movement on the faults, in order to predict the location, shape and plunge of zones of maximum damage / dilation.

Zone of dilation associated with bend on sinistral fault
Applied Structural Control Principles

When you have located a mineralizing structure:

- Determine the displacement direction and sense, so that you can relate changes in dip/strike of the fault/shear to the formation of dilational sites; and

- Relate fault movement and shape to vein/breccia orientations and locations in detail; always make sure you work out how veins / stockworks / breccias relate to faults.

So how does this apply to your area?
Applied Structural Geology in Exploration and Mining

CM2 – Structural mapping, core logging and 3D modelling techniques for mine and exploration geologists
Basic Mapping Principles

- Structural mapping SHOULD be part of everyday geological mapping practice…but this is often not the case.
- Where do I start?
- What do I map?
- What tools do I have?
- Why should I bother?

Rössing open pit, Namibia
**Ore Body Plunge**

So you can decipher the plunge of mineralization!

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**Output Geological Domain Model / Map**

A 3D geological model (or 2D map) is an artificial representation of the rock mass in situ, including the components of lithology, structure and other material properties (mineral, chemical, geophysical etc.)

It is a simplification of reality designed for a practical purpose.

Example Domains:
- Mineralized / unmineralized (or grade shell domains)
- Structural terranes or geometry changes
- Lithological layers or stratigraphic zones
- Alteration type or intensity
- Permeable / impermeable (hydrology)
- Good / bad mineral exploration target areas
- Structurally complex / simple
- Rock mass weak / strong (geotechnical)
**Geological vs. Structural Mapping**

**Geological mapping**
- 90% of effort goes to primary rock identification;
- Outcrop map produced at end of the mapping campaign; and
- Systematic data gathering for later interpretation.

**Structural mapping**
- Strong emphasis on structure, alteration etc;
- Faults, shear zones as rock bodies;
- Integrated geological map that works in 3D; and
- Data interpreted during mapping and used to produce working map during the mapping campaign.

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**Structural Mapping**

Structural mapping includes:

- Determining the geometry (i.e. orientation + shape) of rock units, fabrics, discontinuities;
  - **Mapping contacts is the key**
- Determining movement sense and displacement on structures using available kinematic indicators;
- Determining the history of (structural) events
  - **Mapping in 4D**
- Then place the mineralization within this context.
Traditional vs. Structural Mapping

...somewhere in Tanzania

Should still clearly show what is data and what is interpretation.

What tools do we have?

- Stratigraphy
  - was originally horizontal and laid down in a particular order
  - younging, or “way-up” indicators
- Structural fabrics and deformation
  - know how to recognise them
  - know what processes they represent
- Geochronology
  - cross cutting relationships, structural overprinting, radiometric dating
- Geometrical principles
  - map making and pattern recognition
  - structural balancing
Map Patterns

Au-Cu-Ag Canahuire Epithermal Deposit, Southern Peru

Santos et al., 2011

Magnetic Patterns
Keys to structural mapping

- Collect the data you need, not data for data’s sake;
  - maintain context of what you are trying to achieve
- Map contacts;
- Work in plan and section at the same time;
- Work in 4D – what is the time sequence?
- Start interpreting right from the start!
  - Mapping is iterative, and geological maps should constantly evolve
- Stretch the data and make decisions about relationships; and
- Follow geometrical principles - geology is fractal in nature, pattern recognition is key.

1. Collect the data you need

- The relative size and importance of features should be reflected in your map;
- Don't just map “data”, map and interpret relationships.

EXAMPLE
In the map opposite from an underground crosscut (Hillside gold deposit, Australia), auriferous veins are red and faults are blue. Which faults are likely to be the main controls on grade distribution? (Could also be drill core…)
Vein hosted gold

- Gold is dominantly vein-hosted and grade correlates closely with vein density;
- Fault-bounded zones of different vein density are mapped in the cross-cut;
- **Domain boundaries** can be identified as mappable faults along the boundary between high-grade and medium-grade ore; and
- Defining and mapping the **domain boundaries** enables geostatistics, resource estimation and mine planning to be carried out with greater confidence.

2. Map Contacts

- And be aware of the nature of the contact:
  - Conformable?
  - Unconformable?
  - Intrusive?
  - Faulted?
  - Sheared?
  - Healed by a dyke?
  - Veined?
  - Mineralized?
  - Where does it go in 3D?
3. Work in plan and section

- Lack of exposure, low topographic relief or limited drilling limit the amount of control on 3D geological models. Many possible interpretations may be made from the same data.
- Need to utilize all information available e.g. geophysics, geochemistry etc. to constrain the model and find the most probable interpretation.
- When adding linework to a cross section, always consider how that contact/ore zone would appear in plan view (and vice versa).

Draw block diagrams
4. Think in 4D

- Tectonic regimes change over time;
- An understanding of the event history is fundamental to place mineralization in the correct context; and
- Keep timing in mind.

What age is the veining?

Our interpretations must capture the timing of structures.
5. Start interpreting right away

- Don’t wait till you have a huge amount of data and hope the pattern appears
- Interpret what you see during mapping – gives you something to test
- Provides a context for future data gathering and gives you a template for your 3D model

6. Stretch the data and make decisions

- There is no such thing as a ‘fact map’;
- Only the measured data on the map is ‘true’ – everything else is interpretation;
- BUT the interpretation is the most valuable part of the map; and
- A lot of geology is pattern recognition – outcrop-scale structures are faithful reduced images of large structure.
7. Follow geometrical principles

- Rocks must occupy 100% of their “space” at all times during their deformation history = “structural balancing”;

- So we should be able to reconstruct rocks to their non-deformed state;

- Many cross-sections on published 1: 100,000 & 1: 250,000 maps are markedly “unbalanced” & so must be incorrect.

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Traditional Drill Core Logging verses Core Structural Mapping

Two approaches:

- **Structural Core Logging**
  
  systematic and data-driven

  Vs

- **Structural Core Mapping**
  
  less systematic and interpretation-driven

Both approaches are complimentary.
Structural Core Logging

- Systematic description and measurement of drill core, and recorded in a database, including:
  - Contacts (gradational or sharp) for lithology, alteration and mineralogy;
  - Structural fabrics (foliations, lineations) and cross-cutting relationships;
  - Veins, joints (with infill) and micro-fracturing;
- A large amount of data is amassed, useful for:
  - Statistical analyses of structural frequencies and orientations
  - Define population orientations (e.g. veins) and determining correlations.
- Main downside is that logging becomes a mindless exercise without thought and focus on the big-picture objective.

Structural Core Mapping

- Philosophy is similar to field geological mapping - “Map” domain boundaries, look for pattern changes and Interpret.
- Map and sketch directly on to paper noting any critical structural information:
  - Domain structural pattern changes, folds;
  - Cross-cutting evidence;
  - Bedding-cleavage relationships;
  - Kinematic indicators, lineations / striations etc.
- Focus on areas of interest rather - not systematic.
- Extract data that is critical to the understanding of the system;
- Allows critical relationships to be identified and solved; and
- Particularly useful in exploration environment – ore controls.
Patterns and Relationships from Drillcore

• “Map” the core in section - interpret don’t just collect data;

• Define structural domains from pattern changes and interpret boundary geometries;

• Predict domain boundary intersections (e.g. fault zones) and confirm in core.

Examples of Domain Classes:
1. Strongly sheared or brecciated
2. Faulted - displacement or striations
3. Alteration or strong fracturing
4. Broken core
5. Residual soil / clay.

Patterns and Relationships from Drillcore
Typical Examples

• Predict if all veins are mineralized or is mineralization associated with a preferred orientation or spatial domain, based on geometry of products of deformation;

• Detect other structures that may be mineralization controlling structures or parallel to controlling structures, e.g. faults, folds and foliations;

• Determine local strain axes from kinematic indicators;

• Identify spatial domains associated with fault or joint patterns.

• THESE REQUIRE ORIENTED DRILL CORE.
Orientating Core

- BallMark ® System

- Ezy-Mark Tool
  - Three different gravity and non-magnetic measurements
  - Quality Control System

Ace Core Orientation Tool (ACT)

- 3 accelerometers measure the gravitational direction of the core tube at any time.
- The user enters the time at which the core was broken.
- The instrument guides the user to rotate the tube to the position it was in at the given time.
- The base of the core can then be marked.
- Easy to Use
- No consumables
- “Black Box”
Down Hole Geophysics Tools

- Can generate very accurate orientations;
- Orientation is affected by changes in the magnetic field;
- Picking is complicated by strongly laminated rock;
- Powerful supplementary tool particularly when core orientation fails or is not done.

Measuring Orientation: $\alpha$-\(\beta\)-\(\gamma\) Method

$\alpha$  Angle of planar feature relative to core axis measured along longest axis of ellipse.

$\beta$  Circumferential angle between orientation reference line and the long axis of the ellipse.

SRK Convention:
- Looking downhole;
- Upper surface of core;
- Measured to bottom of ellipse; and
- Measured clockwise

$\gamma$  Angle between a lineation on the plane and the long axis of the ellipse.

SRK Convention:
- Measured clockwise;
- From bottom of ellipse.
Measuring Orientation: ‘Rocket Launcher’

- Allows measurement of true orientation of structural features;
- No post-measurement corrections necessary;
- Allows recognition of structural changes (e.g. fabric deflections) in the core on the fly; and
- Important for core mapping.

Unoriented Drillcore: ‘the Norm’

- Planes in unoriented core define cones in 3D;
- Extraction of meaningful orientation data is very difficult; and
- Of limited use for correlations in highly deformed areas.
Patterns from $\alpha$ angles only (unoriented)

- **Low alpha angle** = structure / layering is nearly parallel to the drill hole;
- **High alpha angles** = structure / layering is nearly perpendicular to the drill hole;
- Intermediate angles eliminate the above two possibilities;
- This can be very useful information during modelling!
- Measure and take note of changes in the alpha angle of layering while logging and look out for fold axes!

Unoriented core can be oriented if it contains a **consistent planar element** (foliation, bedding) whose orientation is known to be consistent over the region of interest:

- *Use this as a reference frame to extract other data.*

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**Unconstrained Geometry from Unoriented Core**

Holes are inclined, but not oriented
Unconstrained Geometry from Unoriented Core

Without oriented data, many possible geometries

If we know orientation and shear sense, we have a chance!

Patterns from Oriented Core

- We can determine form-lines of complex geometries and use geometrical relationships to assist with the interpretation;
- Reduce many possibilities to few or even one; and
- Apply proper structural analysis.
**Patterns from Oriented Core**

Oriented core allows:
- Reduce 3 intersections to one;
- Start using statistical distribution of orientations for geotechnical design;
- Interpolation away from intersection; and
- Increase confidence.

**New Age of Oriented Core Data Analysis - GoCad**

Vein orientations

Foliation orientations
Why do geologists need to think and visualize in 3D?

• Primarily because geology is a 3D geometrical science;
• Interpretations need to make sense in 3D – the geometry must be balanced;
• Since deformation is 3D, most structural interpretations require a good understanding of what is happening in 3D;
• Many of the surficial deposits have now been found and the future of exploration lies in new discoveries beneath cover or buried at depth - to make these discoveries it will be necessary to start considering targeting in 3D; and
• Rock behaviour in mining is a 3D problem requiring full 3D quantification of structural geometries.

3D Rotation - Visualization

• Shepard and Metzler (1971) mental rotation test:

 Which two are the same?

Mental Rotation Test

1. A B C D
2. A B C D
3. A B C D
4. A B C D

Geometrical 3D Visualisation Tools

- Geological maps;
- Cross-section construction using balancing & apparent dips;
- Structure contour analysis;
- Orthographic projection;
- Stereographic projection;
- Computer software;
  - Gemcom, Vulcan, Surpac, Datamine, Gocad, Leapfrog etc.
- Automated interpretation techniques.
Traditional tools - Structure contour analysis

- Concept of structure contours same as topographic contours;

- Structure contours define the surface of a geological feature, for example:
  - fault,
  - shear zone,
  - surface of stratigraphic unit,
  - contact of intrusion

Structure contour analysis

Structure contours are lines that connect points of equal height above a datum level that are contained within a structure (bedding, unconformity, fold, fault etc.)

Structure contours of a planar dipping surface (blue) form straight, parallel, equally spaced lines

(Image courtesy of Fault Analysis Group, UCD, Ireland)
Structure contour analysis

Structure contours of a simply folded dipping surface (blue) form straight, parallel lines. Their spacing and their elevation changes with the shape and elevation of the surface.

- Widely spaced structure contours indicate shallow dip of unit or contact; (= shallow surface slope of topographic contours)
- Close structure contours indicate steep dip of unit or contact;
- Curved contours indicate rounding in surface (e.g. complex folds, intrusions).
Exercise 2: Granny Smith Structure Contours

Granny Smith Exercise

Exercise 2: Granny Smith Structure Contours

You are provided with two maps of the Granny Smith copper deposit, Lovell mine, Wyoming. One shows a geologic map for the Granny Smith deposit. The other shows structure contours for the granite-gneissic contact at Granny Smith. Gold mineralization is associated with the granite-gneissic contact for the Granny Smith deposit.

1. Contour in cross-section representing a low-grade gold horizon along the granite-gneissic contact. Draw in a cross-section the following parameters:
   a. Location of gold mineralization located at elevation or depth contours of the granite-gneissic contact.
   2. What would the effect on the structural regime during gold mineralization?
Granny Smith Exercise

Granny Smith Combined Data

B Granny cross section 6812540 N

- 400mRL
- Weathering front

- Au mineralization
- High grade
- Fault
- Granitoid
- Metasediment
- BIF

443500E
New Computer Aided Techniques

As geologists we need to embrace these new approaches to exploration and mining in order to better understand mineralising systems and ultimately make new mineral discoveries, however,

- **Good fundamental geological skills are still required;**
- **The importance of good field geology is still important;**

The new additional skills required by geologists now and in the near future will be:

- **Good 3D modelling skills using a variety of software platforms appropriate to the task;**
- **Good data mining skills and the ability to integrate and interpret many different datasets from disparate sources;**

Whilst 2D computer techniques will still play an important role for many years in exploration and mining these will by necessity slowly be surpassed by an emphasis on 3D information and techniques.
Modeling Software

- **Geomodeller**
  - Has the ability to accept primary geological observations (such as structural information) to build a 3D geological model that adheres to built-in geological rules;
  - Contact Intrepid Geophysics – Phil McInerney;

- **Gocad – Sparse**
  - Can quickly build structural surfaces from sparse data that represent complex regional-scale geological objects;
  - Contact Mira Geoscience – Gervais Perron;

- **GoCad – SKUA**
  - Is a new implicit geological modelling module from GOCAD, similar to Geomodeller in terms of built-in geological knowledge;
  - Contact Mira Geoscience – Gervais Perron;

- **Leapfrog**
  - 3D interpolation from drillhole data, primarily developed for contouring of assay data, adapted for geological modeling;
  - Contact Zaparo – Andy Abraham;

- **GMP’s e.g. Vulcan, Surpac, Gemcom, Datamine**
  - Produce 3D triangulated surfaces from interpreted polyline input

Other software tools

- **GST Components**
  - 3D geological database and visualisation system, imports from all common file formats and offers superb visualisation capabilities

- **Sirovision**
  - Photogrammetric mapping tool for remote data gathering e.g. pit walls, allows accurate measurement and location

- **Geophysical Inversion**
  - 3D inversion software for magnetics, density and EM data to help constrain and define geometries of geological units in the subsurface.
3-D Models and GIS – Do we still need Stereonets?

- Traditional Stereonet showing planes of faults and intersections
- 3D model + 3D GIS. Area of all west dipping – plunging intersections of major faults on west wall of pit

Conclusions

1. The quality of geological interpretation is still highly dependant on fundamental geology skills needed in exploration and mining.

2. Data collection should be integrated with simultaneous 4D interpretation towards delivering a practical domain-based output.

3. New 3D modelling and querying technologies now offer the ability to rapidly create and update complex 3D models and interrogate large, complex data sets in 3D.

4. These powerful 3D models still need to be based on good geometrical constraints, from maps and orientated core, and geometrical principals enforced by traditional tools.

5. Fostering the fundamental geology skills in conjunction with new technologies is essential to make new discoveries and to solve the complex problems earth science poses that extend beyond and below the surface.
Applied Structural Geology in Exploration and Mining

CM3 – Structural analysis of fault and vein systems
Analysis of faults

- Geometry of faults in 3D;
- Fault networks, patterns and classification;
- Fault growth and dilational jogs;
- Character; Brittle vs. ductile, alteration, veining;
- Timing;
- Kinematics; Movement sense and direction;
- Veining
Fault patterns in 3-D

- Faults form 3-D linked arrays that move co-operatively to accomplish "balanced" deformation of rock masses;
- Too many published interpretations show cross-cutting lineaments and faults without mutual offset.

Fault patterns in Athabasca Basin, Canada

What is wrong with this interpretation?

From Jefferson et al. 2007
Fault networks

Linked arrays of faults:
• Basin linkage in the North Sea, off Norway (top);
• Main faults in the Pannonian Basin, Hungary (bottom).

On a global scale, linked networks of divergent, convergent and transform (strike-slip) plate boundaries form a first-order fracture system in Earth’s lithosphere.
Fault networks

Also 2\textsuperscript{nd} order fault system – transfer faults

Strike-slip pull apart basin

Normal-detachment fault array

Imbricate thrust duplexes
Conjugate Fault Relationships

• Important Factors:
  • Rock type;
  • Confining pressure;
  • Pre-existing anisotropy or surfaces;
  • Subsequent deformation/flattening.

Brittle conjugate faults in sedimentary rocks

Brittle ductile conjugate faults in migmatitic metasedimentary rocks

Riedel Fault Relationships

• R shears small angle to main shear, synthetic movement
• P shears synthetic movement
• R’ shears conjugate antithetic shears, high angles to main shear

Identification of different fault orientations and their kinematics can aid in understanding fault systems as a whole
Sinistral Riedel Fault System

Cerro Bayo Epithermal Silver Deposit
Fault Classification

- Faults are classified by their sense of slip.
- Specific differences in the nature of the fault types reflect their orientation and sense of slip relative to geological layering and the Earth’s surface.

Analysis of faults

- Geometry of faults in 3D;
- Fault networks, patterns and classification;
- Fault growth and dilational jogs;
- Character; Brittle vs. ductile, alteration, veining;
- Timing;
- Kinematics; Movement sense and direction;
- Veining.
Fault Displacement

- Fault displacements vary over the fault surface.
- At a broad-scale, the variations are systematic.
- Tip-lines are rarely regularly-shaped.
- Usually faults are not isolated, but part of an array.

Fault Growth

- Despite the geometrical differences between fault types, the growth of all faults are controlled by two basic processes:
  - Fault propagation and segmentation; and
  - Fault segment linkage.
- These processes account for nearly all aspects of fault geometry and fault rock content.
Fault Propagation and Segmentation

Tip-line bifurcation:
Localized retardation in propagation of the fracture front results in segmented fault array.

Fault Linkage

Displacement 1: Closely spaced segments link
Displacement 2: More widely spaced segments link
Displacement Profile
Fault Linkage: Examples

Dilational jog along low-angle reverse fault

Dilational jog along low-angle normal fault

Segmentation and Dilational Jogs

- Tendency to think in 2D but, in 3D, similar to other fault systems;
- Kinematics are favourable for dilation and fluid flow.
Dilational Jogs

Dilation (Veins) at Fault Steps

Steeper dipping segment of a normal fault

Shallower dipping segment of a reverse fault

Right-handed step on a dextral strike-slip fault (or left-handed step on a sinistral strike-slip fault)

Dilational Jogs

Left-side-up + right-lateral shift = extensional plunge

Right-side-up + left-lateral shift = extensional plunge
Analysis of faults

- Geometry of faults in 3D;
- Fault networks, patterns and classification;
- Fault growth and dilational jogs;
- Character; Brittle vs. ductile, alteration, veining;
- Timing;
- Kinematics; Movement sense and direction;
- Veining.

Fault Zone Heterogeneity

- Fault segmentation and linkage processes result in highly-variable width and content (fault rock types) of fault zones.
- Fault zone thickness can range over 3 orders of magnitude for a particular displacement.
- Drillhole intersections of the same fault will not be the same.
- Consequently, faults are horrible to correlate from drillhole information.
Permeability is unlikely to be the same everywhere on an active fault zone:

• Highest where damage is most intense; and
• Principally localized by irregularities (bends, branches, steps, jogs).

Fault Damage Zones and Permeability

Damage zones around irregularities along fault zone are zones of enhanced permeability

Fault Damage Zone Permeability

Where is the greatest permeability for fluid flow?
Where will the veins, stockwork and highest mineralization concentrate?

Faulkner et al., 2010
Fault Zones and Permeability

- Slip on faults is often triggered by the presence of fluids (e.g.) groundwater.
- Hence, fluids promote fault movement and further increase of permeability.

Fluids diminish the strength of structures

Brittle Faults and Ductile Shear Zones

- Deformation regime depends upon: temperature, pressure, strain rate, composition and the presence of pore fluids;
- Deformation regime commonly changes during progression of an orogeny.
Brittle vs. Ductile Faults

Brittle
- Discrete discontinuities accommodate displacement;
- Commonly faults are segmented on a range of scales; and
- Contain variety of fault rocks (e.g. breccia, gouge) which partially reflect the strain accommodated by the fault.

Ductile
- Deformation is continuous with wall rocks;
- Strongly developed planar and linear preferred orientation fabrics; and
- Strain is reflected in the intensity of the foliation.

Rock-types in faults

- Incohesive gouge and breccia ± pseudotachylite
- Cohesive crush Breccias and cataclasites ± pseudotachylite
- Cohesive foliated high-strain zones and mylonites
Rock-types in faults

- Breccia and pseudotachylite
- Cohesive crush breccias and cataclasites
- Gouge
- Cohesive foliated high-strain zones and mylonites

Analysis of faults

- Geometry of faults in 3D;
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- Character; Brittle vs. ductile, alteration, veining;
- Timing;
- Kinematics; Movement sense and direction;
- Veining.
The Importance of Getting Timing Right

- Application of structural control principles requires that the timing of mineralisation must be carefully matched with the history of activity on the fault system.

Applied Structural Control Principles

- Determine the timing of mineralisation in the event history and match it to the history of movement on the fault/shear zones in the region.
Single progressive deformation event

This cross-section is from a gold deposit in which folds, foliation, faults and veins formed during a single deformation event.

Analysis of faults

- Geometry of faults in 3D;
- Fault networks, patterns and classification;
- Fault growth and dilational jogs;
- Character; Brittle vs. ductile, alteration, veining;
- Timing;
- Kinematics; Movement sense and direction;
- Veining.
Kinematic Analysis

- Only way to be sure of the movement on a fault is if we can observe a displaced marker and a fault lineation.
- Together, these yield absolute displacement.
- Normally we don’t have this information so have to rely on secondary information – *kinematic indicators*.
Shear sense

Ground Rules:
• Shear sense can be reliably determined only on sections at high angle to fault / shear zone and parallel to transport / stretching direction (i.e. lineation);
• If possible, determine direction of displacement before looking for shear sense indicators; and
• You must say which way you are facing to be unambiguous.

To correctly observe sense of shear indicators, look at plane perpendicular to foliation & parallel to lineation

Lineations

• Lineations probably are the most useful of all structures
• 2 basic types of lineations occur in deformed rocks:
  • Intersection lineations; and (See CM4: Analysis of Folds)
  • Stretching, extension or mineral lineations.
Stretching, extension & mineral lineations

Lineations in fault rocks are the main indicators of displacement direction.

The 3 most important lineations include:

1. **Slickenlines** (grooves, striations) on fracture surfaces (slickensides) sub-parallel to fault zone;

2. **Fibre lineations** in vein-fill on fault plane; usually quartz or calcite; and

3. **Stretching / mineral lineations** in the foliation surface in ductile shear / fault zones.

Analysis of faults

- Geometry of faults in 3D;
- Fault networks, patterns and classification;
- Fault growth and dilational jogs;
- Character; Brittle vs. ductile, alteration, veining;
- Timing;
- **Kinematics – Brittle Faults**;
- Veining.
Lineations on brittle fault surfaces

Lineations are common on fault surfaces, either:

1. Due to grooving parallel to the movement direction called "slickenlines" (on fault surface or "slickenside");

2. Mineral fibres that grow on the fault surface parallel to the movement direction.

Lineated brittle fault rocks

Striations (slickenlines) on fault surface (slickenside) dipping steeply

Slickenlines on fault surface, Detour Gold project, Ontario.
Slickenlines on fault surface, Seabee Gold Mine, SK.
**Kinematic Indicators: Brittle Faults**

- **Slickenfibres**
  - Initial fracture
  - Shear and extension
  - Broken - appears step-like

- **Planar Extension Fractures**
- **Crescent Shaped Extension Fractures**
- **Linear Step**
  - Striated secondary fracture
  - Unstratified secondary fracture
  - Unstratified surface

---

**Fibre lineations on fault surface**

Local separation of fault surfaces filled with vein material, commonly thin fibres or films of quartz or calcite.

(Gap faces in direction of movement of opposite face)
**Mineral fibre growth**

In quartz, galena and gold – kinematics during ore formation!

6191M stope sample, Con gold deposit, Yellowknife

**Steps on fault surfaces**

Steps perpendicular to slickenlines and mineral fibres are assumed to face in direction of movement of opposite side of fault.
Steps on fault surfaces (cont.)

How would you classify this fault?

- Dip or strike slip?
- Normal, reverse, dextral or sinistral?

West Bay Fault, Yellowknife, Canada

Steps on fault surfaces (cont.)

Steps perpendicular to slickenlines & mineral fibres;
Surface dips 90 degrees;
What is the sense and direction of shear?
Exercise 3: Fault Problems

breccia with quartz-sulphide matrix
Exercise 3: Fault Problems

(a) a N-S striking strike-slip fault,
(b) a N-S striking normal fault,
(c) an E-W striking reverse fault, or
(d) a N-S striking reverse fault?

granite
fault
200 m
Analysis of faults

- Geometry of faults in 3D;
- Fault networks, patterns and classification;
- Fault growth and dilational jogs;
- Character; Brittle vs. ductile, alteration, veining;
- Timing;
- Kinematics – Ductile shear zones;
- Veining.

Tectonite Fabric Elements

- Stretching Lineation: Aligned and stretched clasts and/or minerals.
- Schistosity: Planar foliation defined by alignment of platy minerals.

- Depending upon the type of strain, the rock may contain planar, linear or both fabric elements.
Foliation Definitions

- **Foliation**: a planar fabric that is usually associated with a deformational origin.
- **Slaty Cleavage**: typical of slates (e.g., weakly metamorphosed shales) — individual aligned mica flakes (too small to observe by eye).
- **Schistosity**: (schistose foliation): typical of moderately to strongly metamorphosed schists — individual mica grains define foliation (large enough to observe in hand specimens).
- **Gneissosity**: (gneissose foliation): typical of high-grade metamorphic rocks — coarser-grained, non-micaceous minerals predominate — folia tend to anastomose around pods of minerals more resistant to deformation.

Tectonite Fabric Elements

- Strong planar (gneissose) foliation
- Flattened conglomerate
Stretching lineations

- Stretching, extension or mineral lineations form parallel to the elongation, stretching or tectonic transport direction in deformed rocks. They are useful as strain or movement indicators;

- Foliations & stretching lineations are part of the 3D rock fabric formed by deformation, i.e. not separate structures, and reflect the 3D nature of the strain.

Stretching lineations (continued)

- Markers (e.g. pebbles, fossils, breccia fragments) provide clear and direct evidence of rock strain and define stretching / extension lineations;

- Most metamorphic rocks do not contain markers. However they commonly exhibit elongation of metamorphic mineral grains that define the rock fabric (e.g. mica, amphibole). These can be visible with the eye, but are commonly microscopic and can be used as a mineral lineation that reflects 3D strain;

- Stretching lineations are very valuable indicators of movement or tectonic transport direction, especially in shear zones.
**Stretching lineation**

Strong stretching lineation in ductile fault zone

Indicates vertical (dip-slip) movement

---

**Stretching lineation**

Strong stretching lineation (quartz and amphibole) in vertical ductile fault zone

Porphyroblasts of staurolite not lineated!!

What does this indicate about timing of ductile deformation vs. metamorphism?

Indicates oblique movement
**Sense of shear in individual zone**

Foliation in ductile shear zones oblique to zone boundaries
Obliquity reflects sense of shear

Caledonian Orogeny, Doughruagh, Ireland

DEXTRAL ductile shear zone

---

**Sense of shear in individual zone**

Hornblendite dike (black) has been highly deformed & thinned in shear zone

Kamila shear zone, Kohistan, Pakistan
S / C fabrics in fault / shear zone

In ductile shear zones, shear commonly occurs in "mini" shear zones — heterogeneous strain

Compare to a pack of cards, except that some deformation occurs between the slip surfaces.

S / C fabrics (continued)

The less deformed layers are equivalent to the margins of the shear zone proper, and may develop an oblique foliation related to the sense of shear.

Individual shear zones are C-surfaces ("cisaillement" is French for "shear"), and oblique folia between them are S-surfaces ("schistocité is French for "foliation")
S / C fabrics in fault / shear zone

What is the sense of shear?

Cape Ray Fault Zone
Dube et al., 1996

S / C Fabrics in Fault / Shear Zone

What is the sense of shear?

Cerro de Maimon,
Dominican Republic
Asymmetrical rigid objects

Clasts of relatively rigid (competent) material like boudins or large crystals (porphyroclasts or porphyroblasts)

What is the sense of shear?

Strain Markers

Boudinaged veins in combination with a lineation can be powerful kinematic indicators.
Strain Markers

What is the sense of shear?

Asymmetrical strain (pressure) shadows

3 possibilities:

1. Asymmetrical elongation of deformed, recrystallized “tails” of porphyroclasts;

2. Asymmetrical fibre overgrowths in “pressure shadows”;

3. Asymmetrical lenses of residual, less deformed matrix, protected by the porphyroclast.
Strain (pressure) shadows

What is the sense of shear?

Shear bands

Shear bands may develop in homogeneous, strongly foliated rocks especially in the most intensely deformed parts of shear zones

Sense of shear in the band is the same as the overall sense of shear in shear zone
Analysis of faults

- Geometry of faults in 3D;
- Fault networks, patterns and classification;
- Fault growth and dilational jogs;
- Character; Brittle vs. ductile, alteration, veining;
- Timing;
- Kinematics;
- Veining.

Veins in fault / shear zones

- Veins form in or adjacent to both brittle and ductile zones, and they are the most useful indicators of direction and sense of displacement.
- Mineralized veins are especially useful - WHY???
- Veins generally form oblique to their related fault, and the sense of obliquity is related to fault movement direction / sense.
Veins exploit pre-existing fabric

Folded bedding parallel quartz vein, Goldenville, Nova Scotia

Bedding parallel vein, Hill End Mine, NSW, Australia

Fold Geometry – Control on Veins

Schematic model of vein formation

Flexural slip

Flexural flow

Tangential longitudinal strain

Vein variation, Sheephead anticline, Bendigo from Cox (2005)

Laminated and extensional veins, Swan decline, Bendigo
### Vein styles

<table>
<thead>
<tr>
<th>Vein Type</th>
<th>Internal Features</th>
<th>Structural Site</th>
<th>Geometry</th>
<th>Formation Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault-fill veins</td>
<td>foliated wallrock slivers; slip surfaces; fibres at low angles to vein walls</td>
<td>shear zone or fault; fold limbs</td>
<td>parallel to host structure</td>
<td>shear fracturing; extensional opening of existing fractures</td>
</tr>
<tr>
<td>Breccia Veins</td>
<td>angular clasts, no rotation</td>
<td>along faults</td>
<td>parallel to host structure</td>
<td>fault slip</td>
</tr>
<tr>
<td>Extensional veins</td>
<td>mineral fibres at high angle to vein walls</td>
<td>outside shear zones; AC joints in folds</td>
<td>planar veins at moderate angle to shear zone; perpendicular to fold hinge</td>
<td>extensional fracturing; extensional-shear fracturing</td>
</tr>
<tr>
<td>Extensional</td>
<td>internal layering: multiple openings</td>
<td>within shear zones</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stockworks</td>
<td>2 or more oblique to orthogonal vein sets</td>
<td>non specific</td>
<td>tabular to cigar shaped zones</td>
<td></td>
</tr>
<tr>
<td>Jigsaw Puzzle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault breccias</td>
<td>vein and wallrock clasts, rotation and abrasion</td>
<td>fault or shear zone</td>
<td>parallel to host structure</td>
<td>fault slip</td>
</tr>
</tbody>
</table>

Adapted from Robert et al. 1994

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### Vein styles

From Robert and Poulsen, 2001
Vein styles: laminated fault-fill veins

Schematic representation of lateral zoning in vein to wallrock ratio

Sketch of individual veinlets amalgamating to form larger laminated quartz lenses. Sigma deposit, Val d’Or

Vein styles: laminated fault-fill veins

Fault-fill veins with carbonate alteration. Motherlode, California

Fault-fill veins with carbonate alteration. Pamour deposit, Timmins

Fault-fill vein. Hoyle Pond deposit, Timmins

Fault-fill veins with sericite alteration. Con deposit, Yellowknife

Robert et al. (1994)
Vein styles: extensional veins

Robert et al. (1994).

- Planar extensional vein x-cutting shear zone;
- Arrays of sigmoidal extensional veins (tension gashes) in shear zone;
- Planar extensional veins within shear zone.

Vein styles: extensional veins

- Extensional quartz-tourmaline vein. Red Lake.
- Quartz tourmaline vein, Buffalo deposit, Red Lake.
- Extensional calcite vein array. Giant deposit, Yellowknife.
- Extensional quartz vein array, Black Fox deposit, Timmins.
Vein styles: stockwork and breccia veins

Stockwork and breccia veins can be regarded as composite structures resulting from a combination of multiple sets of veins and fractures.

Veins as Kinematic Indicators

- Where high pore fluid pressures dominate (many hydrothermal environments), vein orientations can help determine the kinematics.

- Sub-horizontal veins:
  - Contractional.

- Sub-vertical veins:
  - Parallel to faults: extensional.
  - Or
  - Oblique to faults: transcurrent.

After Sibson (1990)
Veins as Kinematic Indicators

Cross-section View

Vein system, Obotan deposit, Ghana

Bogosu Au Deposit, Ghana, West Africa

200 kms

PHANEROZIC
Volta basin
PALEOPROTEROZIC
Granitoid rocks
Sedimentary rocks of the Tarkwaian Group
Sedimentary rocks of the Birimian Supergroup
Mafic igneous rocks of the Birimian Supergroup
Undifferentiated granitoids and gneiss (partly Archean?)
Major thrust faults
Mine or prospect
Veins as Kinematic Indicators

- The Bogoso Mine occurs 60km to the SW of Ashanti along the same regional strike-slip fault system;
- Gold mineralization occurs at bends along the strike-slip system;
- Note vein geometries associated with opposing bends!

Veins in fault / shear zones

Vein (tension gash)

Compression Direction
Tension Veins

**S-shaped en echelon tension veins** indicate a sinistral movement.

**Z-shaped veins** indicate dextral movement.

Increasing deformation.
**Tension Veins**

What is the sense of shear?

**Veins & brittle faults (continued)**

Dextral movement
Vein networks

Relationship between reverse (compressional) fault, dilation and veining.

Vein networks

Relationship between normal (extensional) fault, dilation and veining.
Vein networks

Relationship between strike-slip (wrench) fault, dilation and veining.

Vein networks

Patterns of faulting and associated veining

Indicates two different episodes of faulting
Exercise 4: Epithermal Vein Geometry

Discovery outcrop - narrow silicified fault zone & veins. Fault dips 60 degrees East. 35 g/t Au vein sample.

Narrow silicified fault zone - same as outcrop 4m @ 9 g/t Au.
Fault dips 60 degrees East. 35 g/t Au vein sample.

Dilational Qz vein breccia averaging 25 g/t Au over widths shown.

Narrow quartz veins with variable Au grades.

Narrow silicified fault zone - same as outcrop 2m @ 6 g/t Au

Narrow, crustiform quartz vein - Grading 4 g/t Au over 2m.

50m
Applied Structural Geology in Exploration and Mining

CM4 – Structural analysis of folds and fold systems
CM4 – Structural analysis of folds and fold systems
Folds

- Basic geometry;
- Orientations of bedding and axial planar foliation;
- Fold vergence;
- Intersection lineations as indicators of fold axes;
- Younging and structural facing;
- Fold sequencing and fold patterns; and
- Recognizing transposition.

Fold Geometry

For each fold we can measure:
- Limb orientations
- Fold axis (hinge line)
- Fold axial plane
- Interlimb angle
Fold Type – Based on Interlimb Angle

Isoclinal

Tight

Close

Open
Fold Geometry

Cylindrical folds:
- Rectilinear hinge line;
- Constant limb orientations;
- Planar axial surfaces.

Non-cylindrical folds:
- Curvilinear hinge lines;
- Variable, but usually systematic, limb orientations;
- Planar or curviplanar axial surfaces.

Fold Geometry

Doubly-plunging Folds

- Folds are rarely cylindrical;
- Like displacements on faults, fold amplitudes may vary along strike.
Why do we need to know about folds?

- Many ore deposits occur in orogenic belts and are geometrically related to the structural architecture.
- **Pre-deformation mineralization**: will be folded along with the host sequence;
- **Syn-deformation mineralization**: location and/or plunge or ore shoots commonly related to fold structure; and
- **Post-deformation mineralization**: along inherited structure e.g. faults along fold limbs.
- It is essential to understand the timing relationship between the deformation events and mineralization in order to interpret the structural controls correctly.

Folded Sulphide Ore Zone – Pre-Folding

- Stratiform sulphide thickened in fold closure into an accumulation of sufficient size to form orebody;
- Plunge of ore is plunge of folds; and
- Structural analysis can predict location of fold hinges and thus aid exploration targeting.
Folded Mineralized Zone – Pre-Folding

Folding Makes Space for Fluid Flow

Subhorizontal extension veins

Fault breaching fold hinge
Fold Geometry – Control on Veins

Schematic model of vein formation

Tangier anticline, Meguma district, Nova Scotia

Caribou deposit, Nova Scotia

Goldenville district, Nova Scotia

Flexural slip

Folded vein, Deborah deposit, Bendigo

Vein variation, Sheepshead anticline, Bendigo from Cox (2005)

Laminated and extensional veins, Swan decline, Bendigo
Post-Folding Skarn Mineralization: Antamina, Peru

In folded terranes, hinge zones are good targets for a variety of mineralization styles. Ore plunge is commonly (but not always) parallel to fold plunge.

Where are the fold hinge zones? What is their plunge?
How do we identify folds?

- Bedding orientation changes across a fold hinge;
- Younging direction changes across a fold hinge:
  - Gross stratigraphy;
  - Younging indicators.
- Older rocks in core = anticline; and
- Younger rocks in core = syncline.

Foliations and Folds

Folds are often intimately related to foliation (cleavage or schistosity). Axial planar foliation generally parallels fold axial plane.
Axial Planar Foliations and Folds

Axial planar foliation is often constant, therefore a range in the intersection angle between bedding and foliation occurs.

Bedding and Axial Planar Cleavage

Using bedding-cleavage relationships we can start to determine the geometry of a fold.
Which way is the antiformal hinge?

Crenulation Cleavage

Outcrop showing bedding crenulated by small folds

Alignment of fold limbs forms a crenulation cleavage

Is this outcrop in the hinge or the limb of a larger fold?
Foliation Development and Lithology

• Development of a foliation (cleavage or schistosity) depends on presence of platy minerals (e.g. clays, micas, amphiboles etc.); and
• Foliation can appear very different in rocks with more / less abundant platy minerals.

Foliation Development and Lithology

The muddy horizons have developed a cleavage, and the sandy horizons have not.
Fold Vergence - Parasitic Folds

- The two limbs of an ideal fold are mirror images;
- This symmetry relationship is a powerful tool for determining the position of an outcrop-scale fold on a large structure;
- Small folds on limbs of larger structure are generally asymmetrical; and
- This sense of asymmetry is used to locate fold hinges.

- 'S' folds - limbs
- 'M' or 'W' folds – hinge
- 'Z' folds - limbs
Parasitic Folds

'S' Folds in Sand/Silts

Parasitic Folds in Psammites

Fold axial planar cleavage

Parasitic Folds (continued)

Additional examples:

domainal development of parasitic folds
**Vergence in the Field**

Parasitic folds are especially useful to locate the position of axial traces of major folds in areas of poorly exposed, tight isoclinal folding.

**Vergence Reality**

Variable plunge causes apparent changes in vergence.

Always determine vergence when looking DOWN-PLUNGE.
View Folds Down-Plunge

This vertical section is up-plunge (so vergence is opposite to map view) and fold profile is stretched.

Down-plunge section gives true view of fold geometry and same sense of fold vergence as map.

Orientations of Major Folds

• How do we determine the orientations of major folds?

• The following data is available from most folds:
  • Axial planar foliation;
  • Bedding or earlier foliation that defines the fold; and
  • Parasitic folds.

• The intersection of these planes yields an intersection lineation that is parallel to the fold axis.
Intersection Lineation

- The intersection of bedding and cleavage form an intersection lineation, which is parallel to the fold axis.

- On fold limbs, the lineation is best observed on cleavage surfaces.
Intersection Lineation

Common Intersection Lineations

Bedding/cleavage intersection.

Crenulations of an earlier foliation.
Intersection Lineation

- Not to be confused with mineral stretching lineations which may be either parallel or perpendicular to the fold axis

Bedding-Cleavage Relationship (vergence)

Bedding-cleavage relationships can be used to determine the position of an outcrop-scale fold in a larger structure.

Is the nearest antiform located to the left or right of this outcrop? (or: what is the vergence?)
**Bedding-Cleavage Relationship (vergence)**

- Using only bedding-cleavage relationship, the antiform is inferred to be to the right of the outcrop i.e. vergence is to the right.

![Diagram of bedding and cleavage angles in fold limbs](image)

**Structural Facing**

- **Structural Facing** is rather complexly defined as: the direction of younging resolved in the foliation at right angles to the fold axis;

- **Facing**: the direction in which the axial plane of a fold passes through younger layers. This term applies to the whole fold.

- **Younging**: the direction towards which a rock unit or layer decreases in age. This direction changes around a fold.
Geometry and Facing

- Direction of younging in the cleavage plane is the structural facing (direction);
- Facing provides information on structural history.

The following slides examine each of these outcrops.

Fold Geometry at Depth

- Change in younging direction suggests that outcrops are on opposite limbs of a fold;
- In outcrop A, bedding is steeper than cleavage;
- In outcrop B, bedding is shallower than cleavage.

Fold is synformal but…
**Fold Geometry at Depth**

.. the fold is also an anticline!

Fold is a synformal anticline.

**Facing — Outcrop A**

Is the facing direction upwards or downwards?

Graded bedding
Facing — Outcrop A

The graded bedding youngs upwards, but faces downwards on the cleavage surface.

Facing — Outcrop B

Is the facing direction upwards or downwards?

Cross-bedding
Facing — Outcrop B

The cross-bedding *youngs and faces downwards* on the cleavage surface.

Why facing is important?

Downward facing implies earlier inversion
Exercise 5: Fold Problems
Fold Sequencing

What structures would you select as being potentially critical in this outcrop?

Polyphase Folding

Structural succession
- Primary compositional layering (S₀);
- Early penetrative foliation parallel to layering (S₁), shown by minor veins;
- Isoclinal folding of S₀ and S₁ around F₂ and development of new axial planar foliation S₂;
- Folding of S₀, S₁ and S₂ around F₃. No axial planar foliation is observed.
Fold interference patterns are a function of the relative orientations of the different fold phases.

BUT ALSO:
On the outcrop, the pattern will depend on the orientation of the exposed surface.

Only 2 fold phases!

Overprinting Deformation Events: Fold Interference

TYPE 1 or Dome-and-Basin Fold Pattern is produced where fold axial traces are at high angle and both fold generations are upright or inclined.
Overprinting Deformation Events: Fold Interference

TYPE 2 or Arrowhead / Mushroom Pattern is produced where fold axial traces are at high angle, but one fold generation is upright to inclined and the other is recumbent or reclined.

After Ramsay, 1976
**TYPE 3 or Wavy Tail Pattern (coaxial)** is produced where the fold axes are parallel or sub-parallel, and one generation of fold is upright to inclined and the other is recumbent or reclined.

After Ramsay, 1976

**Fold Interference**

What type of interference pattern is defined here?

Refolded folds in gneiss, Ruby Mountains, Elko County, Nevada (From NBMG Photograph Archive)
Analysis of Multiply-Folded Areas

- Start with the last fold event – fold axes will be linear, fold axial planes will be planar; both will have consistent orientation over reasonable area
- Use regional data – patterns may be more obvious on large scale than on pit/mine or outcrop

Analysis of Multiply-Folded Areas

- Once you have an understanding of the geometry of the last fold phase, work backwards to ‘unfold’ previous deformation phases (e.g. by looking at bedding/cleavage asymmetry etc.)
Analysis of Multiply-Folded Areas

Even the most complex areas can be puzzled out with a bit of time and patience.

Foliation Generations

- It may be possible to distinguish between different generations of foliation and relate these to different fold events; and
- If so, it is possible to analyze structure using $S_2/S_1$ relations etc. as analogy to $S_1/S_0$ relations in regions with only one phase of folding.
Foliation Generations

• But remember that foliation is developed to different degrees in different rock types – some may show \( F_2 \) folding with no new foliation, whereas others may have penetrative \( S_2 \) foliation that obliterates earlier \( S_1 \) cleavage.

Foliation Generations

• Also remember that some rocks develop an early bedding-parallel foliation - it is common to have one more phase of foliation than of folding!
• The foliation may be related to extension rather than folding – look for other evidence e.g. boudinage.
Transposition: Folding and High Strain

- When the %$#&*# really hits the fan…

Sub-parallel sand lenses in silty shale form depositional(?) texture with enigmatic origin…

- Transposed folds are often more easily defined by their ‘enveloping surface’
**Transposition: Folding and High Strain**

- Implications for exploration
- Mapped distribution of high grade appears to join up across strike
- Enveloping surface defines folded layer

**Transposition in Thin Section**

- To illustrate the guiding principal that geological structures are repeated on all scales: transposition of a silty layer in a graphitic schist. (Long axis of section 5mm).
Sheath Folds: Folding and High Strain

- Sheath folds have curvilinear fold traces, and the fold axes reverse their plunges around a point;
- Sheath folds initiate as cylindrical folds with axes perpendicular to the transport direction and stretching lineation;
- With progressive shear, the axes rotate to become parallel to the stretching lineation.

Hanmer and Passchier, 1991

(Twiss and Moores, 1992)

Things to Remember

- Fold symmetry
  - Parasitic folds
  - Vergence (careful of plunge!)
- Fold–fabric relationships
  - Axial planar foliation
  - Folded?
  - Mineralization?
- Structural facing
  - Need ‘way-up’ indicators
  - Important for identifying overturned beds, especially where ‘way-up’, alone, doesn’t work
- Fold sequencing
  - Don’t be intimidated by ‘crazy’ patterns
  - Be mindful of the orientation of the exposed surface
- Folding and High Strain – Transposition and Sheath Folds
  - Enveloping surface
  - Competence contrasts
  - Rotation of fold axes

REMEmber:
Folds are fractal. Small scale mimics larger scales. Relationships identified on the outcrop scale can be applied to the deposit scale and larger.
General Discussion and Questions

THANK YOU!

Баярлалaa
Applied Structural Geology in Exploration and Mining

Exercises
Exercise 1: Fluids and Plumbing

Calculate how much hydrothermal fluid is required to form a 5 million ounce gold deposit.

- Assume 100% efficiency in depositing the gold from the hydrothermal fluid at the deposit site;
- Assume the solubility of gold in the hydrothermal solution is 0.03 ppm;
- Assume 1 ppm = 1 gram per tonne;
- Assume 1 ounce is equal to 31 grams;
- Assume 1 litre of hydrothermal fluid is equal to 1 kilogram; and
- Assume 1000 kilograms is equal to 1 metric tonne.

Method:

1. Convert 5 million ounces into grams;
2. Calculate how many tonnes of hydrothermal fluid are required to form the gold deposit based on the solubility of 0.03 ppm (0.03 gpt); and
3. Calculate how many litres of hydrothermal fluid this is equal to.

Calculate how much hydrothermal fluid is required to form a 135,000 t uranium deposit (e.g. MacArthur River)?

- Assume 100% efficiency in depositing the gold from the hydrothermal fluid at the deposit site;
- Assume the solubility of uranium in the hydrothermal solution is 6 ppm;
- Assume 1 ppm = 1 gram per tonne;
- Assume 1 litre of hydrothermal fluid is equal to 1 kilogram; and
- Assume 1000 kilograms is equal to 1 metric tonne.

Method:

1. Convert 135,000 t into grams;
2. Calculate how many tonnes of hydrothermal fluid are required to form the uranium deposit based on the solubility of 6 ppm (6 gpt); and
3. Calculate how many litres of hydrothermal fluid this is equal to.
Exercise 2: Granny Smith Structure Contours

You are provided with two maps of the Granny Smith Au-Cu deposit, Laverton district, Australia. One shows a grade map for the Granny Smith deposit. The other shows structure contours for the granite-greenstone contact at Granny Smith. Gold mineralization is associated with a major ductile shear zone that occurs at the granite-greenstone contact.

1. Construct a cross-section representing a key high grade gold location along the granite-greenstone contact, then use it to answer the following questions:
   
a. Is gold mineralization preferentially located at shallower or steeper sections of the granite-greenstone contact?

b. What could this tell you about the structural regime during gold mineralization?
GRANITE DEPTH CONTOUR

20m contours
Exercise 3: Fault Problems – Part 1

Fault Analysis Problem 3A: Exercise on mapping & interpreting faults

Is the fault sketched in Fig. 3.1 a normal, reverse or strike-slip fault? Why?

Figure 3.1: Sketch of fault and drillholes
Fault analysis problem 3B

(a) Does the fault shown in Fig. 3.2 have a prospective site on it? Why?

(b) What assumptions have you made in reaching this conclusion?

(c) What information would you seek in the field?

Figure 3.2: Does this fault have a prospective site?
Fault analysis problem 3C

Is the rock sample sketched in Fig. 3.3 from:

(a) a N-S striking strike-slip fault,
(b) a N-S striking normal fault,
(c) an E-W striking reverse fault, or
(d) a N-S striking reverse fault?

Figure 3.3: Sketch of fault outcrop
Exercise 4: Drilling Out an Epithermal Vein / Fault System

The drill section attached summarizes the results of the initial diamond drilling beneath a mineralized fault + vein which outcrops as shown. Before planning additional drilling, it is important to try to work out as much as you can about the structural (and other) controls on the localization of mineralization. Understanding the structural controls will enable you to plan the most effective and efficient drilling program to outline the mineralization and define the resource. It is also important to plan drilling to maximize the acquisition of useful information.

After you have examined the drill section, answer the following questions.

1. What is your initial interpretation of the structural controls on mineralization?
2. What additional structural information would you try to acquire in the outcrop and / or drill core to test and / or refine this interpretation?
3. A visit to the discovery outcrop shows that quartz fibres lineations on the fault plane pitch very steeply on the fault surface. Narrow quartz veins in the outcrop are vertical and vein / core axis angles are consistently about 30 degrees. Construct a cross-section showing the likely structural controls.
4. Has the drilling thoroughly tested the potential on this section? Justify your answer.
Discovery outcrop - narrow silicified fault zone & veins.
Fault dips 60 degrees East. 35 g/t Au vein sample.

Narrow silicified fault zone – same as outcrop
4m @ 8 g/t Au.
Fault dips 60 degrees East.
35 g/t Au vein sample.

Dilational Qtz-vein breccia averaging 25 g/t Au over widths shown.

Narrow quartz veins with various Au grades.

Narrow silicified fault zone – same as outcrop
2m @ 6 g/t Au

Narrow, crustiform quartz vein –
Grading 4 g/t Au over 2m.
Exercise 5: Fold Problems

Several folds are illustrated in Fig. 5.1. Sketch the form of bedding on each face of the block diagrams. Describe and classify these folds. Indicate also the structural facing direction on each block diagram, where appropriate.
Figure 5.1: Block diagrams