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Geology: from exploration to reservoir modelling

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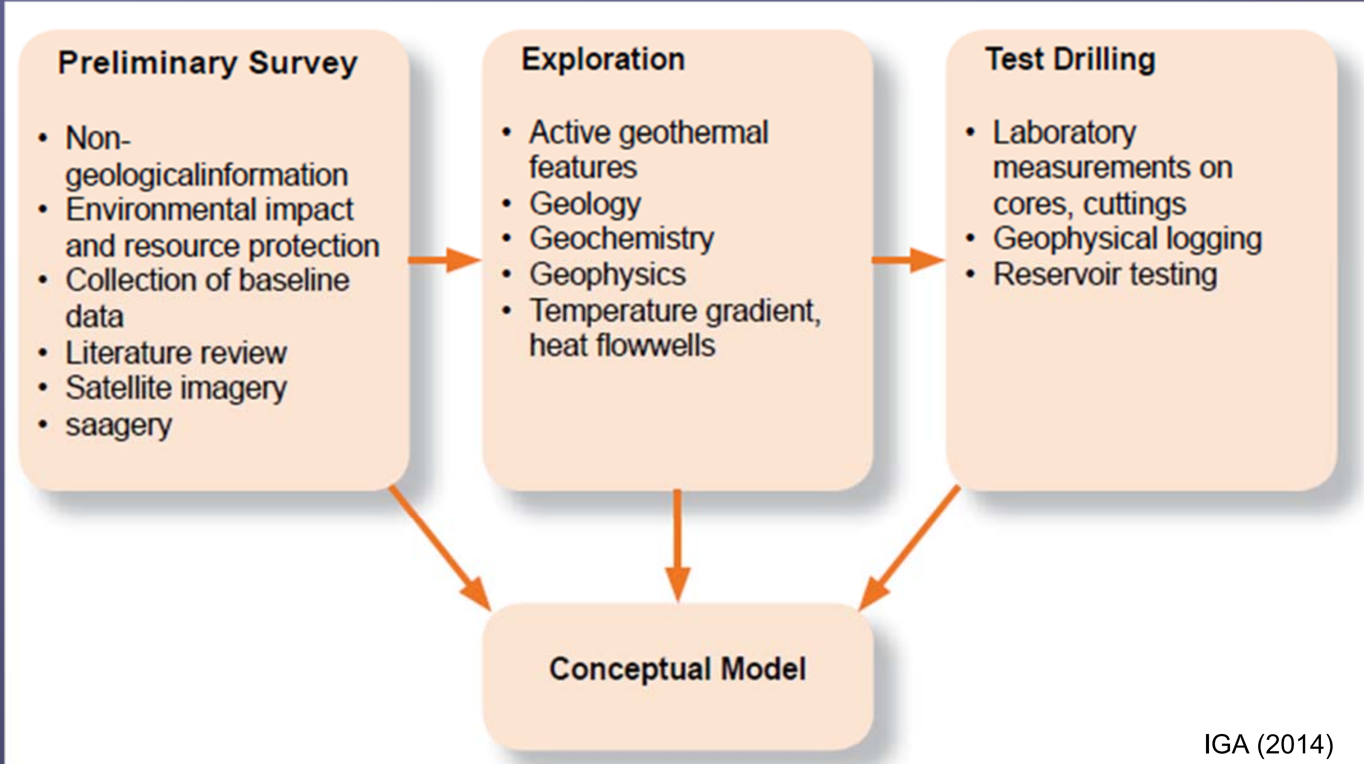
Outline

- Geology in geothermal exploration
  - Geothermal Plays
- Faults & fracture vs fluid flow
- 3D Modelling: why and how
- 3D Modelling: Applications and case study
  - Petrel pratical demonstration (Gullfkas Demo data)
  - Guardia Lombardi example (Vigor Project)

Geothermal Projects

The "Best Practices Guide for Geothermal Exploration" (IGA, 2014) divides the process of developing geothermal projects into eight phases as follows:

1. **Preliminary survey**
2. **Exploration**
3. **Test drilling**
4. Project review and planning
5. Field development
6. Power plant construction
7. Commissioning
8. Operation



IGA (2014)

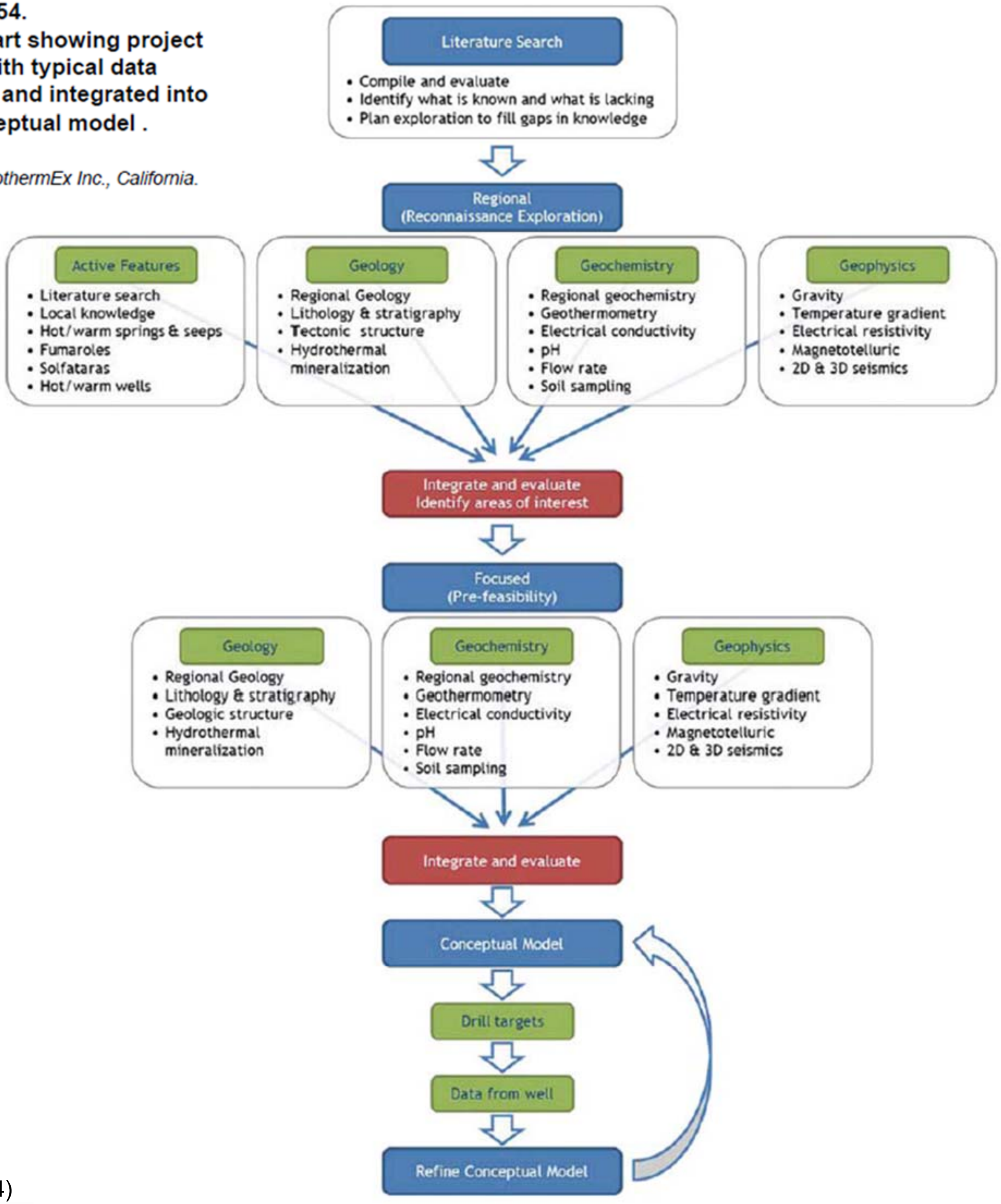
Geology is a key ingredient during all the life of a geothermal project and, particularly, during the first three phases.

Flow Chart

A different representation of the first three phases

Figure 4.54.
Flow chart showing project stages with typical data acquired and integrated into the conceptual model .

Source: GeothermEx Inc., California.



IGA (2014)

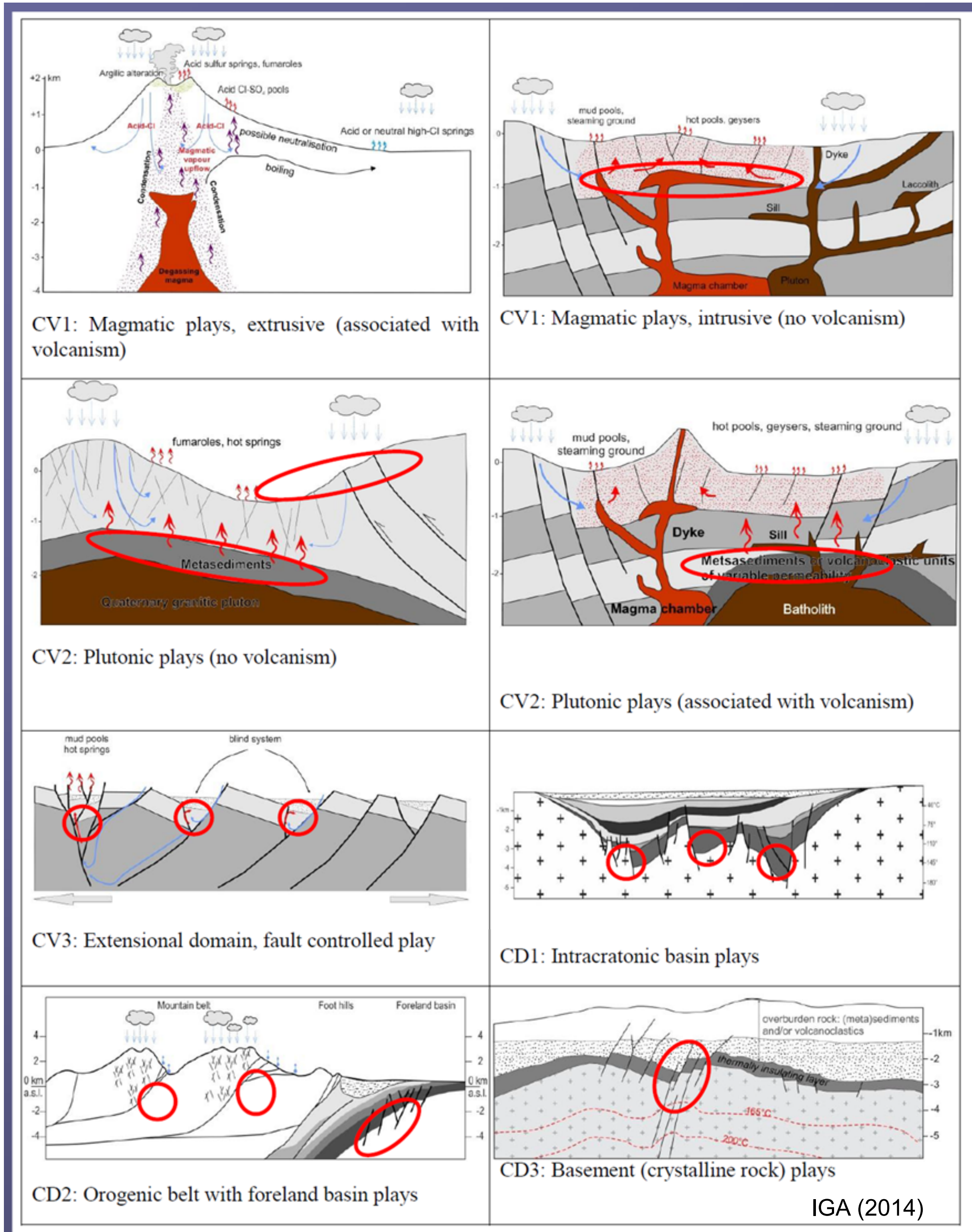
Phase 1: Preliminary Survey

- Understanding of the legal, social, environmental, and geological parameters to get confidence that development of a power plant will be allowed should a viable geothermal resource be discovered
- Work program to assess the already available evidence for geothermal potential within a specific area and to identify relevant geothermal play types to guide subsequent activities

MAPS	DATA FROM LITERATURE	PURCHASABLE DATA
• Topographic map(s) showing geothermal license area(s)	• Active geothermal features	• Maps
• Map(s) showing areas licensed to others around subject license area(s)	• Geological data and reports	• Aerial photos
• Map(s) of easements or other rights of use	• Tectonic history	• Satellite imagery
• Map(s) of land use restrictions	• Geochemical data and reports	• Digital elevation model
• Geological maps	• Geophysical data and reports	• Geological data
• Geophysical maps	• Surface temperature data	• Geochemical data
• Other maps	• Subsurface temperature data from existing wells	• Well logging data
• Regional heat flow	• Seismicity records	• Geophysical data
		• Satellite imagery,
		• Aerial photogrammetry
		• LIDAR

IGA (2014)

- Published data and other information typically sought during the literature review
- Geographic scope may be regional or national. At the highest level, the survey seeks to identify geological settings that might host economically viable geothermal systems
- Regional GIS and 3D models may be useful for data integration and visualization



Geothermal Plays: 1

- Geothermal play: conceptual model of how a number of geological factors might generate a recoverable geothermal resource at a specific structural position in a certain geologic setting
- The main division of geothermal play types follows that of Rybach (1981) based on the dominant heat transfer mechanism, namely, convection (CV) and conduction (CD) dominated
- Red marked areas indicate the region with the highest chance of production in each play type.

Geothermal Plays: 2

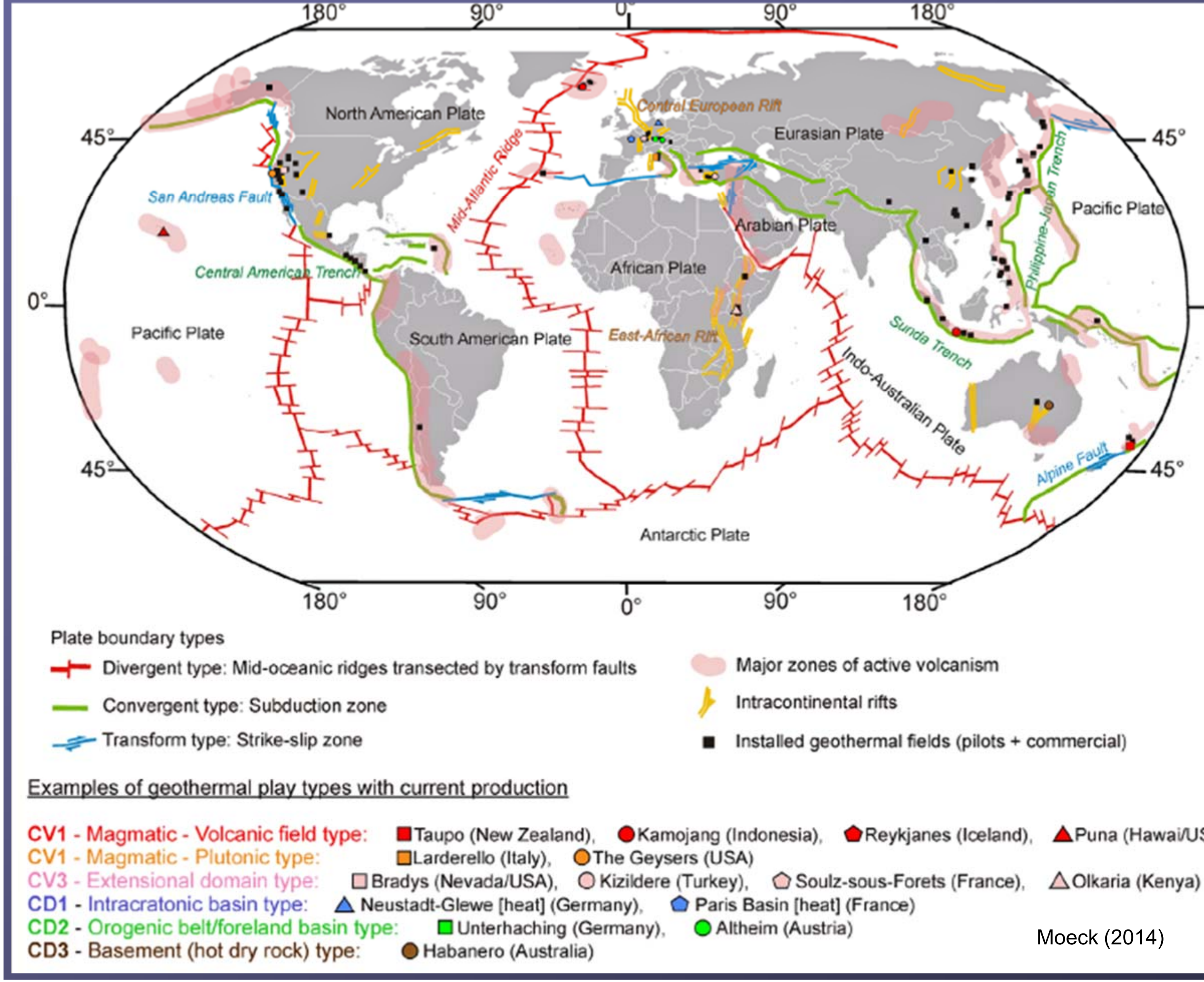


Plate tectonic framework controls the thermal regime, hydrogeological regime, fluid dynamics, fluid chemistry, faults and fractures, stress regime, and lithological sequence

Phase 2: Exploration

GEOLOGICAL DATA

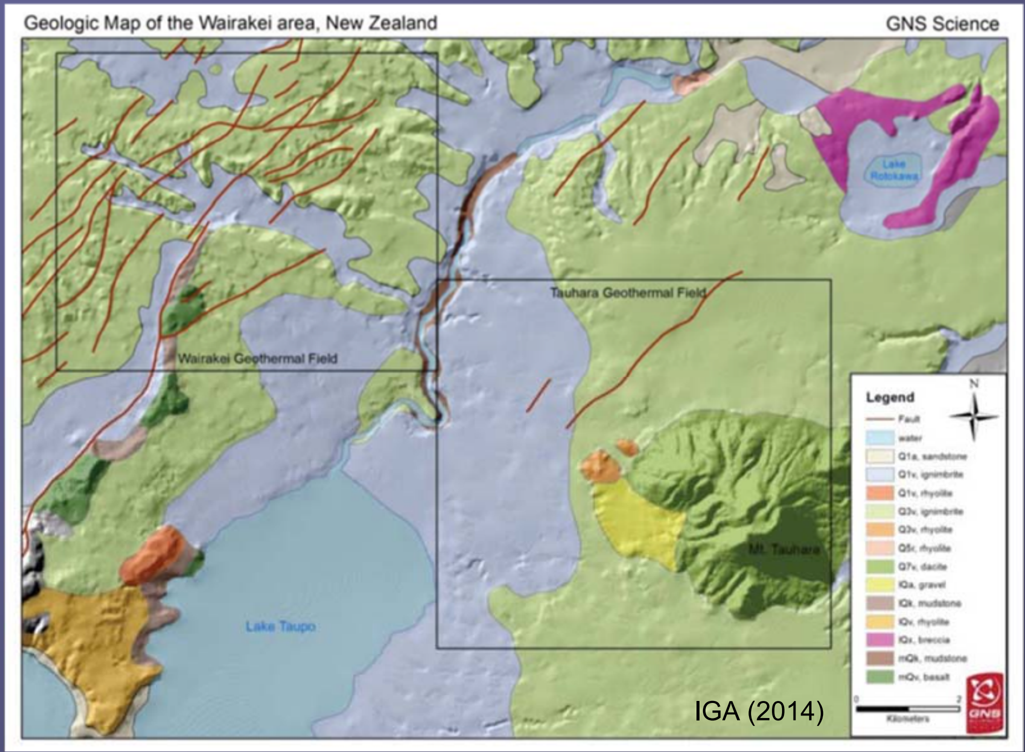
- Geological map(s) of license area(s)
- Geological cross sections of license area(s)
- Summary descriptions of stratigraphy and lithology with stratigraphic columns
- Summary descriptions of regional and local structure with accompanying maps
- Identification and characterization of potential heat source(s)
- Identification and characterization of potential reservoir unit(s)
- Presence of mineralization associated with hydrothermal systems

IGA (2014)

- All previous relevant data will have been assessed, revealing where key data gaps and critical geological uncertainties remain.
- Efficiently and effectively minimizing geological uncertainties by filling these data gaps is the goal of the Exploration Phase of the project.
- Geological data for the project area should be presented in the form of geological maps, structural maps, stratigraphic columns, cross sections, and 3D models
- Definition of the likely geothermal play
- The geological analysis should also identify any uncertainties and data gaps that remain unresolved after the ExplorationPhase.

Geological Mapping

- Check accuracy and suitability of existing maps
- If necessary, plan and carry out new geological surveys in areas of particular relevance
- The data should include lithology, stratigraphy, hydrothermal mineralization, geological structure, and tectonics

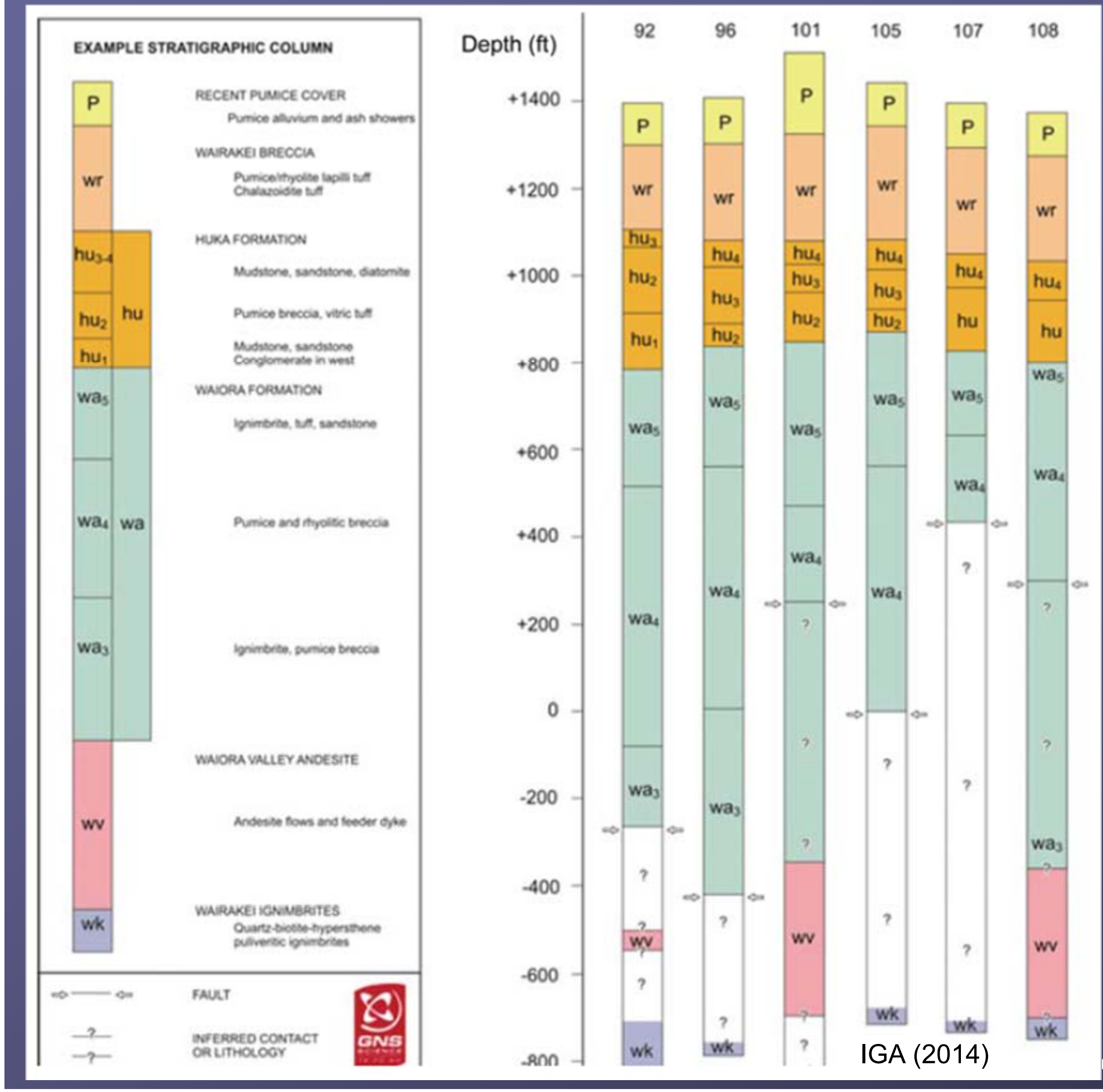


IGA (2014)

- This information should indicate which units or structures could provide fluid pathways or host a geothermal reservoir
- The possible heat source for the geothermal system should be also identified or inferred
- A map should be also prepared to identify potential geological hazards in and around the project area (e.g., volcanic activity, landslides, areas prone to flooding)

Lithology & Stratigraphy

- Definition of a stratigraphic column
- Comparison and correlation between wells



IGA (2014)

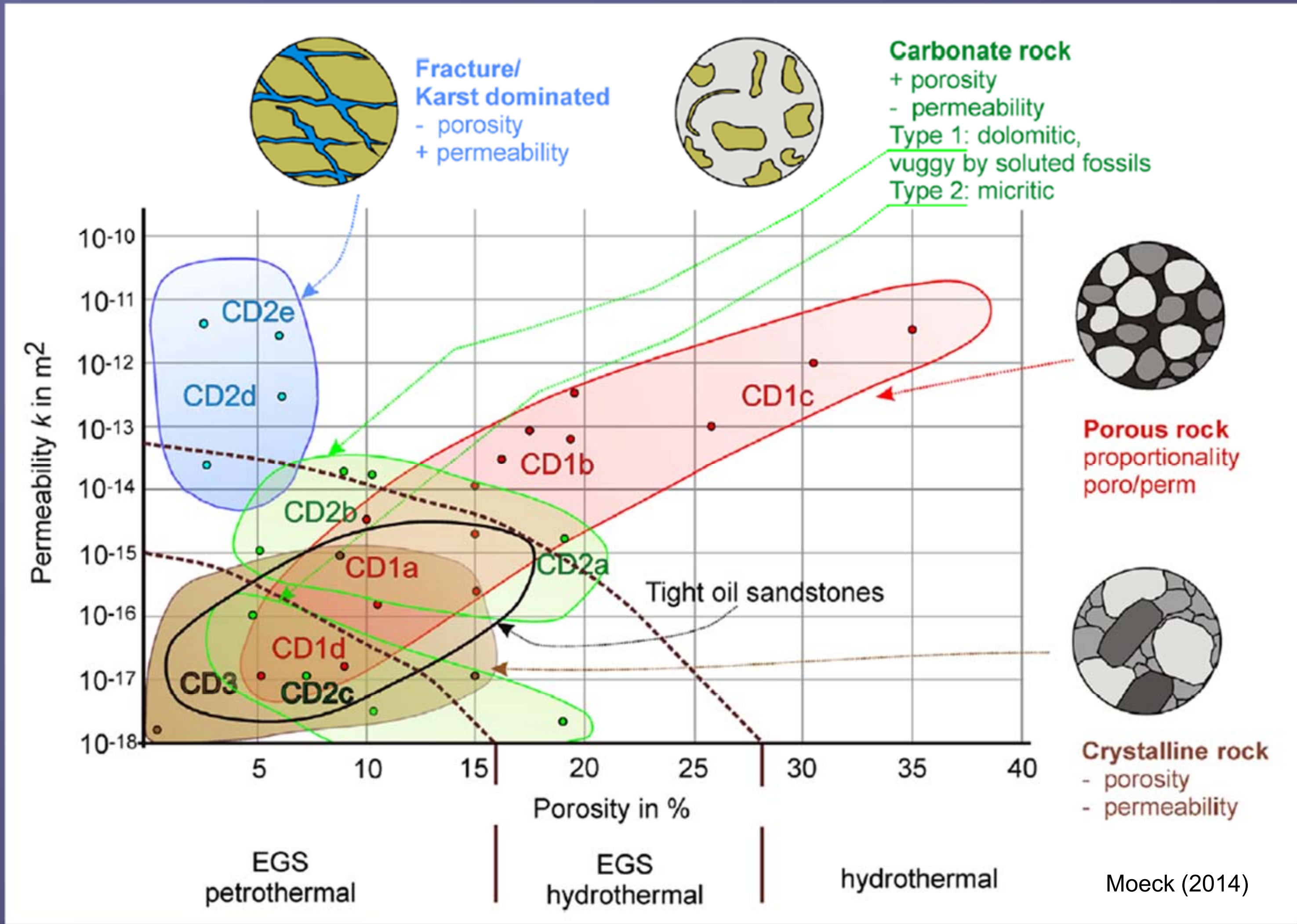
Identify possible:

Reservoir Rock with high primary permeability include sandstone, limestone, quartzite, marble, gneiss, lava flows, breccia, and pyroclastic flows. The presence of brittle rock units that can sustain fractures when deformed may provide fracture-controlled (secondary) permeability

Cap rocks (aquitards and aquicludes) with low permeability such as clays, silt, shale, schist, and other rock types.

Distribution of low permeability and high permeability rocks may therefore define fluid flow pathways, resulting in a geothermal reservoir

Porosity vs Permeability



Porosity and permeability relation of different geothermal reservoirs

Porosity/permeability domains are characteristic for different reservoir rock types

Well Logs Interpretation

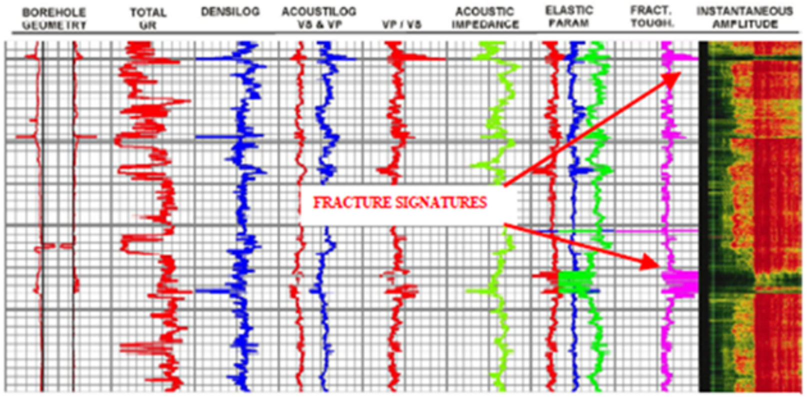


Fig. 5 – Fracture signatures from geophysical logs

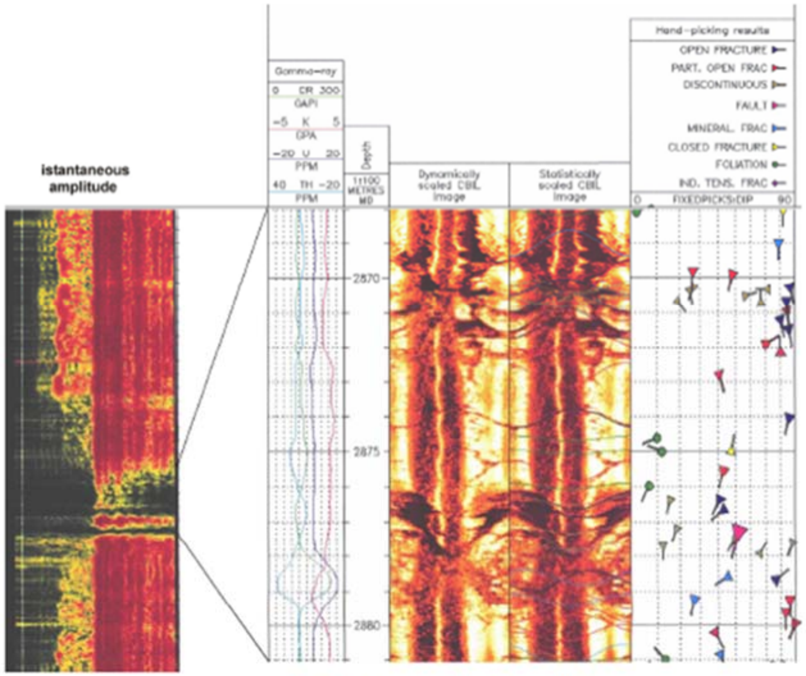
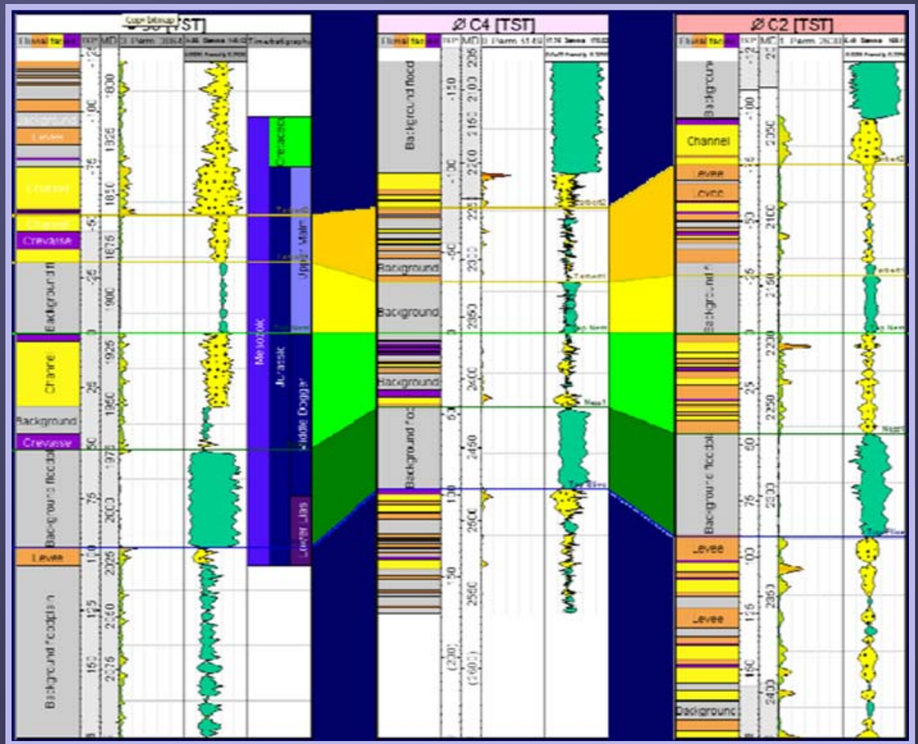


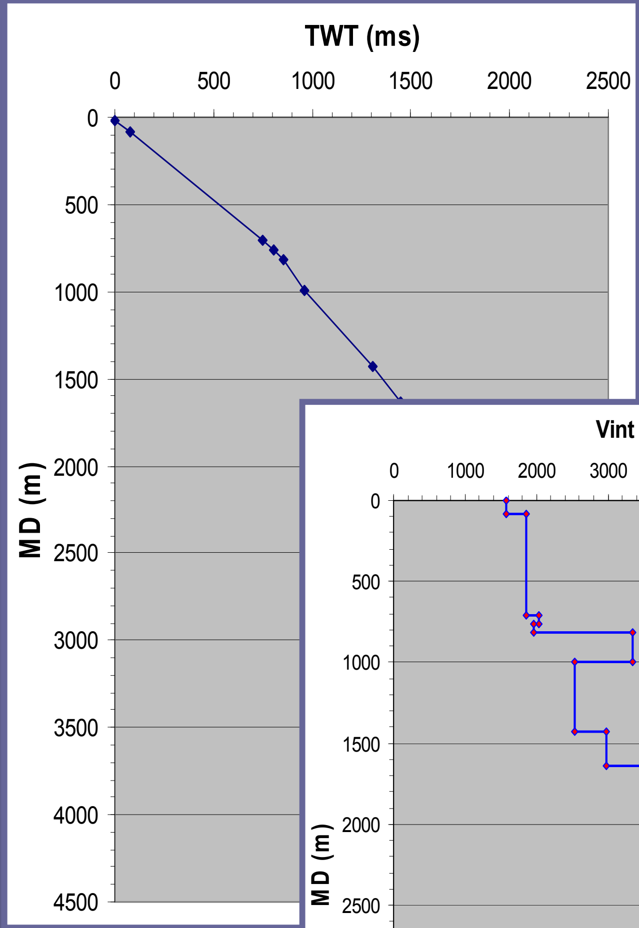
Fig. 6 – Fracture analysis from CBIL

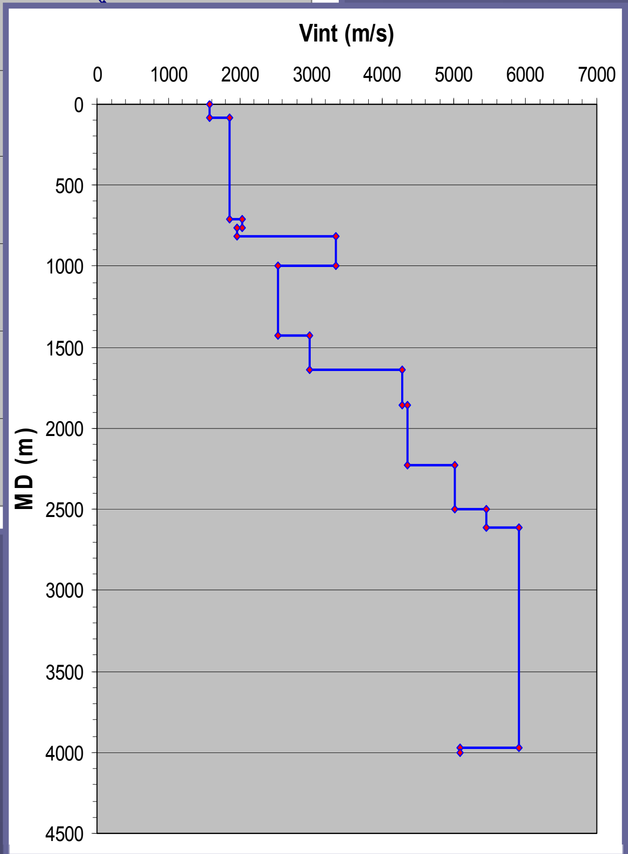
Batini et al. (2002)

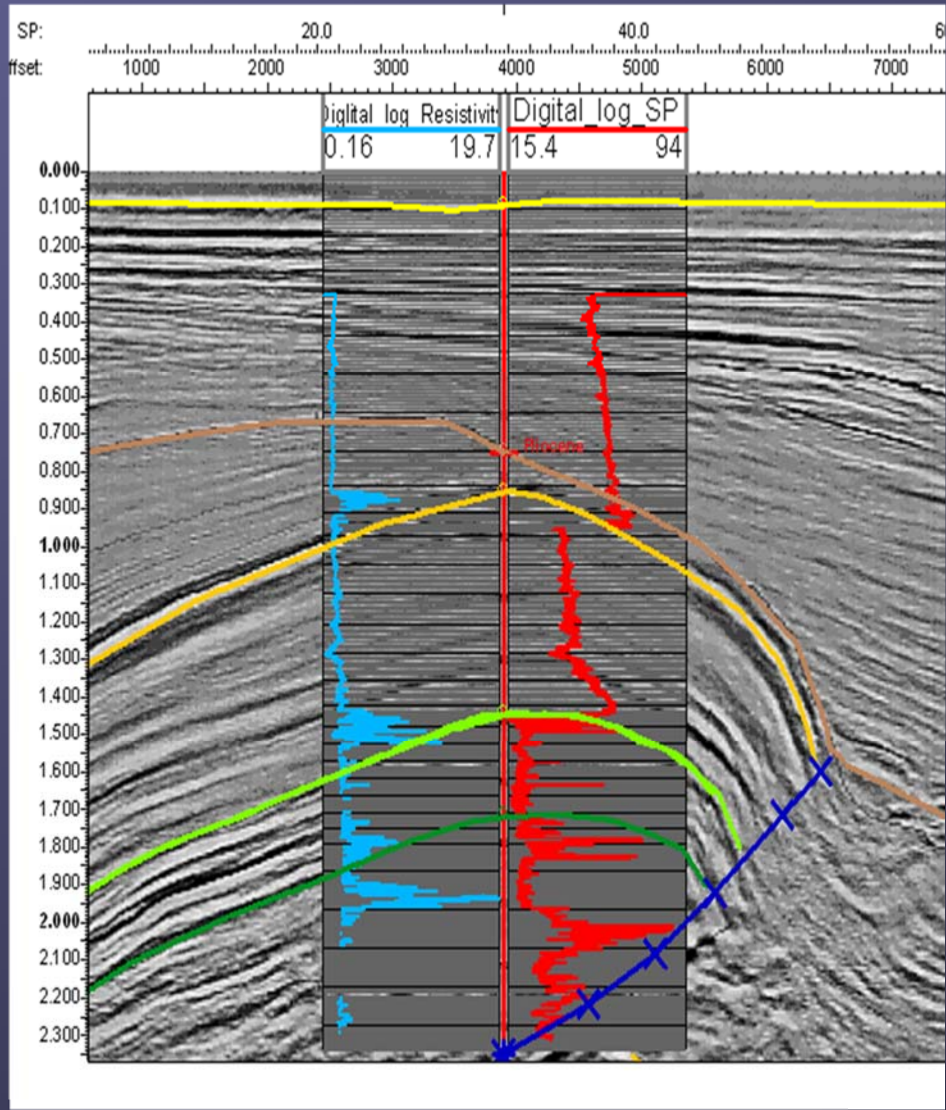
- Formations characterization
  - Lithology, Porosity, Fluids etc.
- Wells correlation
- Fractures detection (Image Logs)



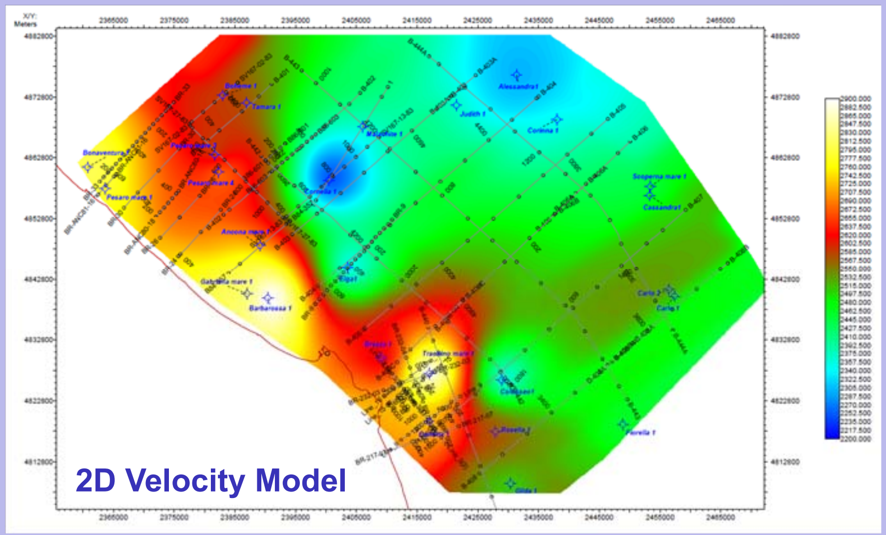
Well to Seismic Tie





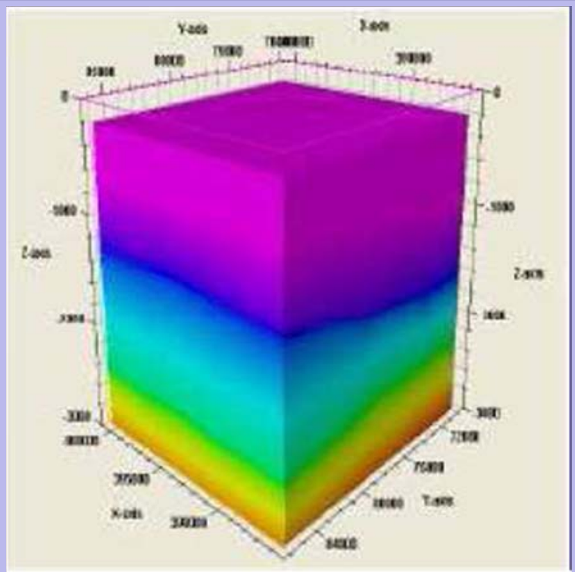


Time-Depth Conversion

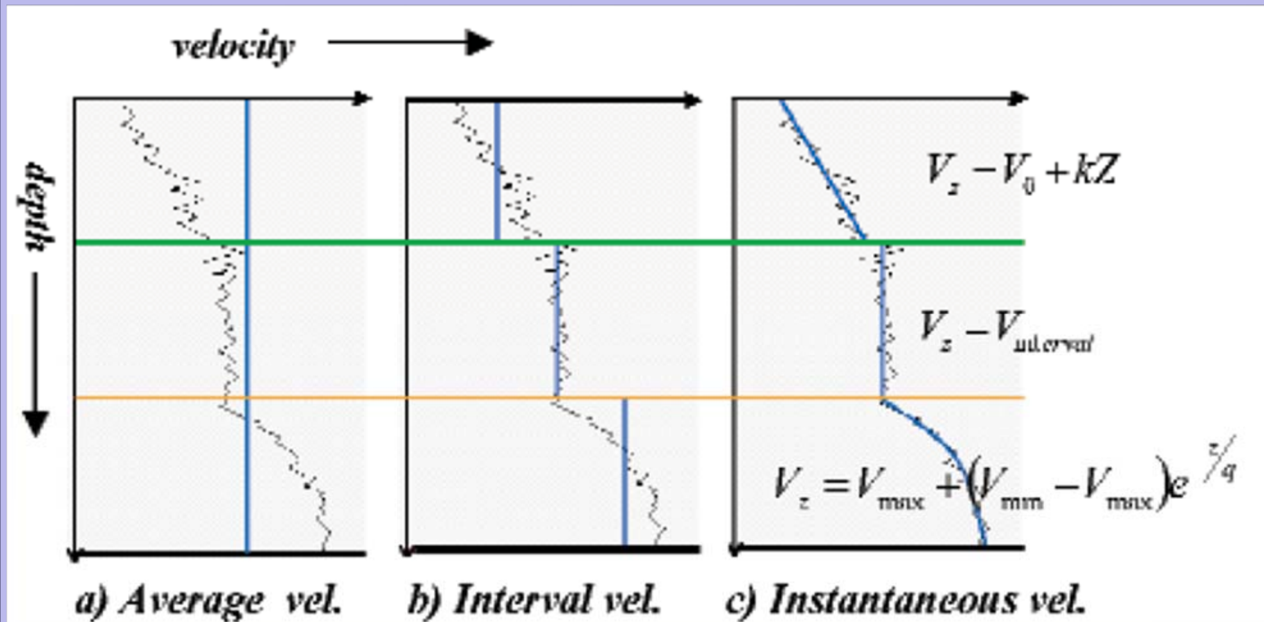


2D Velocity Model

- Velocity data (e.g., check shots, vertical seismic profiles)
- Build a velocity model
  - Specify geological intervals
  - Define velocity functions for each zone
- Domain convert horizons, surfaces, seismic, faults, wells,…

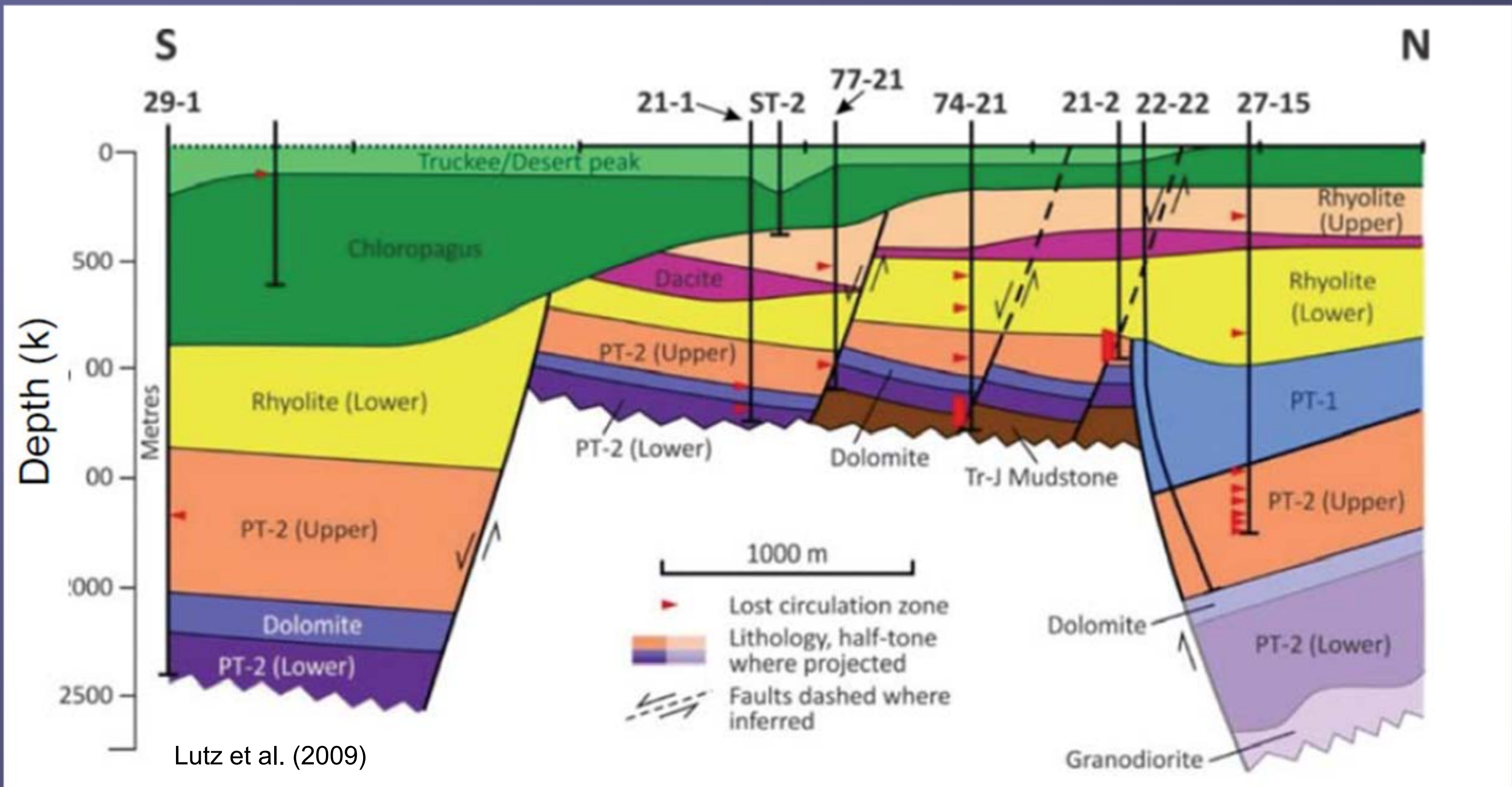


3D Velocity Model



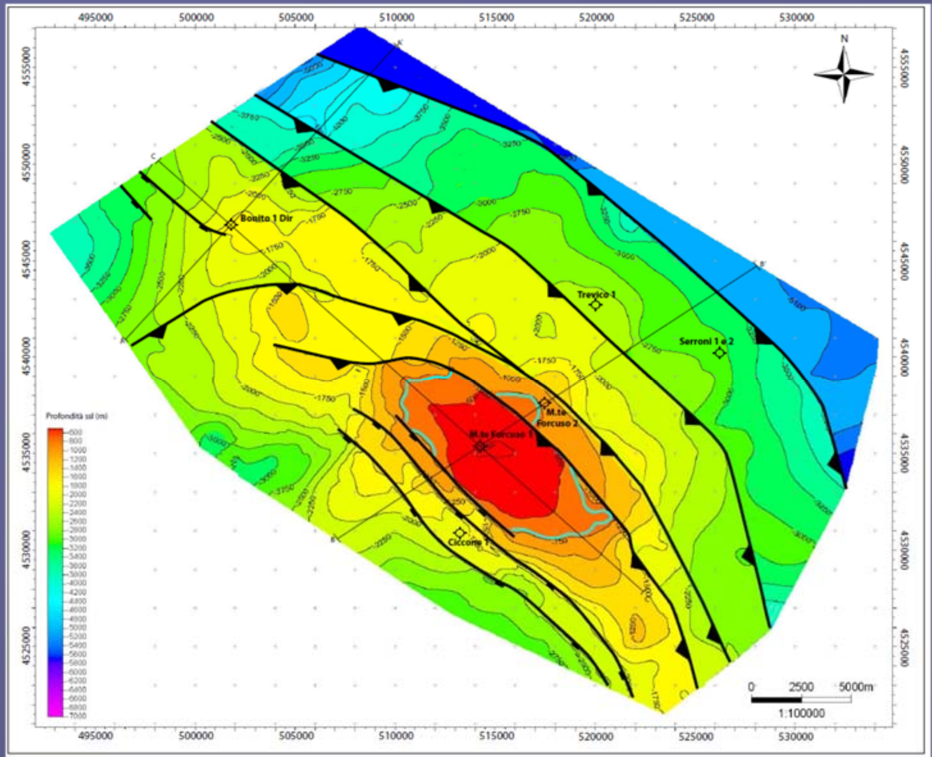
Geological Cross-Sections

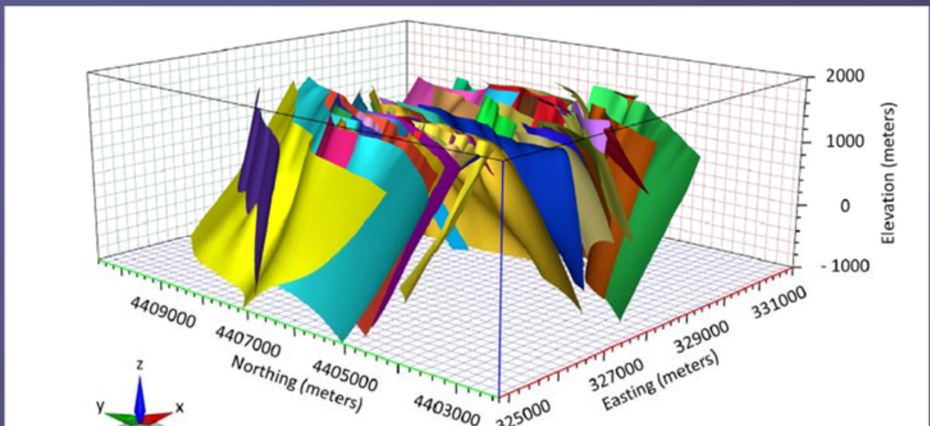
- As more and more subsurface data becomes available from the ongoing exploration, multiple cross-sections should be constructed through the project area to illustrate the basic stratigraphic and structural framework of the geothermal play
- Data from existing wells may also be useful to constrain subsurface data and structures.



2D geologic cross section through the Desert Peak geothermal system

Structural Setting

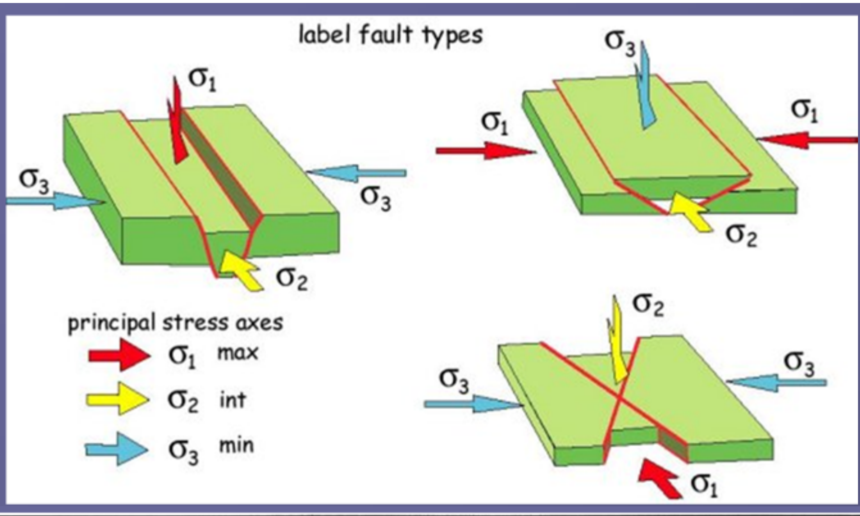


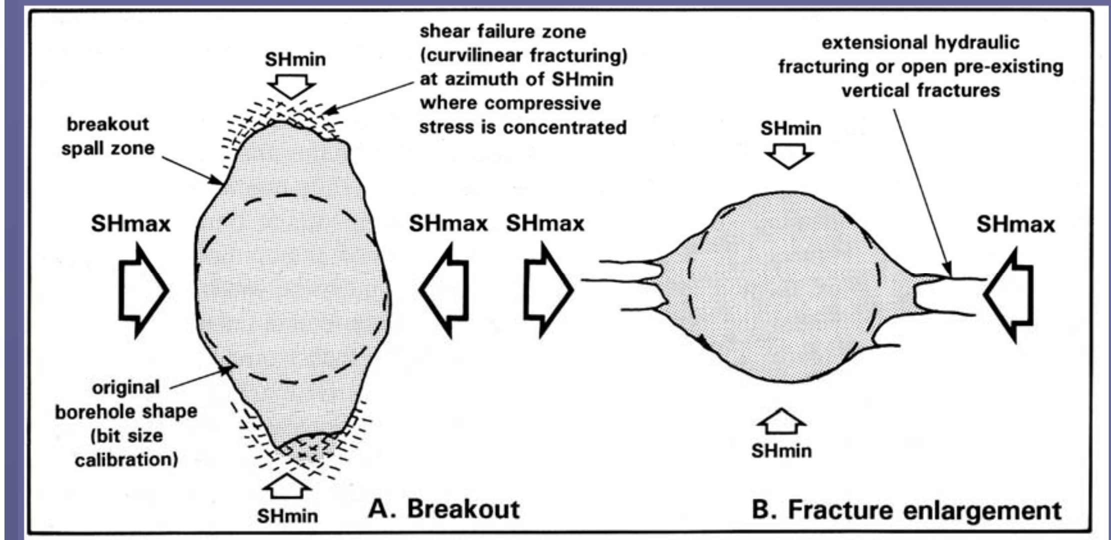


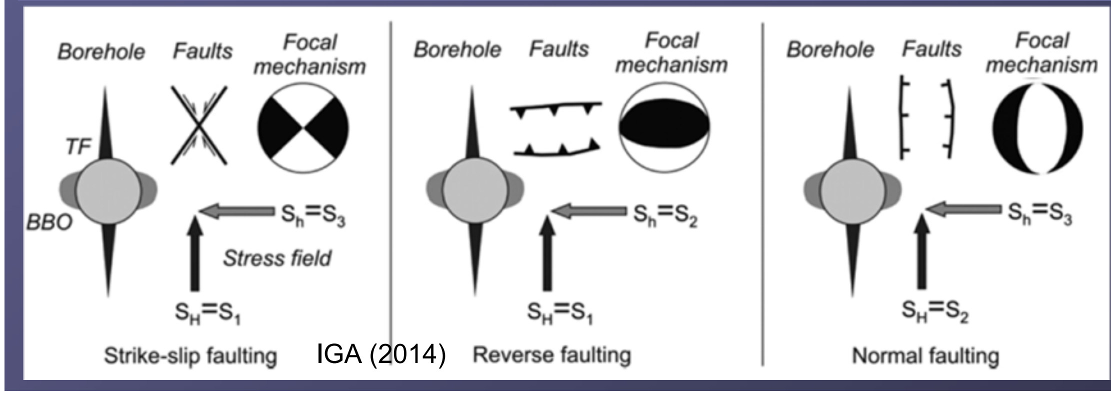
Jolie et al. (2015)

- Analysis of both regional and local geologic structure enables an understanding of the geological context of the project area
- Of particular interest are large-scale extensional features (such as grabens and metamorphic core complexes) or any other structural features that are the result of crustal thinning
- Location, orientation, and distribution fault zones are important, as these faults can play many roles in a geothermal system, from fluid conduits to barriers to fluid flow as well as creating or enhancing secondary permeability

Stress Field: 1







IGA (2014)

- The prevailing stress field influences the distribution and preferred orientation of permeability pathways in natural geothermal systems and controls the growth of engineered reservoirs during hydraulic stimulation
- Borehole breakouts can form when the drilling mud pressure is below hydrostatic formation pressure in underbalanced drilling, while tensile fractures are initiated when the mud pressure exceeds the fracture gradient
- Breakouts, focal mechanism and structural data provide indication about the regional stress field orientation

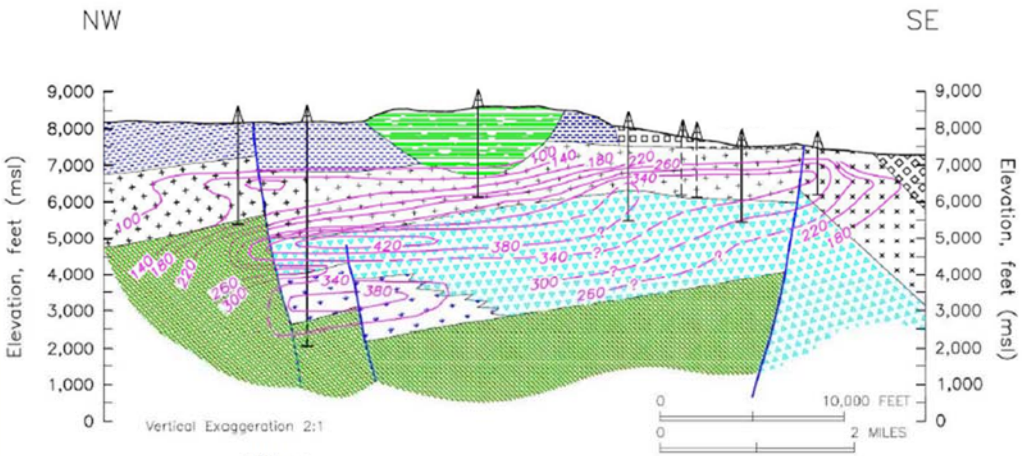
Stress Determination

METHOD	2D/3D	ADVANTAGES	LIMITATIONS	SUITABILITY
Overcoring	2D/3D	Most developed technique	Scattering due to small tested rock volume; requires drill rig	Reservoirs <1,00 m depth
Doorstopper	2D	Works in joined and highly stressed rock	Only 2D; requires drill rig	Shallow and deep reservoirs
Focal mechanisms	3D	For great depth	Only stress regime and stress orientations; information only from great depth	Regional stress regime estimate; at early project stage; in seismically active areas
Analysis of geological data	2D/3D	Low cost field work; applicable also in 3D seismic	Very rough estimation; only together with additional information	At early project stage before drilling; during geological reconnaissance
Borehole breakouts	2D	Relatively quick; Occurs in most deep boreholes	Only orientation; theory needs to be further developed for magnitudes	Shallow and deep reservoirs
Leak-off tests (LOT)	2D	Popular method in hydrocarbon exploration; quick	Requires open borehole; only S_h; disturbed by water chemistry and injection test	Shallow to deep reservoirs; stress profiles can be obtained
Hydraulic test on preexisting fractures (HTPF)	2D/3D	Can be applied when high stress exists, when LOT or over-coring fails	Time consuming; requires open borehole with fractures of variable orientation	When other methods fail, in low permeability rock
Core disking	2D	Quick estimate on core material	Requires several meters of drill core material; only qualitative	When coring material is available
Geophysical measurements	2D/3D	Usable for great depth on drill cores	Complicated measurement on micro-scale; methods need further developing	Estimation of stress state at great depth and only when core material is available

- Stress in units of pressure or megapascals (MPa) cannot be measured directly but can only be derived through a range of techniques of perturbing the rock mass, measuring displacements or strain, or measuring hydraulic parameters (IGA, 2014). Different methods may be applicable at different stages of the project.
- Stress does not behave linearly, either laterally or vertically. Stress field measurements are affected by stress disturbing factors such as geological environment (e.g., nearby faults, geo-mechanical anisotropy in rock mass), borehole location and orientation, and the technical circumstances of the measurement method itself.

Conceptual Model

A fine conceptual model with many useful elements



Lithology
Stratigraphy
Structure
Wells
Temperature distribution

Where would you drill, and why?

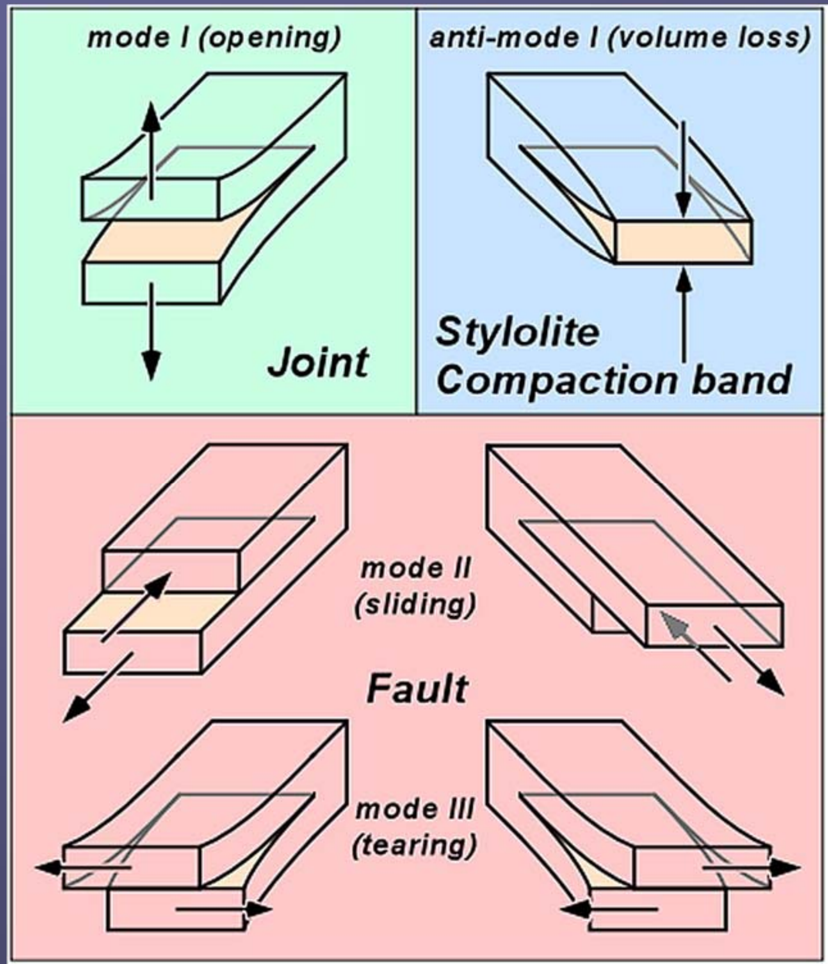
Robertson-Tait (2013)

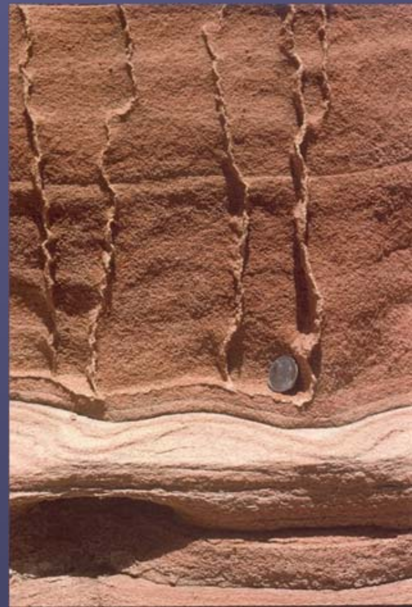
- A conceptual model is a schematic representation of the current best understanding of a geothermal system, consistent with all known data and information.
- The first iteration of a conceptual model for any new project might be little more than a generic representation of the type of geothermal play under investigation.

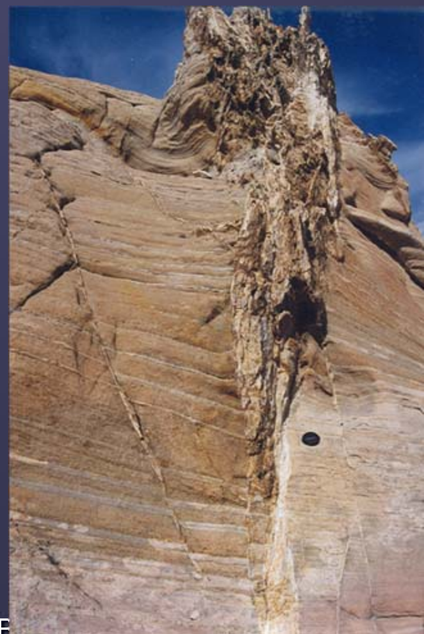
- While the initial conceptual model is expected to be crude or incomplete, it is important to have an initial model that can be refined and improved as the exploration, test drilling and field development phases proceed and more data become available
- During the Exploration Phase, the conceptual model of the geothermal system is continually updated as new data are gathered. The model needs to contain sufficient geological, hydrological, and tectonic information to allow a first pass estimate of reservoir depth, temperature, and extent.
- This is used during the Test Drilling Phase to target production scale wells toward lithological units and/or geological structures with the highest probability of delivering commercial flow rates of geothermal fl uids.

FAULTS & FRACTURE VS FLUID FLOW

Fracture Types







Mode I fracture – Opening mode (a tensile stress normal to the plane of the crack),

Mode II fracture – Sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front),

Mode III fracture – Tearing mode (a shear stress acting parallel to the plane of the crack and parallel to the crack front).

Mohr Diagram

Shear failure can only occur if differential stress σ_1-σ_3 is greater than four times the tensile strength of the rock (T)

Extensional failure can only occur if the Mohr circle touch the failure envelope at point B (i.e., the differential stress must be < 4T)

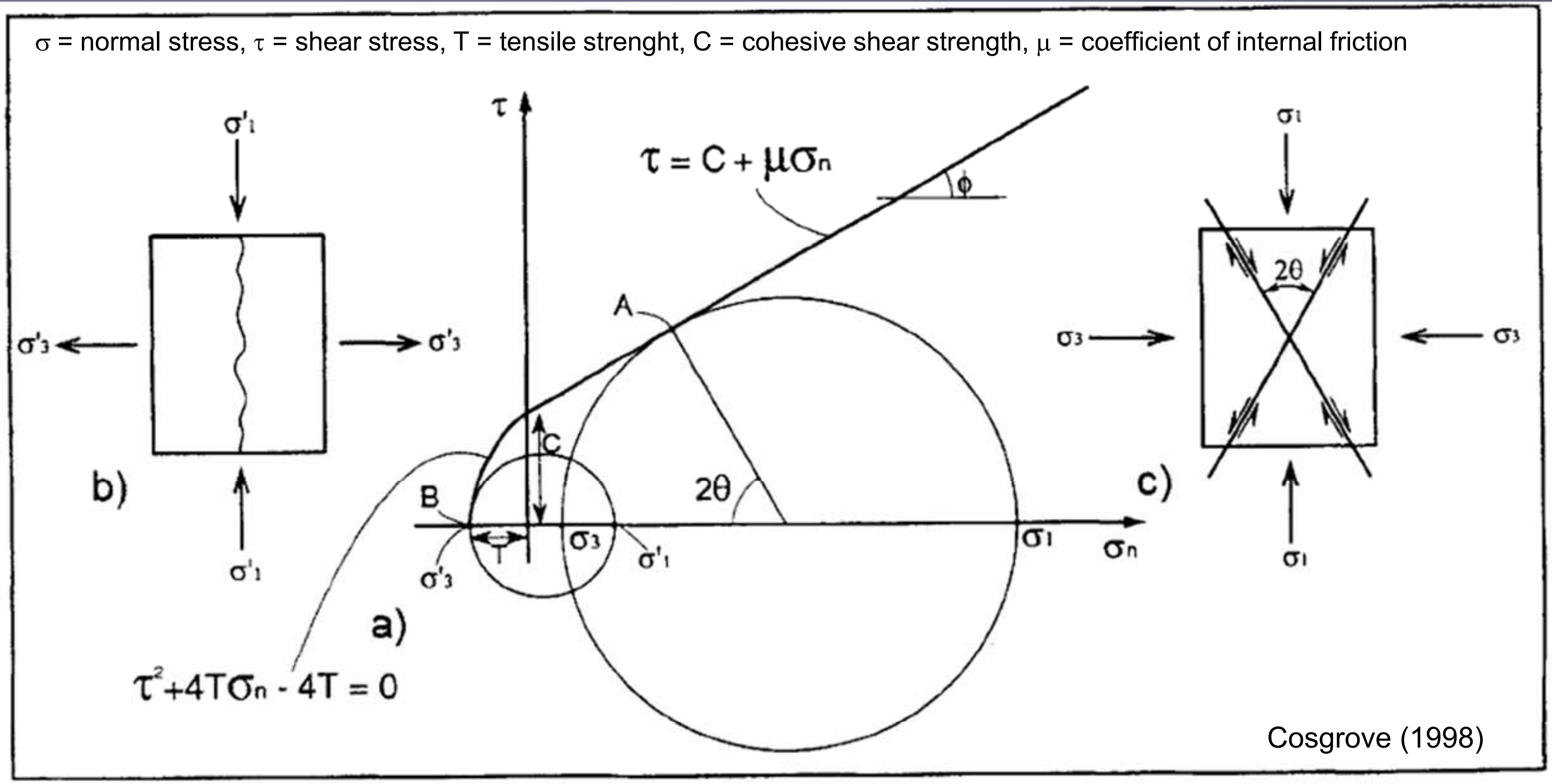
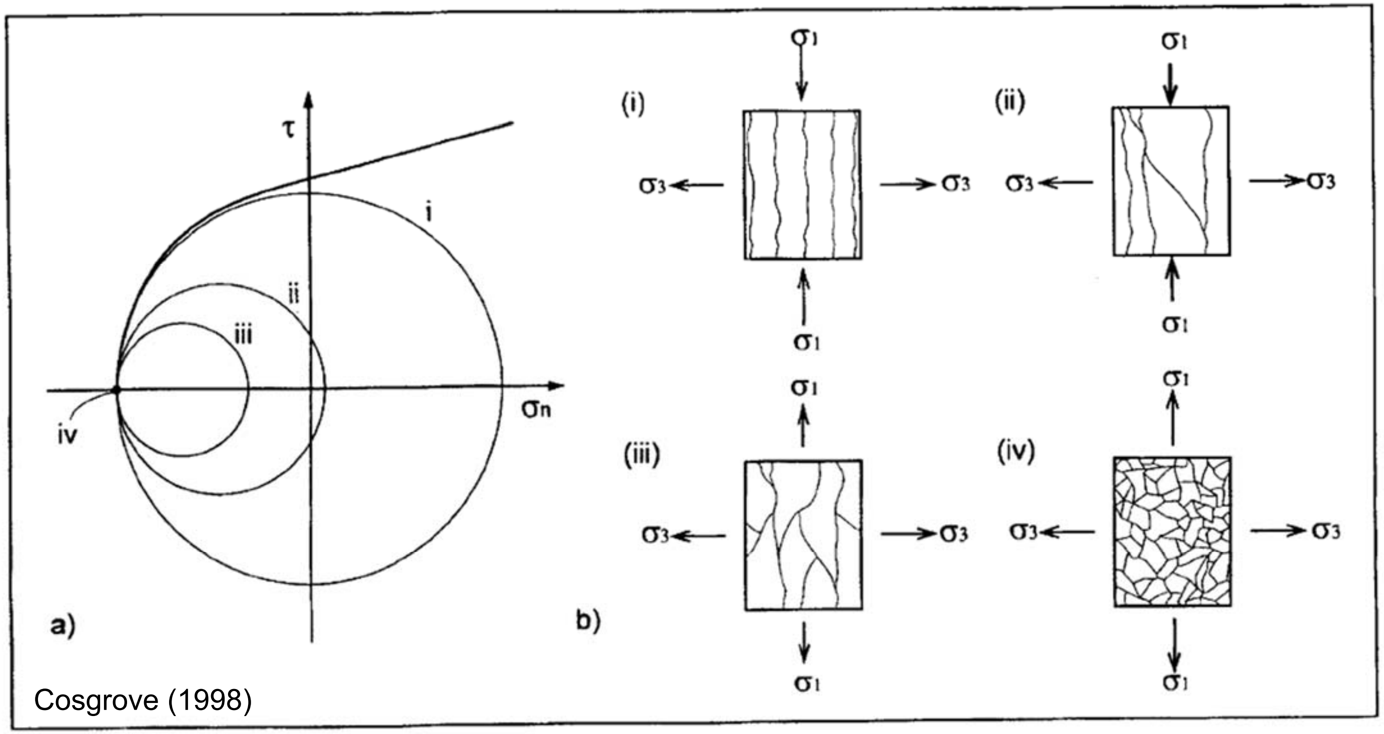


Fig. 5. (**a**) The Navier–Coulomb/Griffith brittle failure envelope. The two Mohr circles represent stress states that would give rise to extensional failure (the smaller circle) and shear failure. (**b**) and (**c**) show the relationship between the principal stresses and extensional failure and shear failure planes respectively.

Stress States

Fractures form parallel to the maximum principal compression σ_1 and open against the least principal compression σ_3

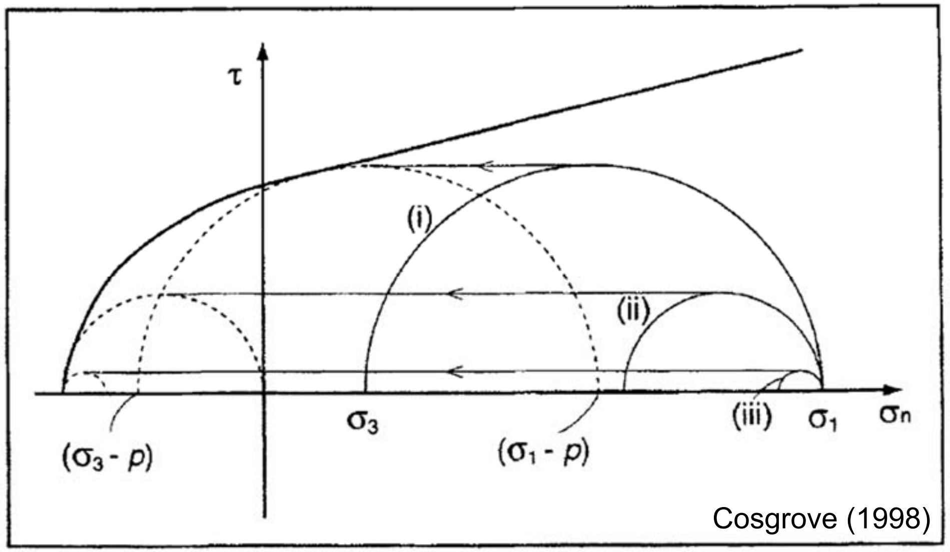
As the differential stress becomes progressively lower the tendency for the extension fractures to be aligned will become less and less until, when the differential stress is zero (hydrostatic stress), they will generate a “breccia texture”



Cosgrove (1998)

Fig. 7. **(a)** Four Mohr circles that represent four stress states that will give rise to extensional failure (i.e. $\sigma_1 - \sigma_3 < 4T$). **(b)** (i)–(iv) show the organization of the extensional fractures for each stress state.

Hydraulic Fracturing



Cosgrove (1998)

The state of stress in the Earth's crust tends to be compressional. Nevertheless extensional fractures are quite common since failure occurs by hydraulic fracturing

A state of lithostatic stress in a rock will be modified by the fluid pressure *p* to an effective stress state σ_1-*p*, σ_2-*p* and σ_3-*p*, (i.e., Mohr circle will be moved to the left by an amount equal to *p*)

It is a common misconception that the result of hydraulic fracturing in sediments and rocks is the formation of randomly oriented extension fractures (breccia textures)

All three circles can be driven to the left by a fluid pressure until they intersect the failure envelope, when hydraulic fracturing will occur:

- stress state i) will cause shear failure,
- stress state ii) will cause aligned extensional failure and
- stress state iii) will cause brecciation of the rock by the formation of an almost random array of extension fractures.

Vertical and Horizontal Stress

In a tectonically relaxed basin the main source of stress is due to the overburden.

If the boundary conditions are such that horizontal strains are prevented by the constraints of the rock mass surrounding the area of interest, then it can be shown that the vertical and horizontal stresses are related by Eqs 1 and 2

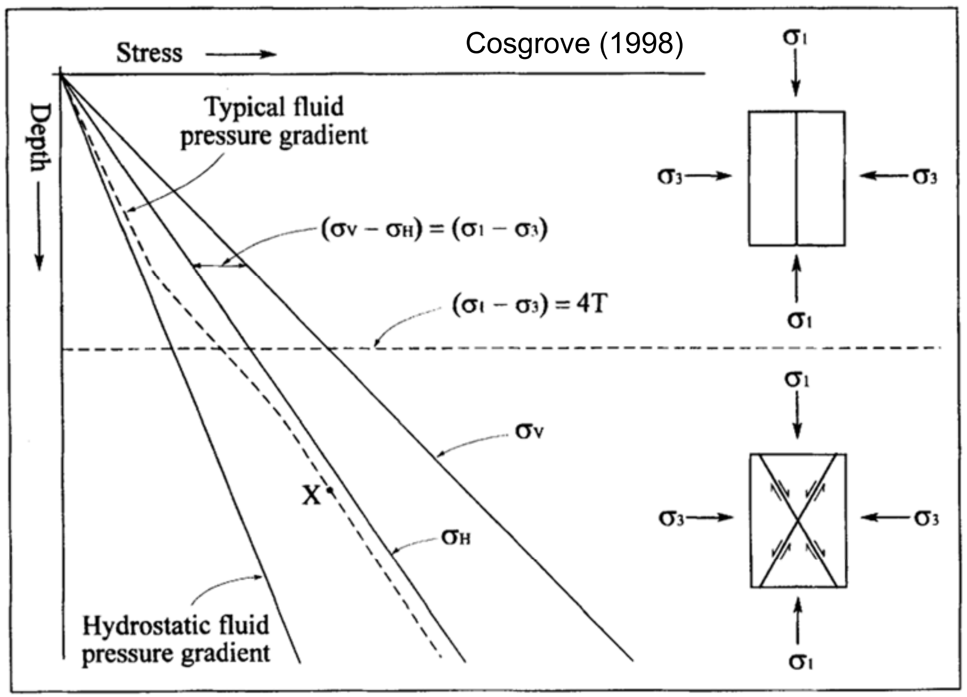


Fig. 9. Plot of variation of vertical and horizontal stress and fluid pressure with depths according to Eqns 1 and 2 which assume that the stresses are generated by the overburden in a tectonically relaxed basin. The expression of the hydraulic fractures is determined by the differential stress which increases with depth. At the depth when it exceeds $4T$ the fractures change from extensional to shear.

$$\sigma_H = \sigma_V/(m-1)$$

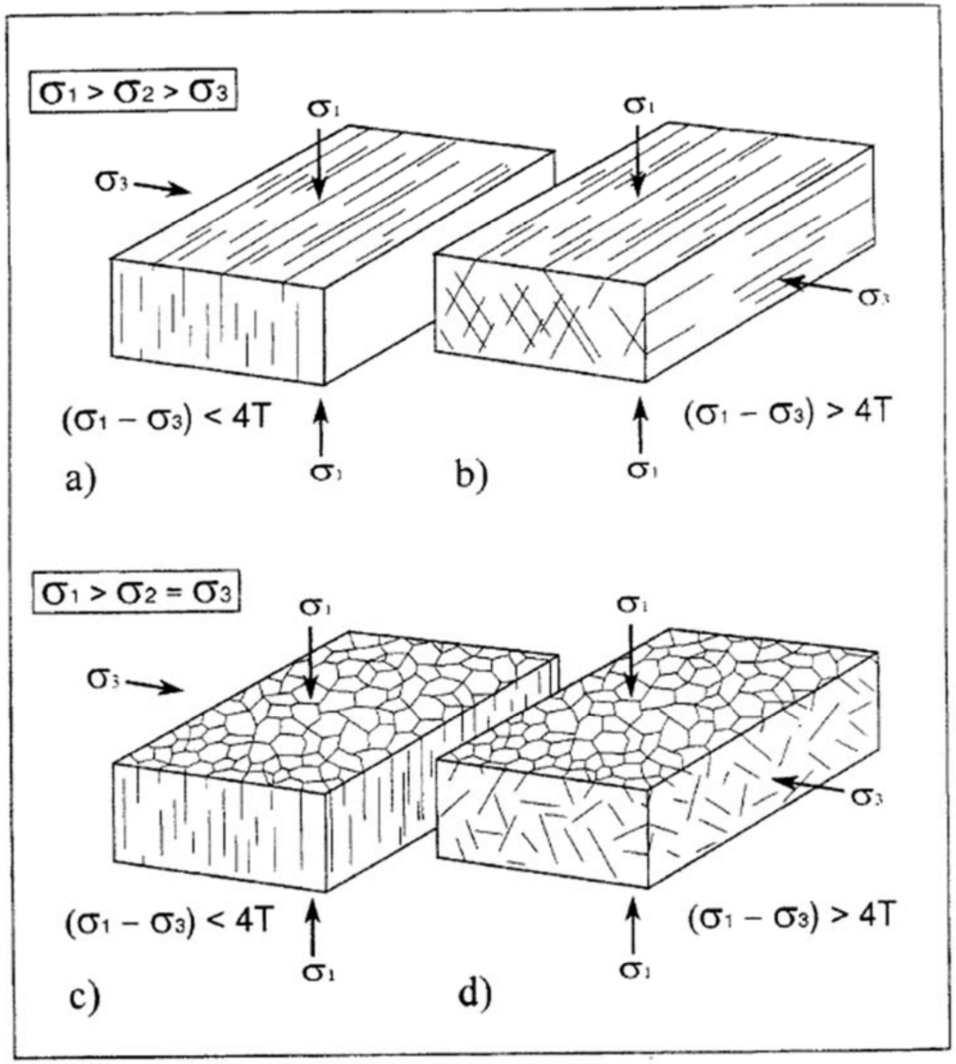
Eq. 1: m is Poisson's number (reciprocal of Poisson's ratio)

$$\sigma_V = \sigma_1 = z\rho g$$

Eq. 2: z is the depth, p the average density of the overlying rocks ,and g the acceleration due to gravity

If the overburden has a constant density and Poisson's number does not change with depth, then the vertical and horizontal stresses increase linearly

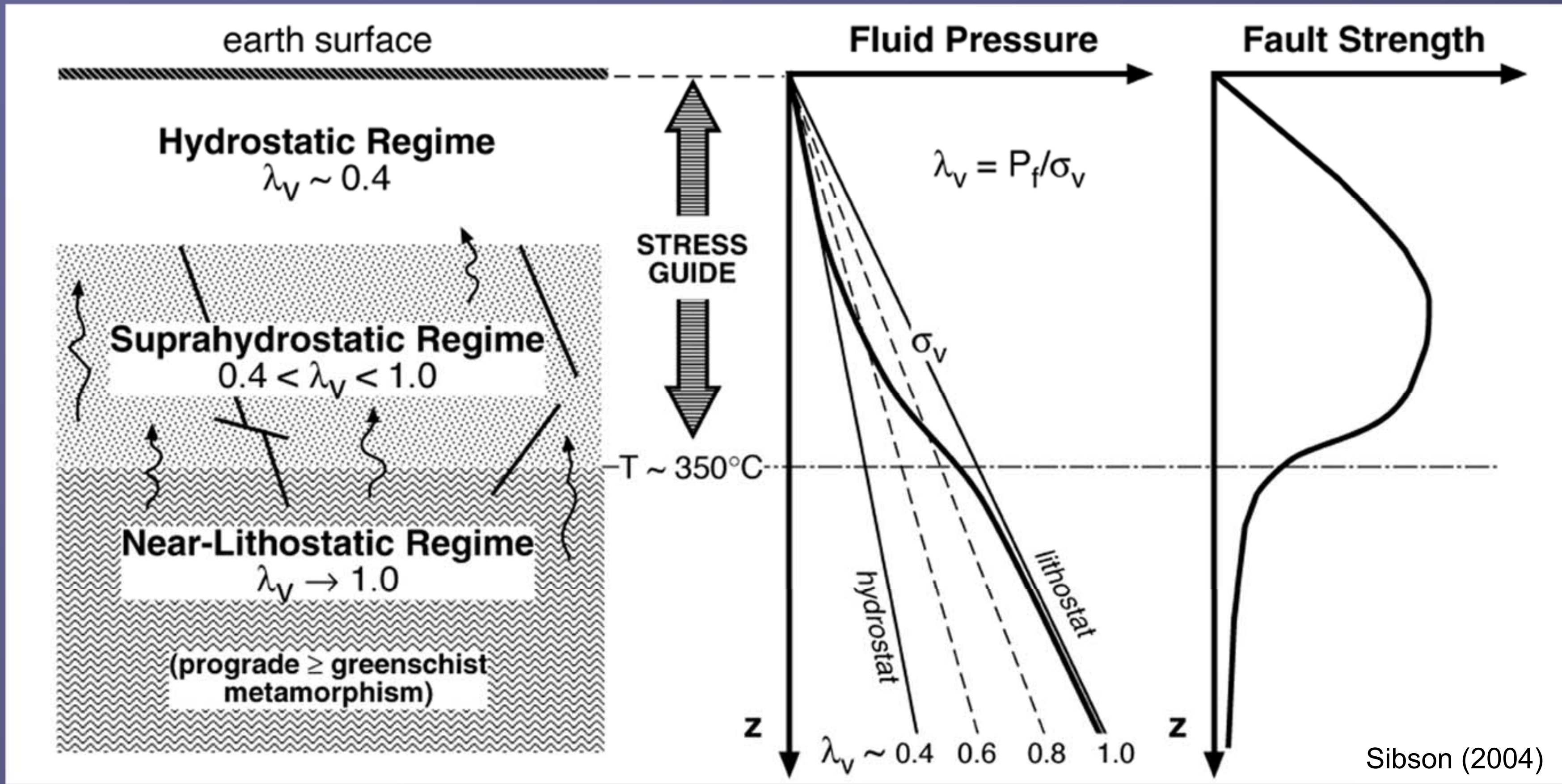
3D Organization Hydraulic Fractures



Cosgrove (1998)

Fig. 10. The three-dimensional organisation of hydraulic fractures: (**a**) when $\sigma_1 - \sigma_3 < 4T$ and the two horizontal principal stresses are unequal; (**b**) when $\sigma_1 - \sigma_3 > 4T$ and the two horizontal principal stresses are unequal; (**c**) when $\sigma_1 - \sigma_3 < 4T$ and $\sigma_2 = \sigma_3$; (**d**) when $\sigma_1 - \sigma_2 > 4T$ and $\sigma_2 = \sigma_3$.

Fluid-pressure Profile



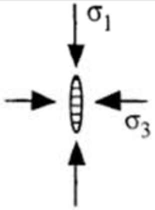
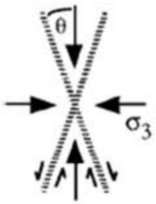
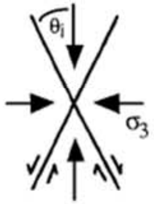
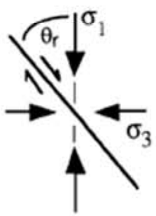
Pore-fluid factor, $\lambda_v = P_f/\sigma_v$ defines fluid-pressure level at different depths

Hypothetical fluid-pressure profile through the carapace to a region undergoing prograde metamorphism

Brittle Failure

Sibson (1998)

Table 1
Criteria for brittle failure and reshear ($\mu_i = \mu_s = 0.75$)

Failure mode (field of application)	τ/σ_n' space; P_f dependence	Orientation with respect to stress field ($\sigma_v = \sigma_1$)
Extensional (Griffith criterion) $(\sigma_1 - \sigma_3) < 4T$	$\tau^2 = 4T(\sigma_n - P_f) + 4T^2$ $P_f = \sigma_3 + T$	
Extensional-shear (Griffith criterion) $4T < (\sigma_1 - \sigma_3) < 5.66T$	$\tau^2 = 4T(\sigma_n - P_f) + 4T^2$ $P_f = \sigma_3 + \frac{[8T(\sigma_1 - \sigma_3) - (\sigma_1 - \sigma_3)^2]}{16T}$	
Compressional-shear (Coulomb criterion) $(\sigma_1 - \sigma_3) > 5.66T$	$\tau = C + \mu_i(\sigma_n - P_f)$ $P_f = \sigma_3 + \frac{[8T - (\sigma_1 - \sigma_3)]}{3}$ for $\mu_i = 0.75$	
Reshear of cohesionless fault (Amontons law)	$\tau = \mu_s(\sigma_n - P_f)$ $P_f = \sigma_3 - \frac{(\sigma_1 - \sigma_3)(1 - 0.75\tan\theta_r)}{0.75(\cot\theta_r + \tan\theta_r)}$ for $\mu_s = 0.75$	

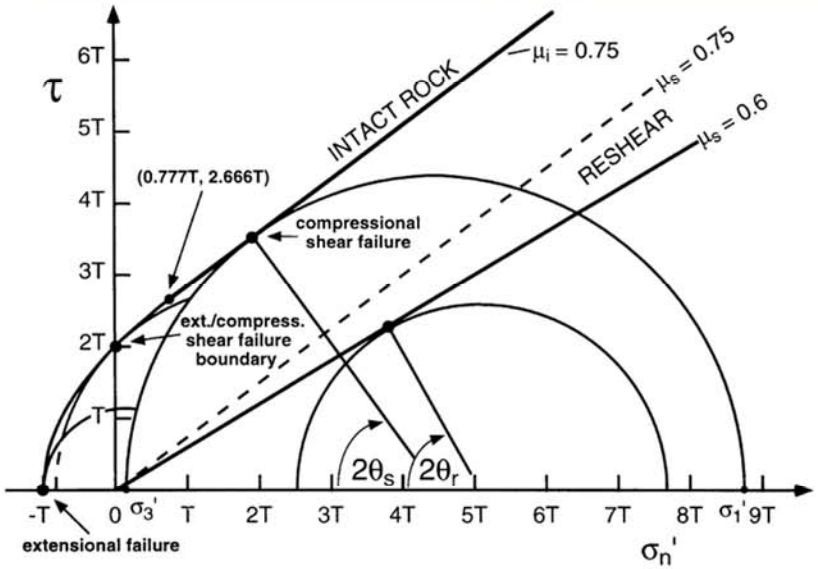
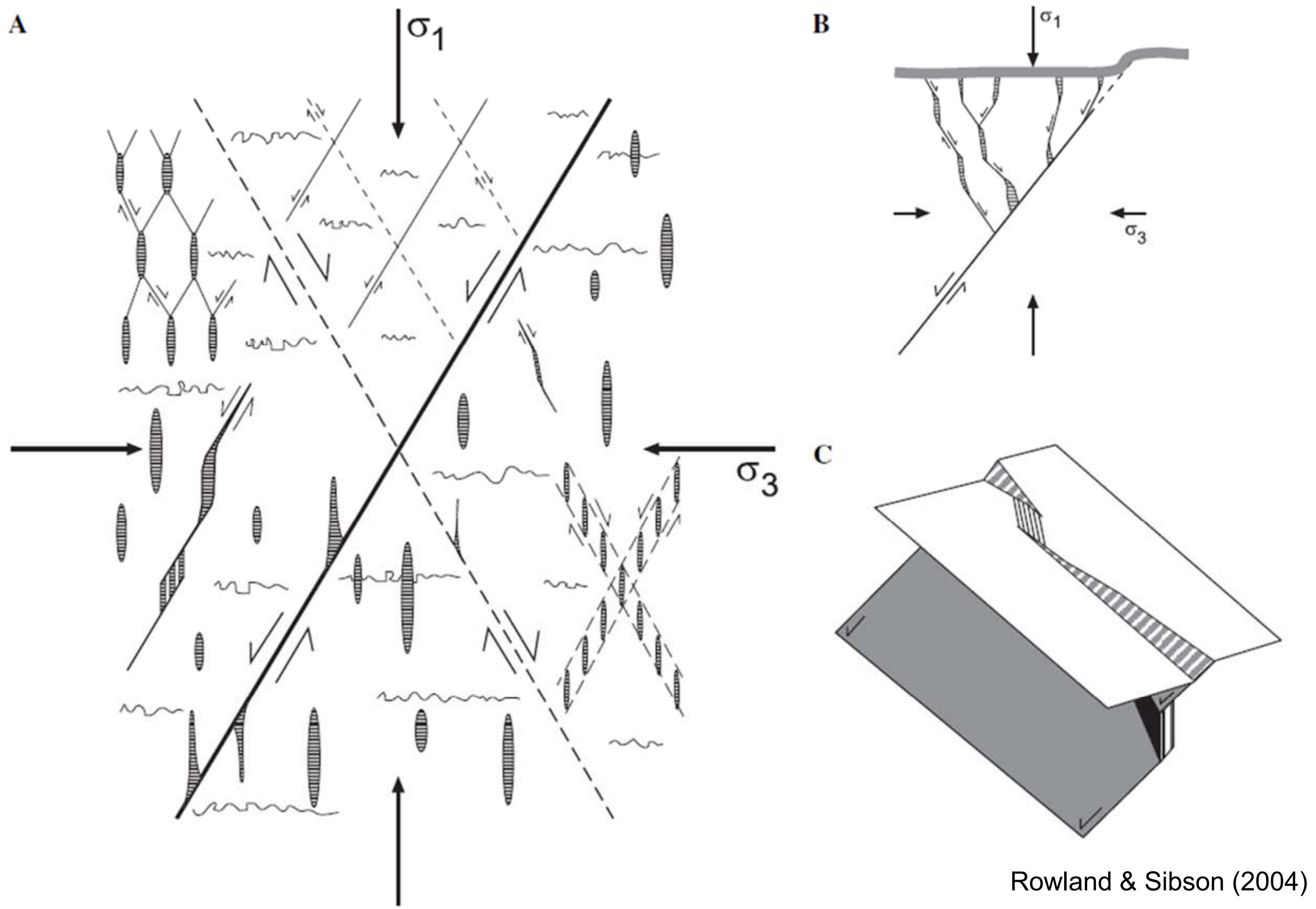


Fig. 1. Generic Mohr diagram showing a composite Griffith–Coulomb failure envelope for intact rock normalized to tensile strength, T, with $\mu_i = 0.75$ in the compressional field, plus reshear criteria for cohesionless faults with $\mu_s = 0.6$ and 0.75. Critical stress circles are shown representing different failure modes for intact rock and a reshear stress state for an optimally oriented existing fault with $\mu_s = 0.6$. μ_i is internal friction of intact rock; μ_s is static friction for reshear.

Stress-controlled Permeability



Rowland & Sibson (2004)

Fig. 6. (A) Stress-controlled components of structural permeability in various combinations within an extensional stress field with $\sigma_v = \sigma_1$; note the common intersection of all stress-controlled components in the σ_2 direction; shear-sense indicators define faults (compressional shears); extension fractures and extensional-shear fractures are cross-hatched; stylolites shown by squiggly lines; (B) high-permeability horsetail mesh developed in near-surface hanging wall of a normal fault; (C) gently raking dilational jog within normal fault zone, showing surface expression (from Sibson 2000).

Brittle Failure Mode Plots

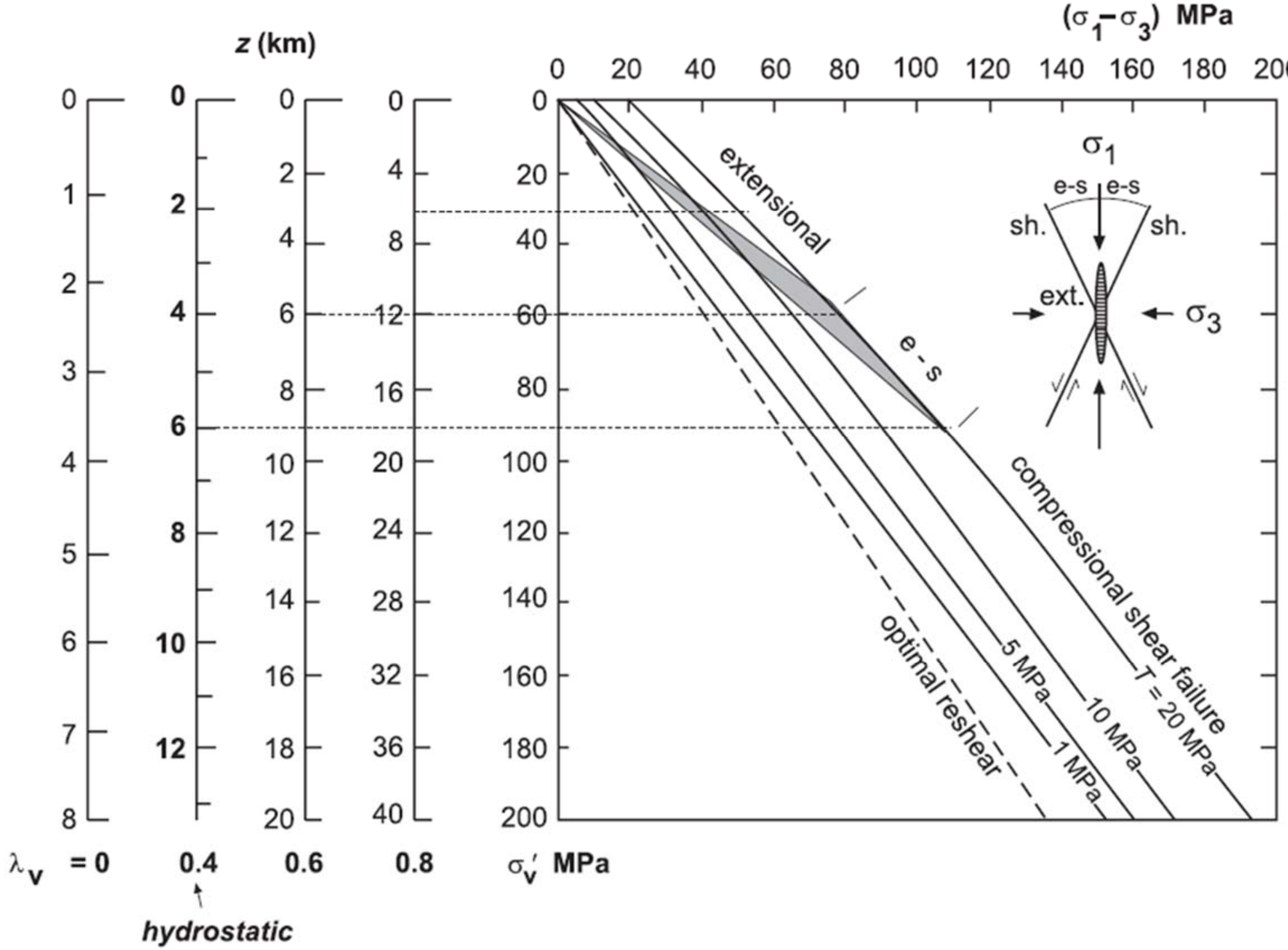
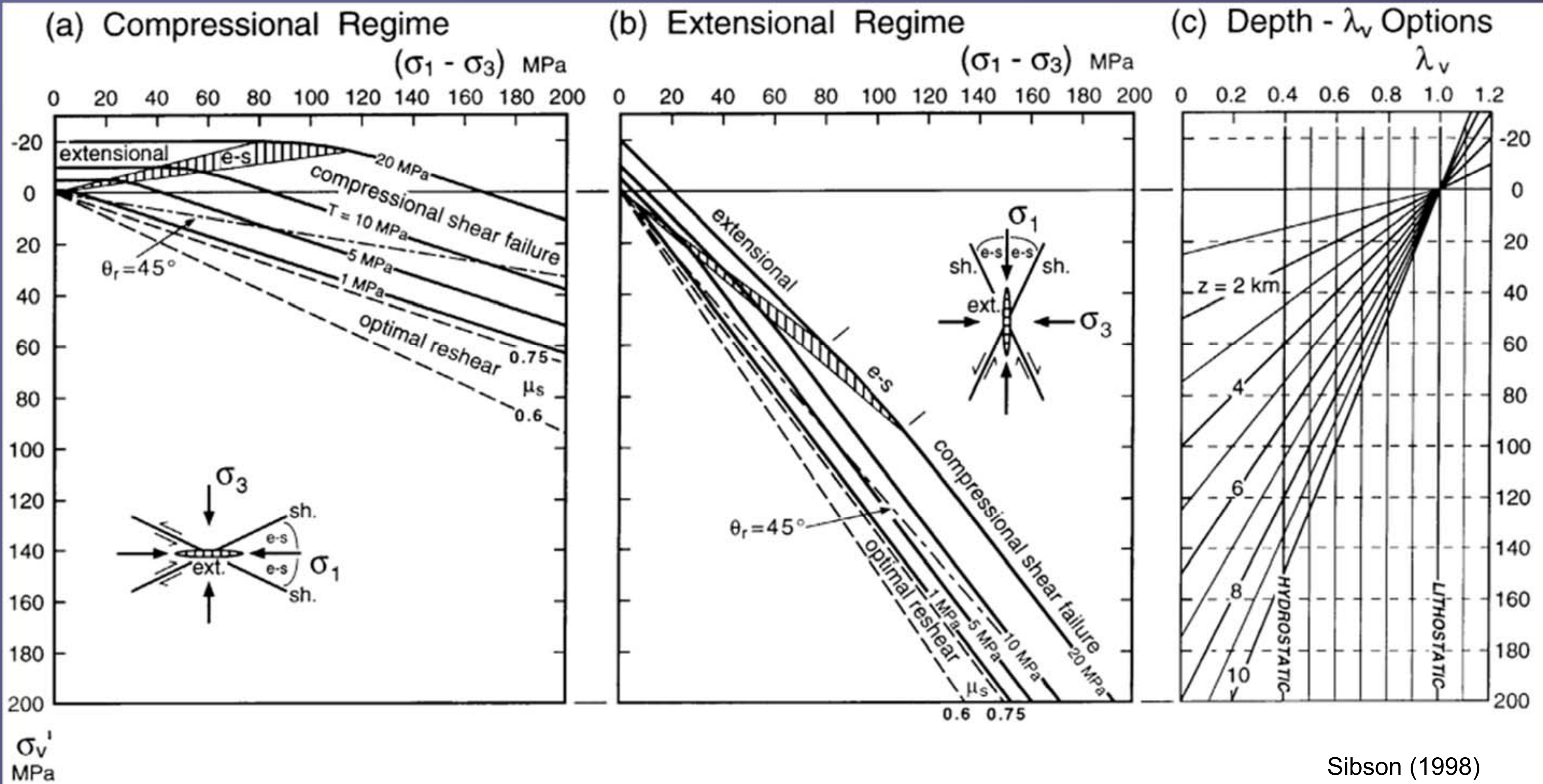


Fig. 7. Brittle failure mode plot of differential stress ($\sigma_1 - \sigma_3$) versus effective vertical stress σ'_v in an extensional regime with $\sigma_v = \sigma_1$ (after Sibson 2000). Effective vertical stress can be equated to depth for different values of the pore fluid factor, λ_v. Failure curves are plotted for intact rock, ($\mu_i = 0.75$), with $T = 1$, 5, 10 and 20 MPa and the reshear condition of an optimally oriented cohesionless normal fault, ($\mu_s = 0.6$) Different failure modes are outlined. Note that at depths <6 km, extensional-shear failure is possible in high-tensile-strength rocks under hydrostatic pressure conditions. Inset shows orientation of the three modes of brittle failure with respect to σ_1: sh, compressional shears (faults); e-s, extensional-shears; ext, extensional fractures.

Brittle Failure Mode Plots



Sibson (1998)

Fig. 2. Brittle failure mode diagrams for: (a) compressional; and (b) extensional tectonic regimes, plotting differential stress at failure, $(\sigma_1-\sigma_3)$, against effective vertical stress, σ_v'. Solid bold lines define the failure conditions for intact rock with various values of tensile rock strength, *T*. The fields occupied by the different failure modes are labelled on the plots with the fields of extensional-shear failure cross-hatched. Expected orientations of extension fractures (ext.), Coulomb shear fractures or faults (sh.), and extensional shear fractures (e-s) are shown in the insets. Also shown are reshear criteria for optimally oriented cohesionless faults with $\mu_s=0.6$ and 0.75 (dashed lines), and for $\theta_r=45°$ when $\mu_s=0.75$ (dash–dot lines). In (c), values for σ_v' can be equated to specific depth and fluid-pressure combinations.

Fault Zones

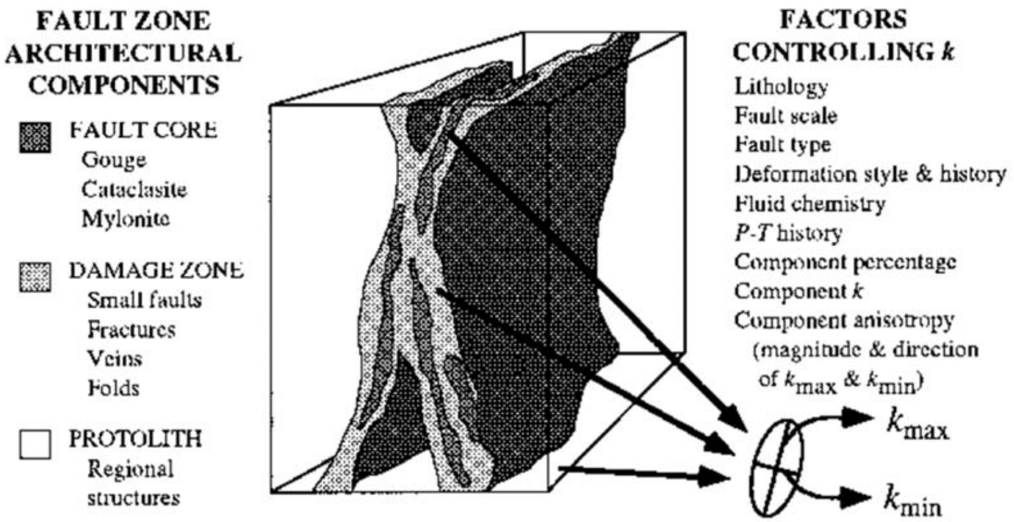


Figure 1. Conceptual model of fault zone with protolith removed (after Chester and Logan, 1986; Smith et al., 1990). Ellipse represents relative magnitude and orientation of the bulk two-dimensional permeability (*k*) tensor that might be associated with each distinct architectural component of fault zone.

Caine et al. (1996)

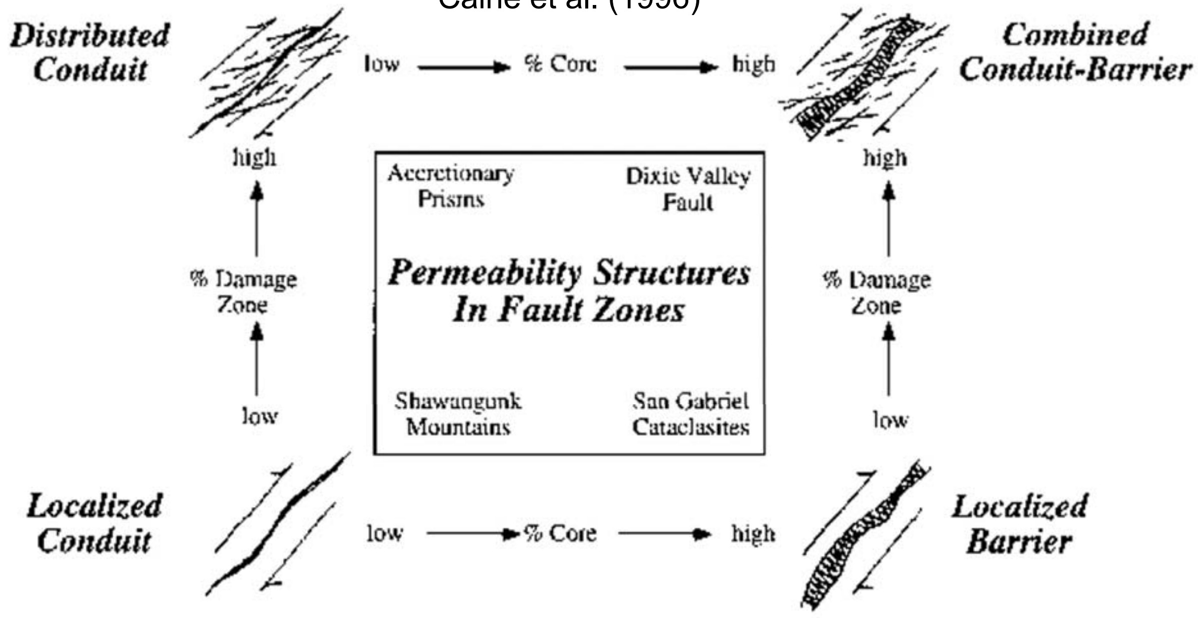
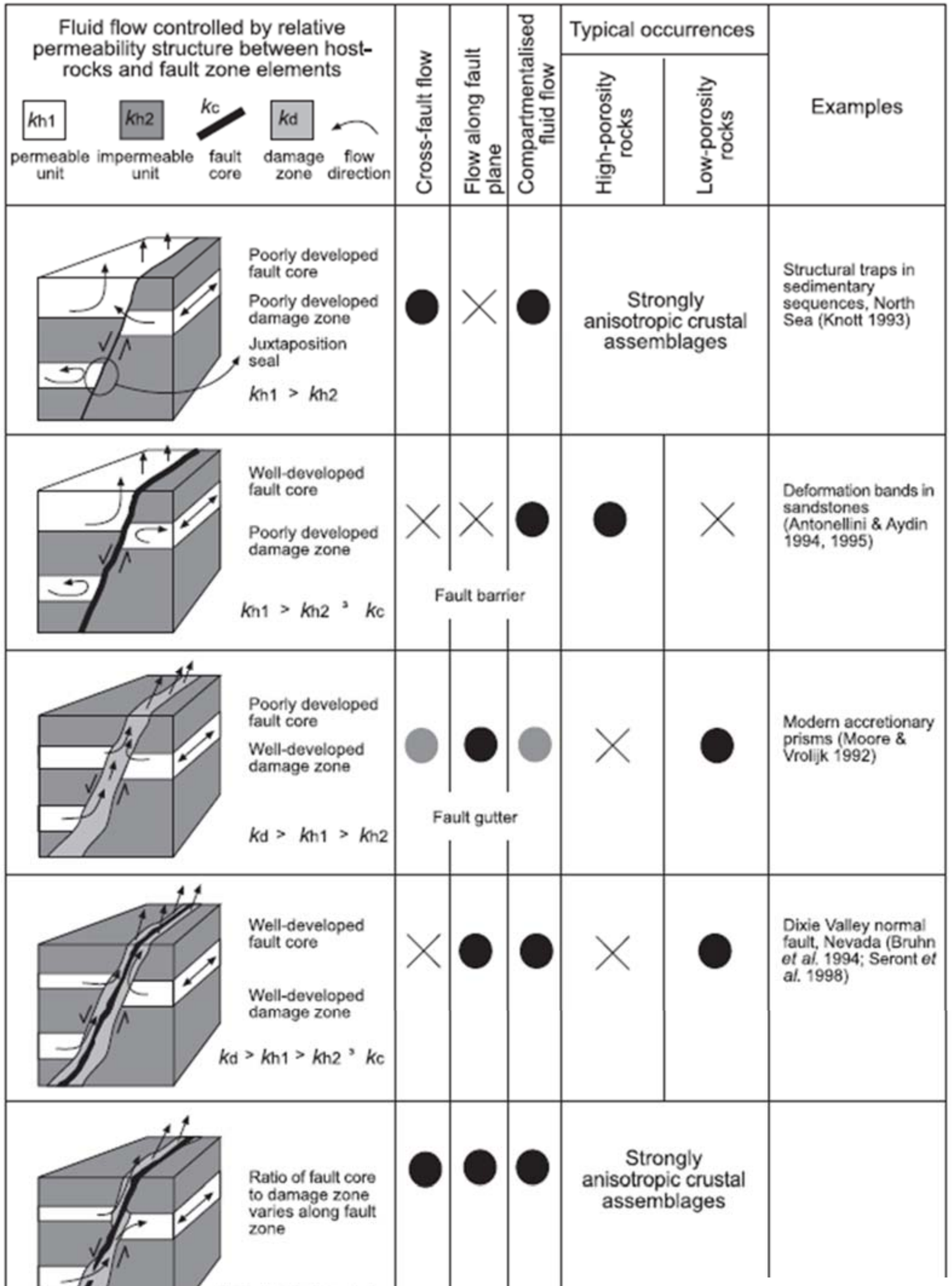


Figure 2. Conceptual scheme for fault-related fluid flow.

Faults can act as barriers or conduits for subsurface fluid movement, depending on their kinematic evolution their position within the current stress field, and the type of rock surrounding them.

The dimensions and transmissivity of the fault core and damage zone depend on the rock type surrounding the fault and on the kinematic evolution of a fault

Fault vs Fluid Flow



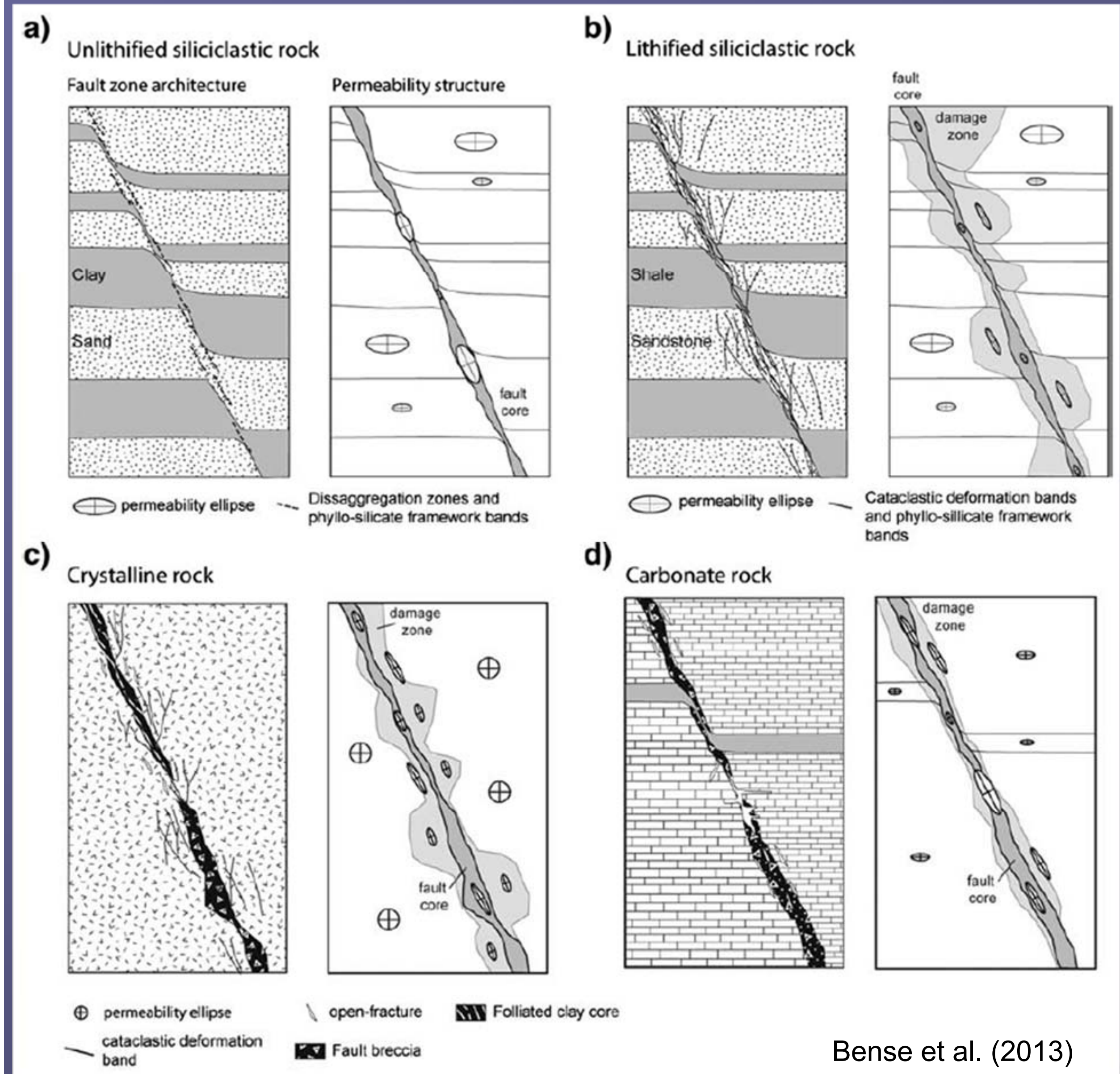
Rowland & Sibson (2004)

Static fluid interactions with normal faults comprising different ratios of fault zone elements

Flow is assumed to be buoyancy driven.

Grey circles indicate that fault–fluid interactions may vary according to the magnitude of the permeability contrast

Fault Architecture vs Permeability

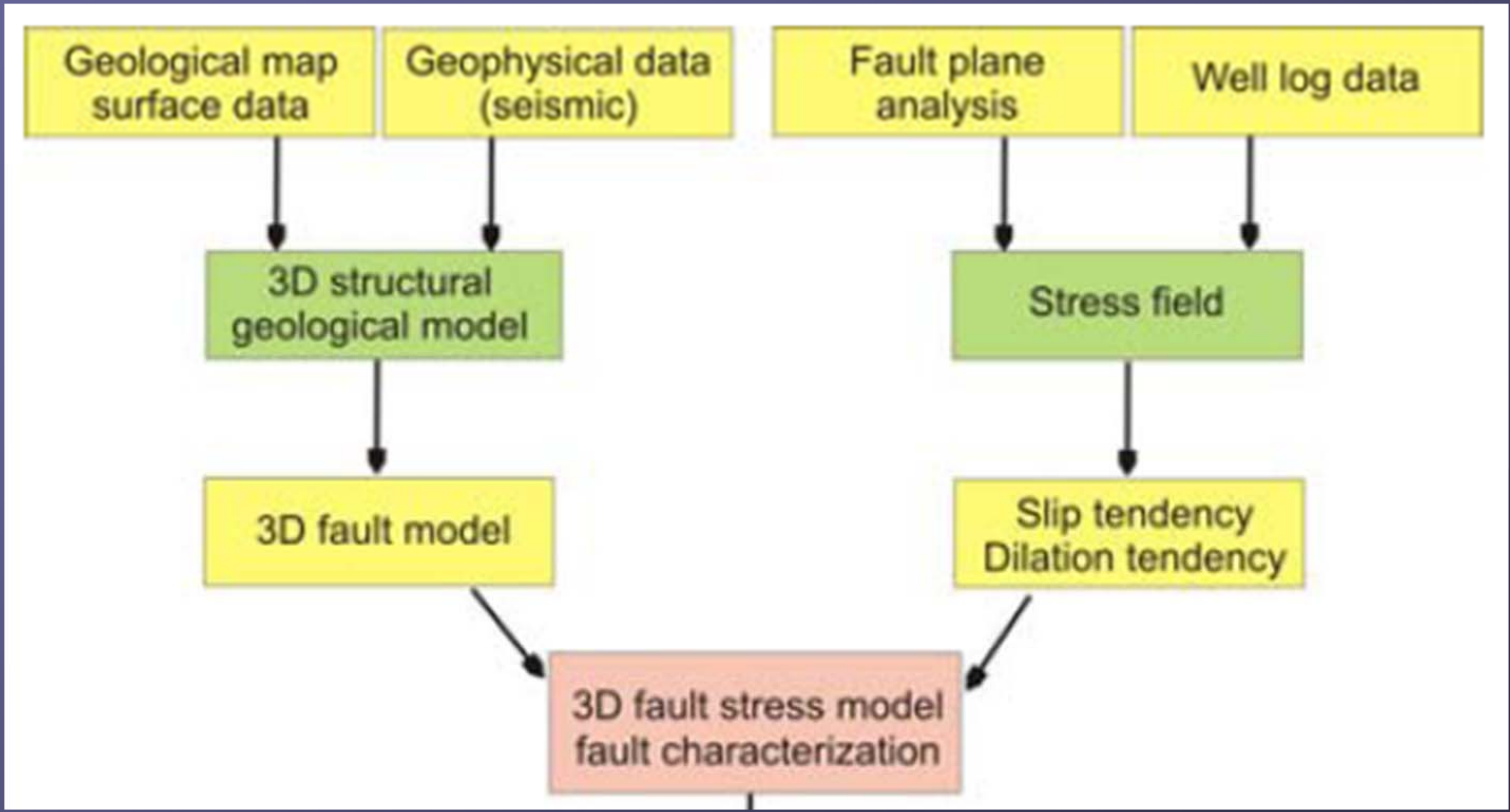


Bense et al. (2013)

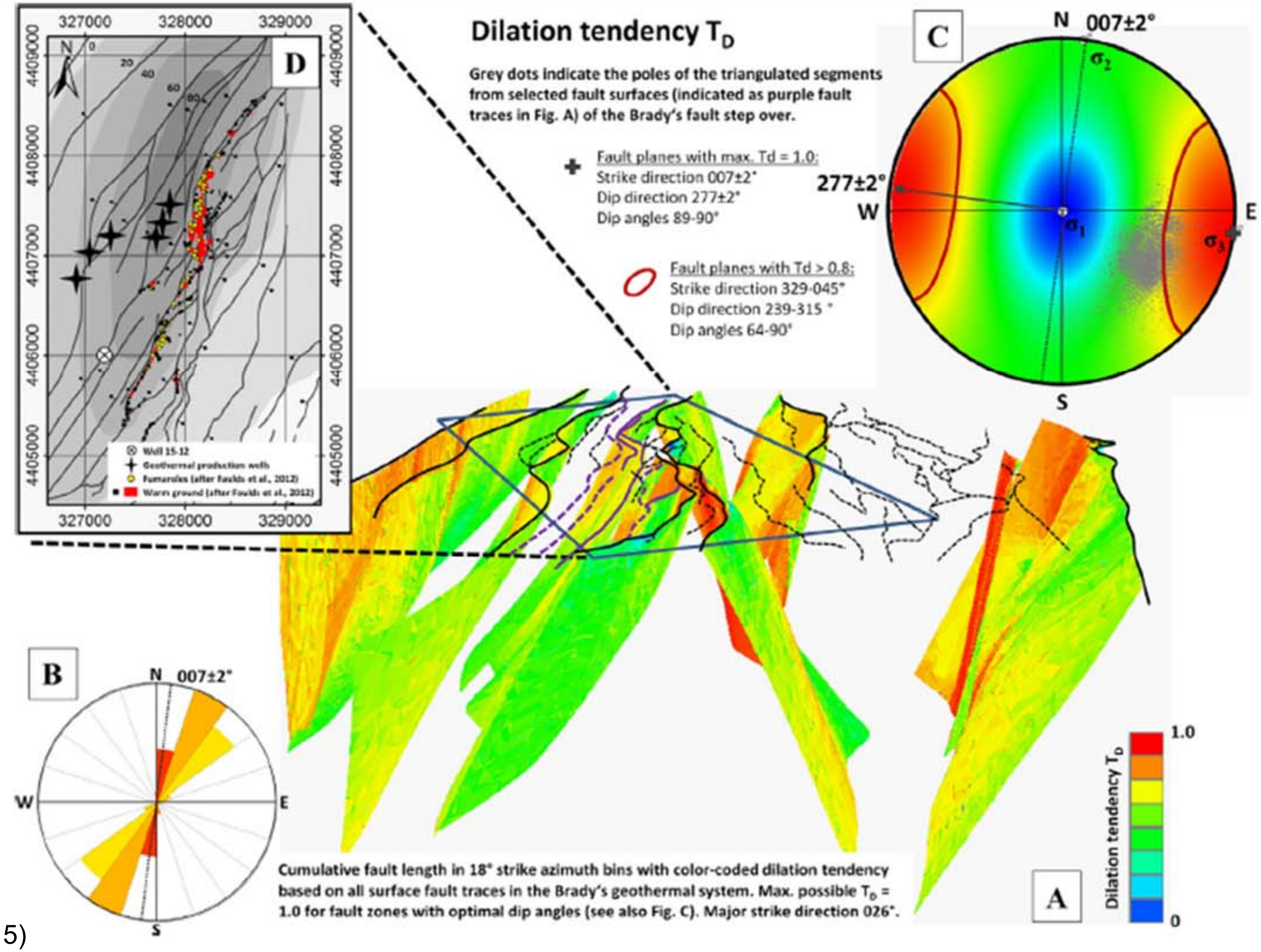
Examples:

- sandstone may develop deformation bands that act as fluid barriers in fault damage zones whereas, under the same conditions, carbonate rocks or granites may develop a fracture network that acts as a fluid conduit
- Faults reactivated multiple times or faults offsetting clayrich formations may be filled with clay ("fault gouge"), becoming barriers to subsurface fluid movement. In contrast, carbonate rocks may dissolve and "karstify" in the fault core, turning the fault into a conduit for fluids.

Geomechanics



Dilation Tendency



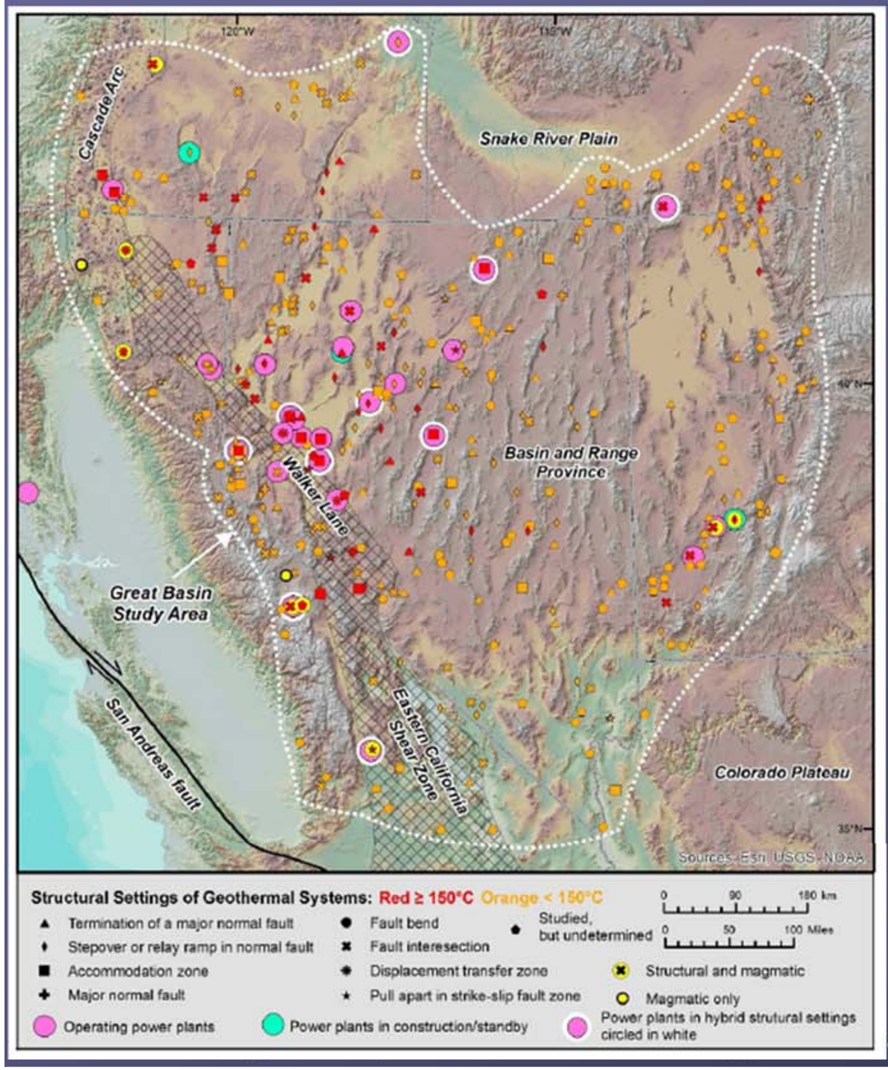
Jolie et al. (2015)

Fig. 12. (A) Dilation tendency for selected faults of the Brady's geothermal system. Other fault zones are indicated by their surface fault traces using dotted lines. The purple lines have been used for the stereo plot (see (C)). (B) The rose diagram illustrates the maximum dilation tendencies that fault zones could have for each strike azimuth bin. (C) Stereo plot with dilation tendency values from selected fault surfaces (see purple lines in (A)). Dilation tendency greater than 0.8 is outlined by a red ellipse. (D) The plot shows the main geothermal surface manifestations and the central area affected by subsidence at 20 mm interval contour lines (from Oppliger et al., 2005). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

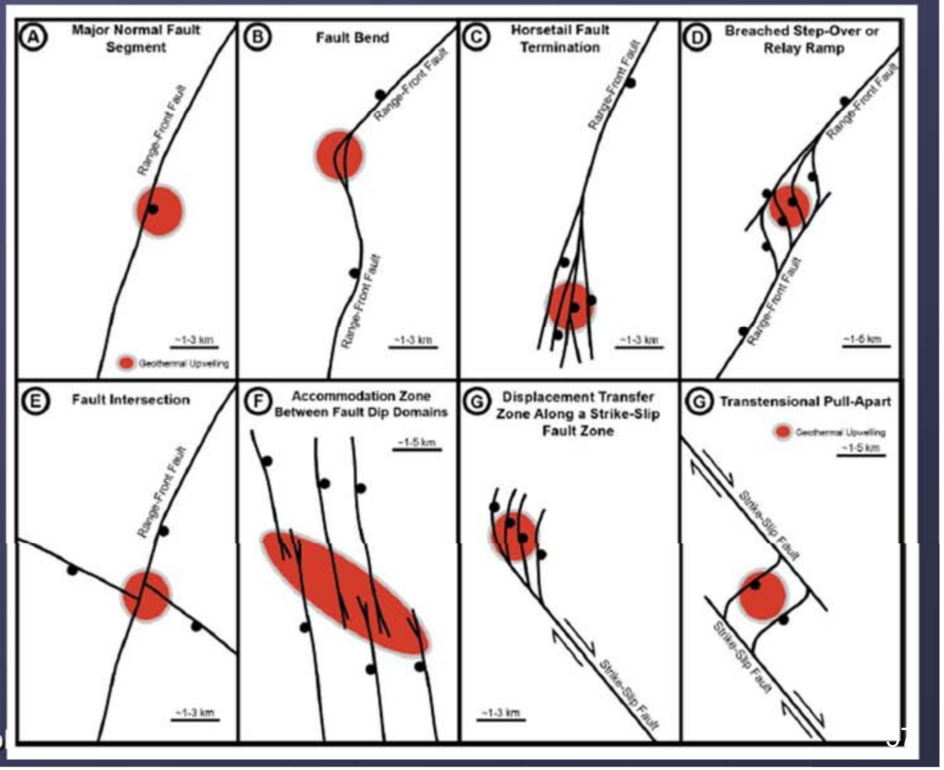
Favorable Structural Settings

Structural settings of geothermal systems in the Great Basin region (Faulds & Hinz, 2015)

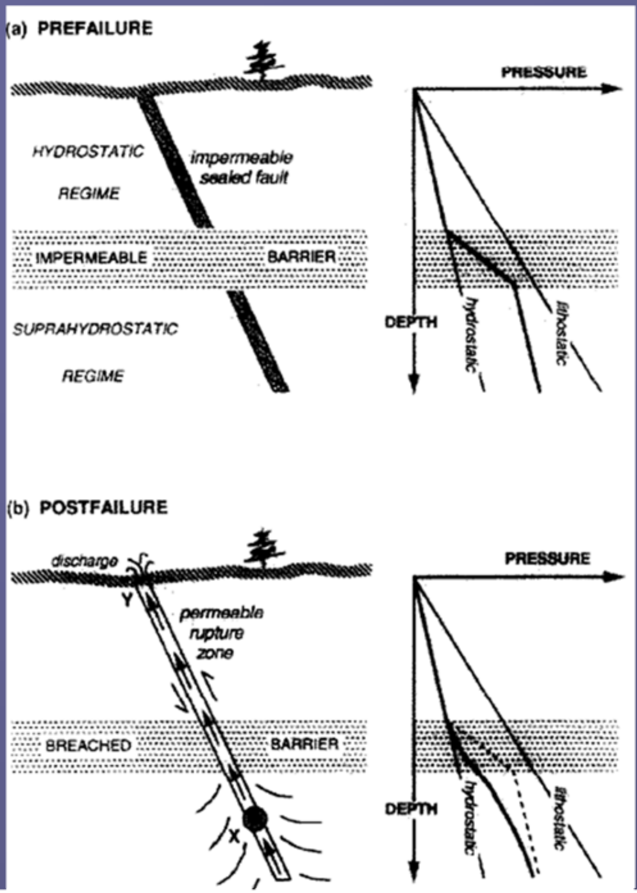
Step-overs, terminations, intersections, and accommodation zones correspond to long-term, critically stressed areas, where fluid pathways would more likely remain open



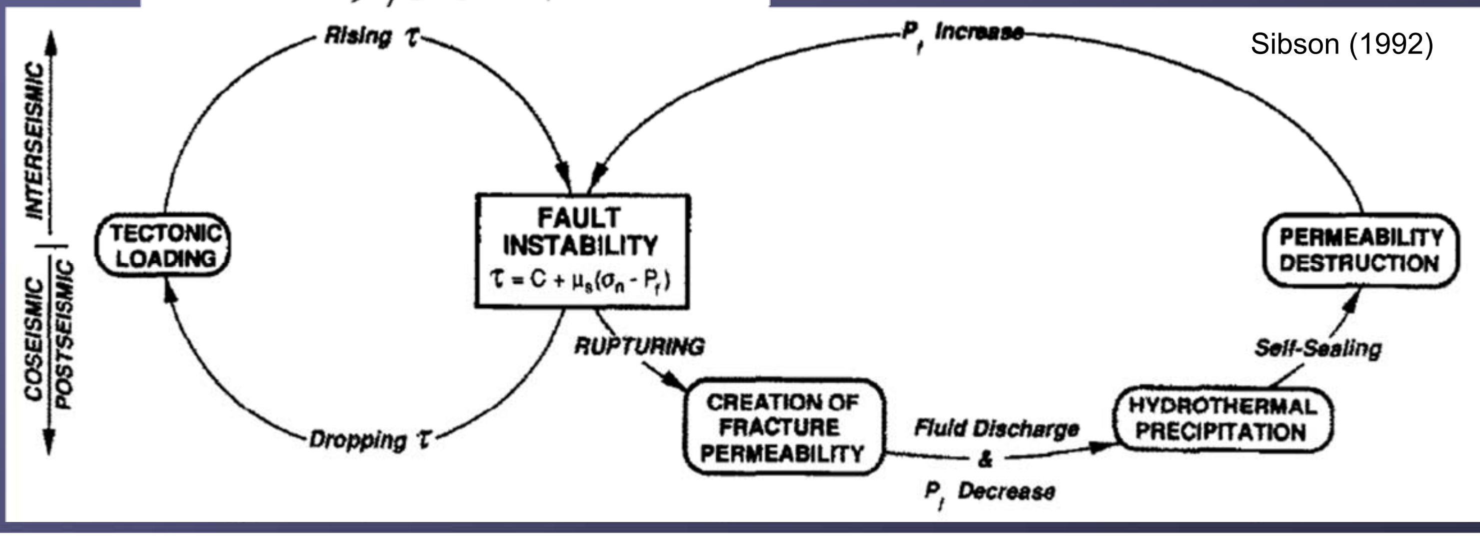
A) Major normal fault. B) Bend in major normal fault. C)Fault tip or termination with main fault breaking into multiple strands or horsetailing. D) Fault step-over or relay ramp breached by minor connecting faults. E) Fault intersection. F) Accommodation zone, consisting of belt of intermeshing oppositely dipping normal faults. G) Displacement transfer zone, whereby major strike fault terminates in array of normal faults. G) Transtensional pull-apart in major strike-slip fault



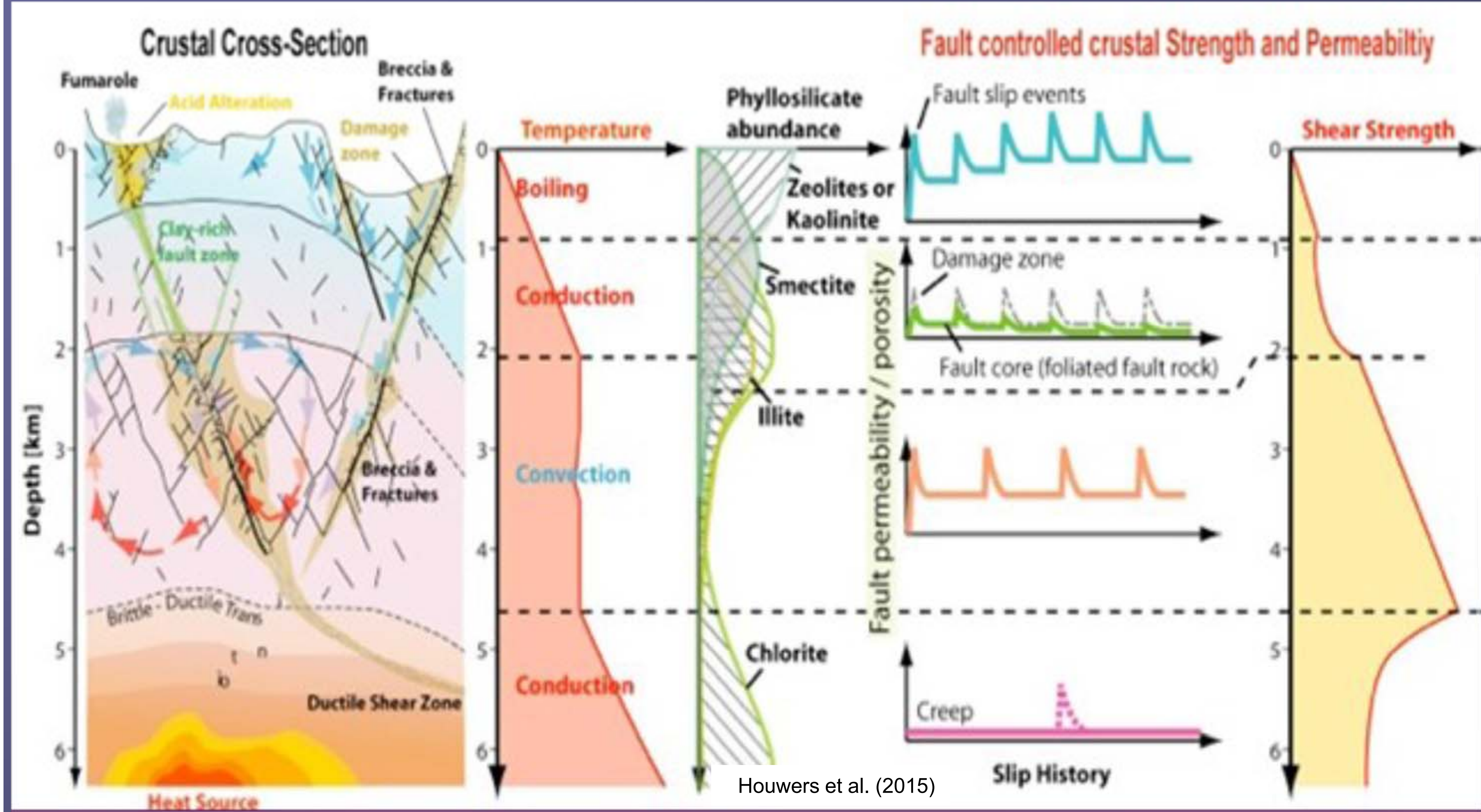
Fault Valve Activity



Schematic representation of fault-valve behaviour, illustrating gradients in fluid pressure pre- and post-failure when a rupture (X-Y) breaches the transition between hydrostatic and suprahydrostatic fluid pressure regimes.



Fault Zone vs Depth

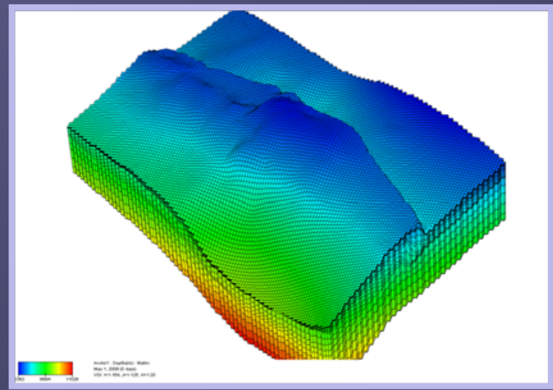


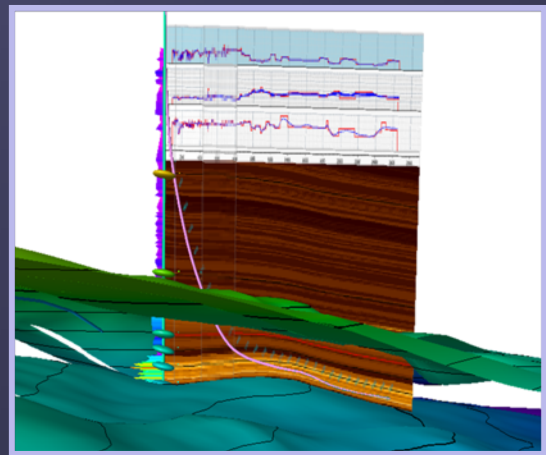
Houwers et al. (2015)

3D MODELLING

3D Modelling: Why?

- Geology is 3D by its nature
- 3D environment useful for data visualization and integration
- Required input for subsequent numerical simulations of reservoir behavior
  - Reservoir models to predict peformances under condition of exploitation
  - Geomechanics modeling to assess fault stability
- Design well paths
  - identify targets
  - adjust trajectories dynamically in a 3D canvas to find the optimal solution





3D GeoModels

- Two different approaches to 3D geomodelling (Calcagno, 2015)

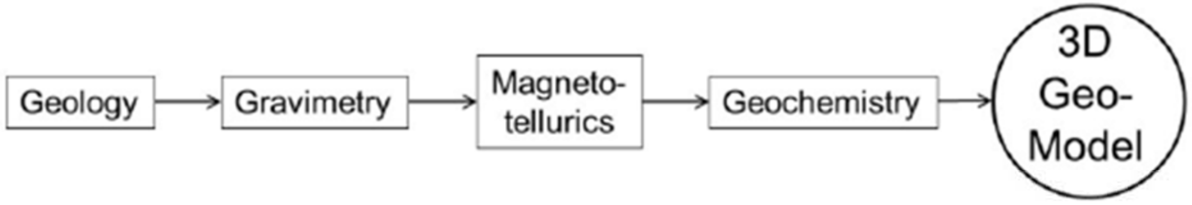


Figure 1: Workflow is the classical way for combining data. The 3D geomodel is the final result of sequential interpretations.

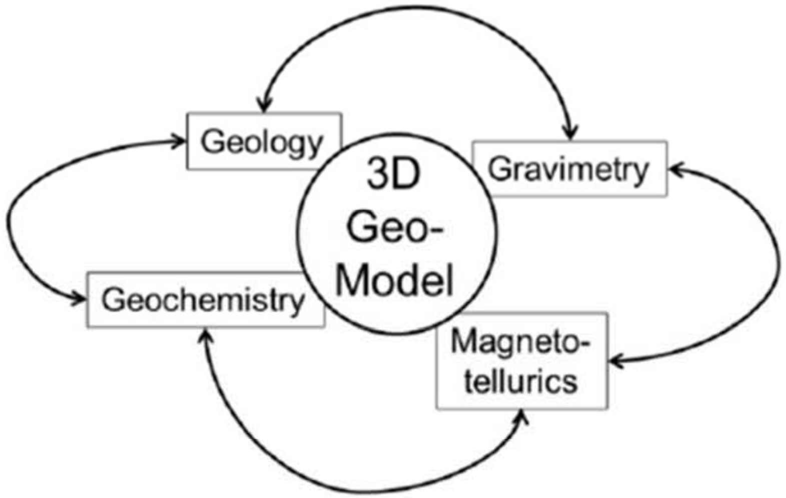
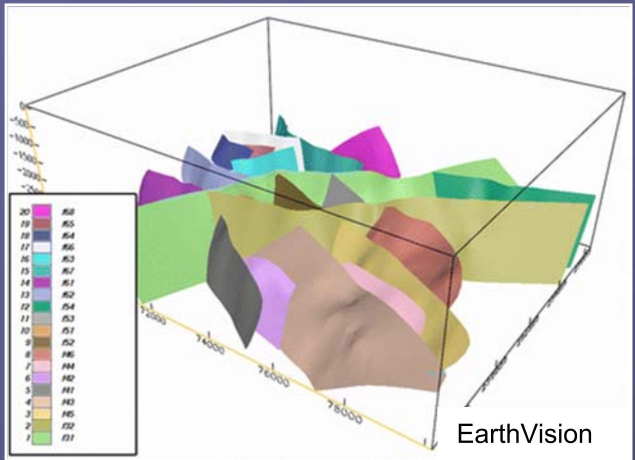
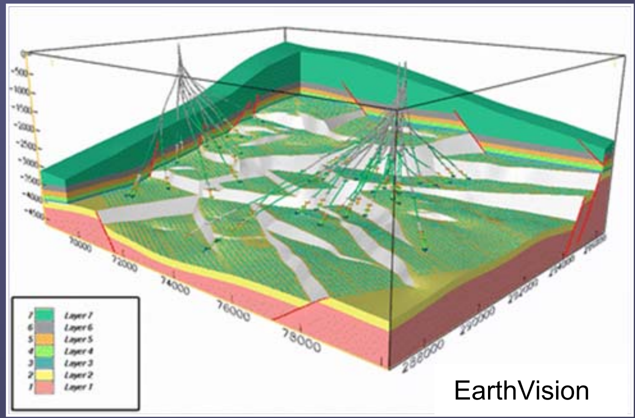


Figure 2: The 3D geomodel is the central part of the democratic interpretation. Scientific fields cooperate and interact to enhance the interpretation.

Modelling Procedure

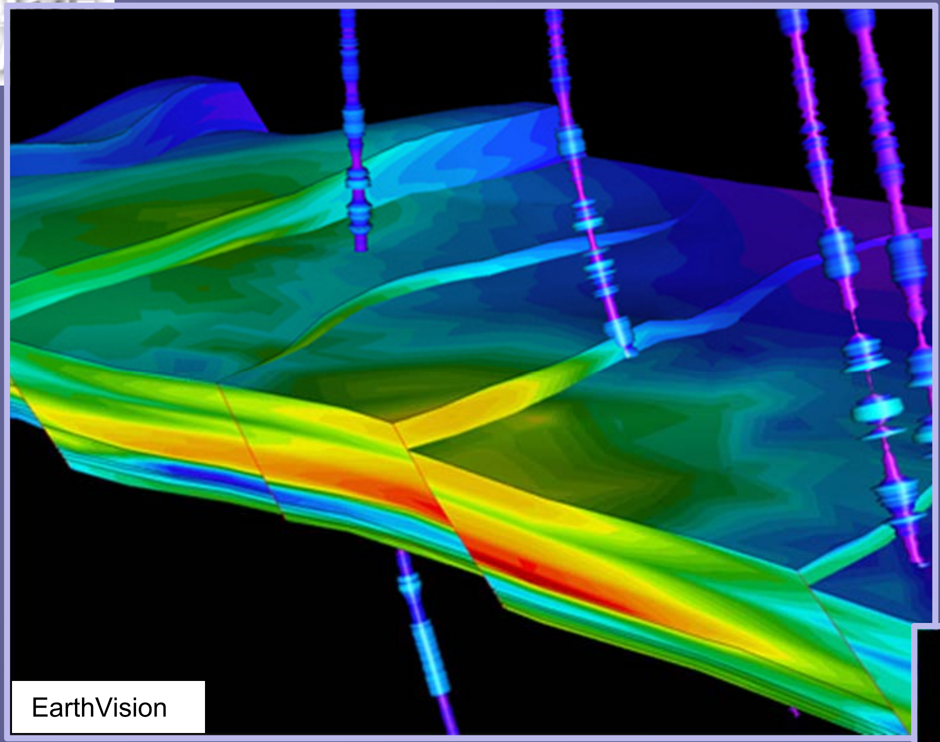
- The modelling procedure often involves, as a first step, the reconstruction of the fault network. In this way the modelled volume is subdivided in blocks by fault surfaces. Geological surfaces are then interpolated separately within each block.





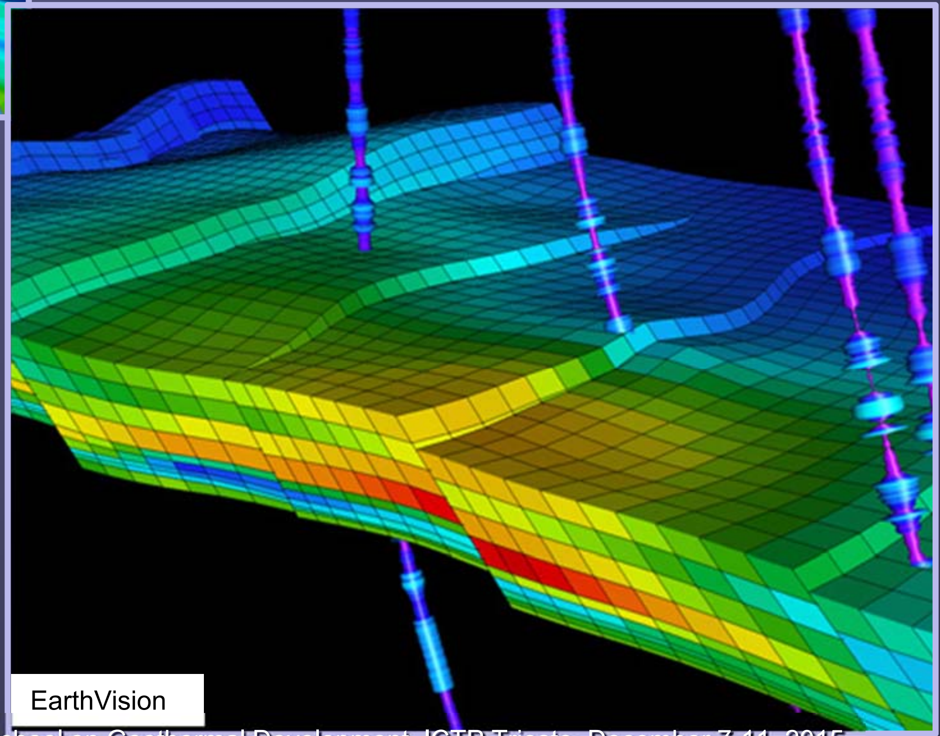
- In complex geological setting (e.g., thrust belt, salt tectonics), a validation of the structural interpretation may be appropriate. 2D/3D software tools (e.g., Move, LithoTect or Geosec) for structural restoration and analysis can help in building more robust structural models.

Property Modelling

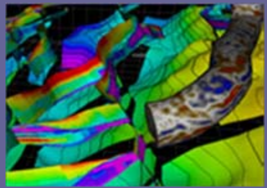


Property modelling within a faulted 3D geological model

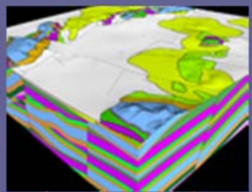
Geocellular model to be exported in numerical modelling softwares (e.g., fluid flow, geochemical reactions, geomechanical assessment)



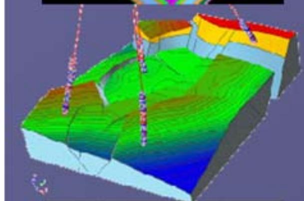
Interpretation & Modelling Softwares



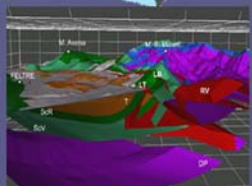
- **Petrel®** **(Schlumberger): Petrel geology capabilities, all unified with the geophysical and reservoir engineering tools, enable an integrated study by providing an accurate static reservoir description.**



- **EarthVision®** **(Dynamic Graphics): 3D model building and visualization. Accurate well positioning, reservoir characterization, and environmental analysis are made easy.**



- **Skua-Gocad®** **(Gocad Research Group, Paradigm): developed by a multidisciplinary team of researchers striving to define new approaches to build and update 3D subsurface models.**
- **DecisionSpace®** **(Landmark/Halliburton): integrated platform for interpretation and modelling of subsurface dataset.**



- **Move®** **(Midland Valley): 2D/3D structural modelling software (allows 2D/3D restoration and forward modelling)**
- **Kingdom®** **(Seismic Micro-Technology): well and seismic reflection data interpretation**

… and a lot more: GeoModeller, RMS Roxar,, EVS & MVS, FastTracker, GSI3D, Leapfrog, RockWorks, Surpac, Vulcan, Geographic, etc.

(see also http://www.3d-geology.de/software/geology_and_mining/)

3D Modelling Softwares

- Apparently show similar functionalities but each software has its own strengths and pitfalls
- Some software originally developed within the framework of scientific project promoted by research consortium (e.g. GoCad) or by specific need of National Geological Surveys (e.g., UK BGS -> GSI3D or France BRGM -> 3D GeoModeller). Other are fully industrial initiatives
- Require training
- Educational/Academic licences often available (e.g. Petrel, but commercial use can be very expensive - up to hundreds thousand of Euros for full suites)
- Choice requires to be targeted to specific needs (huge dataset? 3D seismic? Structurally complex areas?) with a costs/benefits analysis
- Faulted terrains represent always a challenge for modelling exercises
  - Some software are not able to manage faults. Others can but results quality can be very different in heavy faulted areas
  - Low angle thrusts and magmatic intrusion significantly complicate the modelling procedure