# Fold and Thrust Belts:

## an attempt to outline the controls on Hydrocarbon Habitats, and some illustrative examples.

A presentation to PESA (NSW branch), February 8th 2011.

# FTBs: characteristics.

**Fold and Thrust Belts are characterised by:-**

•complex trap geometry

• complex burial / unroofing history and thermal / diagenetic history

• significant transient effects

• limited period between onset of HC generation, migration, and trap development

• complex history of fill and spill

• significant local variation, both along and across strike

**Other challenges can be:-**

• difficult terrain, hence frequently poor seismic quality  (at least initially

• high cost of operations (seismic and drilling)

• environmental constraints (human, and fauna / flora)

# FTBs: Global Studies

• **Amoco study: 24 FTBs x 20 play elements x 6 possible risk levels.**
**Conclusion: presence of high quality source rock dramatically reduces the risk of all other play elements, except trap delineation.**

•**Shell study: focussed on Sub-Andean FTB.**
**Conclusion: key factors were rich source rock in mature kitchen, and charge co-eval / post trap formation. Given this, any trap style / resvr can work.**

•**Chevron study (~1999): focussed on trap and seal risks.**
**Conclusion: top seal rarely a severe risk, but fault / lateral seal is. (Still lack ability to predict presence/effectiveness of fault seal).**

•**Encana study (Cooper, 2007):**
**The 6 richest FTBs have no common set of structural attributes – i.e. structural success factors are not necessarily repeatable. What they all do have in common are rich source rocks and regionally effective resvr/seal pairs.**

No earth-shattering conclusions from dozens of man-years of work

Meneses-Rocha and Yurewicz (1999) AAPG 83; and Cooper (2007) GS Sp Pub

# FTBs: Global Studies

**IFP SubTrap study – did actually come up with some interesting conclusions.**

1. Best sandstone resvrs are clean coarse quartz sands of cratonic origin (Mirador (Eo) of Cusiana; Navajo (J) of W. USA).
   Sst diagenesis dominated by syn-tectonic effects (esp LPS).
2. Carbonate resvrs generally in pre-tectonic passive margin sequence. Pre-tectonic diagenesis much more important. Syn-tectonic diagenesis often phi/K-enhancing.
3. In many sub-thrust resvrs, total K can be significantly reduced by the presence of
   - pyro-bitumens – thermal cracking of early-migrated oil by later burial
   - tars – biodegradation due to meteoric water influx after uplift
   - asphaltenes – influx of gas into pre-existing oil pool, or major pressure change
4. Risk of H2S – thermo-chemical sulphate reduction (evaps + HC at depth).

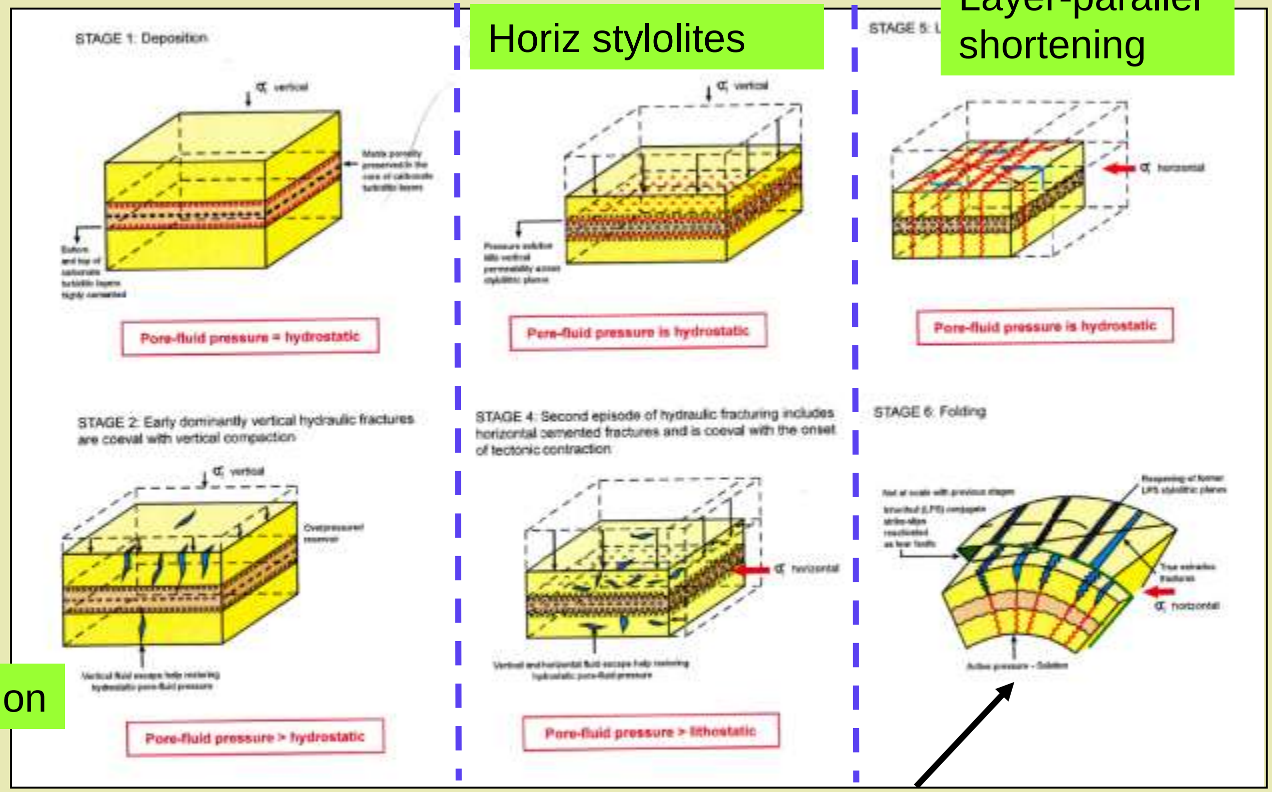
Roure et al (2005) Rev IFP 60 (1)

# FTBs: reservoir diagenesis: (IFP)

Despite complex diagenesis (see right) viable phi/K can be maintained by:-

- over-pressure
- late dissolution of early calcite cement
- HC trapping

Carbonates only



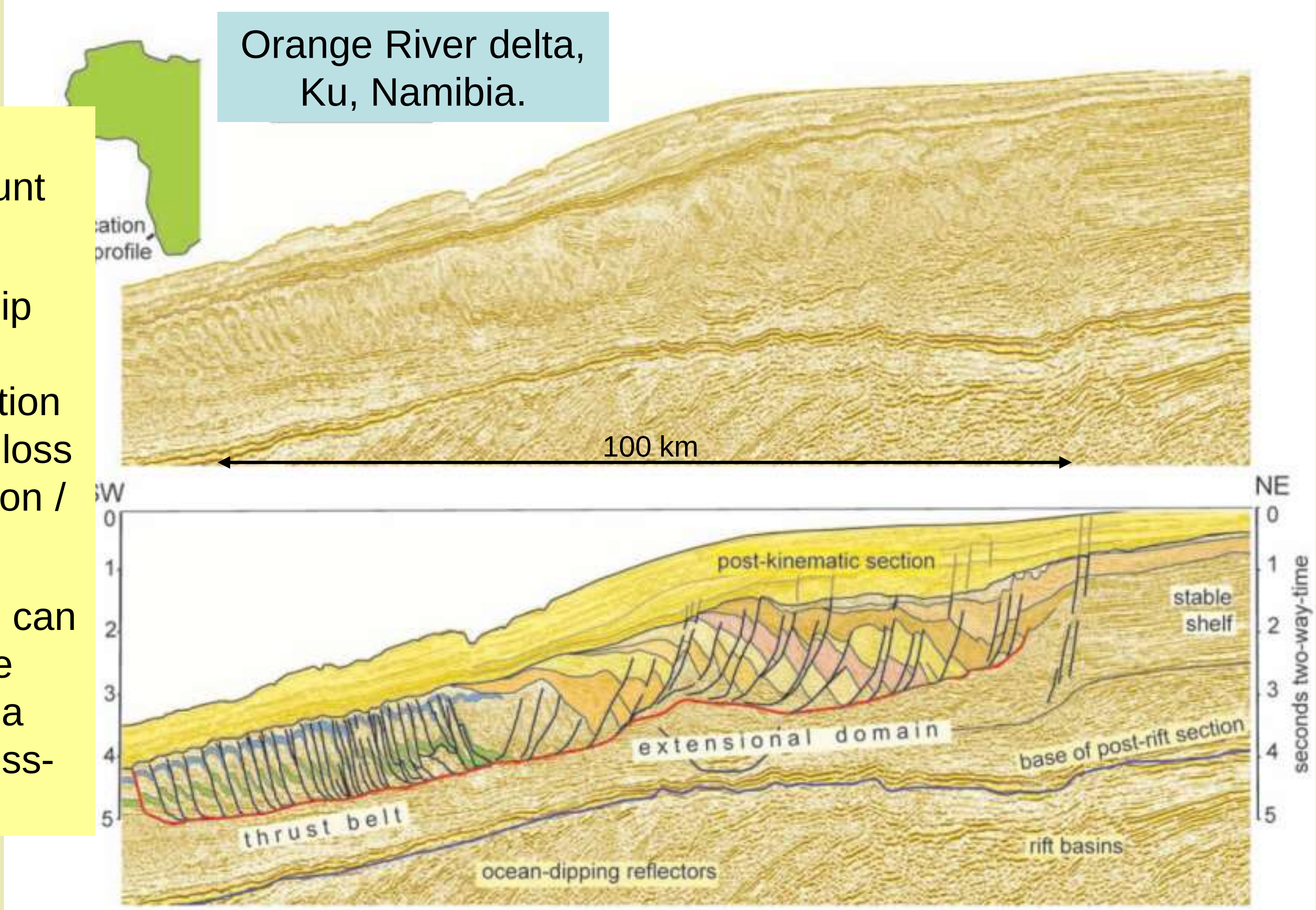

**Actual folding / thrusting is very late in the diagenetic evolution of resvrs. Is generally positive – fractures; leaching of calcite.**

Stage 7: uplift, cooling → fracturing, leaching, deposition of tar / asphaltenes

Roure et al (2005) Rev IFP 60 (1)

# FTB: Layer Parallel Shortening (LPS)

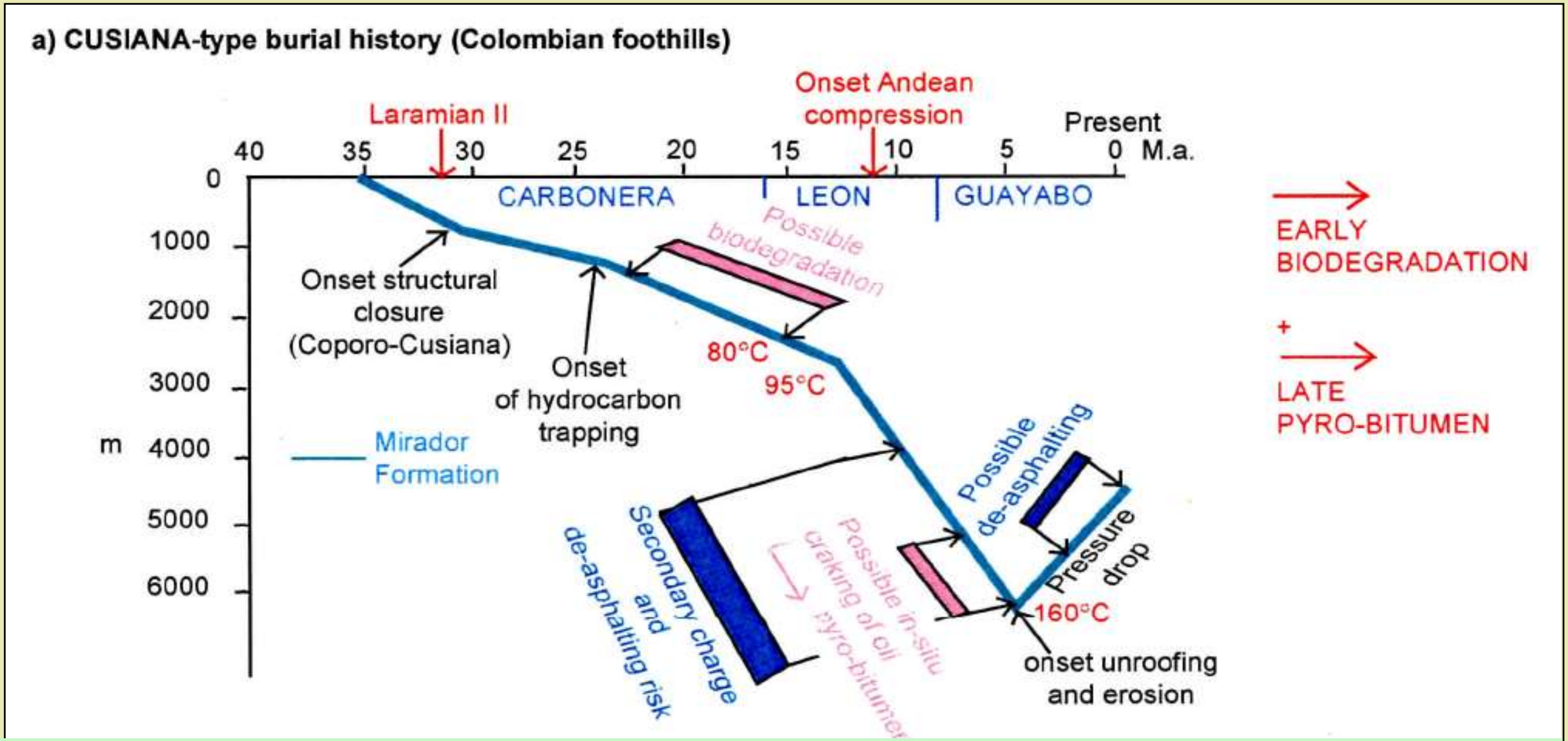
Orange River delta, Ku, Namibia.




- First qualitative estimate of amount of LPS in FTB.
- To balance updip extension and downdip contraction requires volume loss (lateral compaction / LPS) of 18-25%.
- Significant LPS can render invalid the bed length criteria for balancing cross-secctions

Butler and Paton (2010) GSA Today

# FTB: oil degradation risks (IFP)




Burial – temperature curve of typical Sub_Andean sandstone resvr showing:

1. Early charge can result in bio-degradation if resvr temperature <~80*C
2. Increasing burial can result in further charge with more gassy oil – deasphalting risk
3. As maximum burial reached, risk of cracking of oil and deposition of pyro-bitumen
4. Possible de-asphalting (or even biodegradation) with uplift and pressure reduction.

Roure et al, 2005, Rev IFP 60

# FTB: Global Studies (IFP)

**IFP SubTrap study – con.**

1. Late orogenic extension can cause major uplift of FTB and foreland basin – calibrated from VR, To, coal rank, and AFTA data – gradually freezes SR expulsion.

2. Essential is the combination of outcrop, source rock and reservoir studies, and basin modelling – giving a regional understanding of fluid migration; timing of tectonic stresses; and timing of rising topography, with the objective of understanding the sequence of HC charge into FTB prospects and the adjacent foreland basin.

3. Rates of thrusting = 2 – 4 km/Ma (Pyrenees)

4. Recent paper updates IFP FTB methods: Roure et al (2010) Geol Soc Sp Pub 348.

Roure et al, 2005, Rev IFP 60

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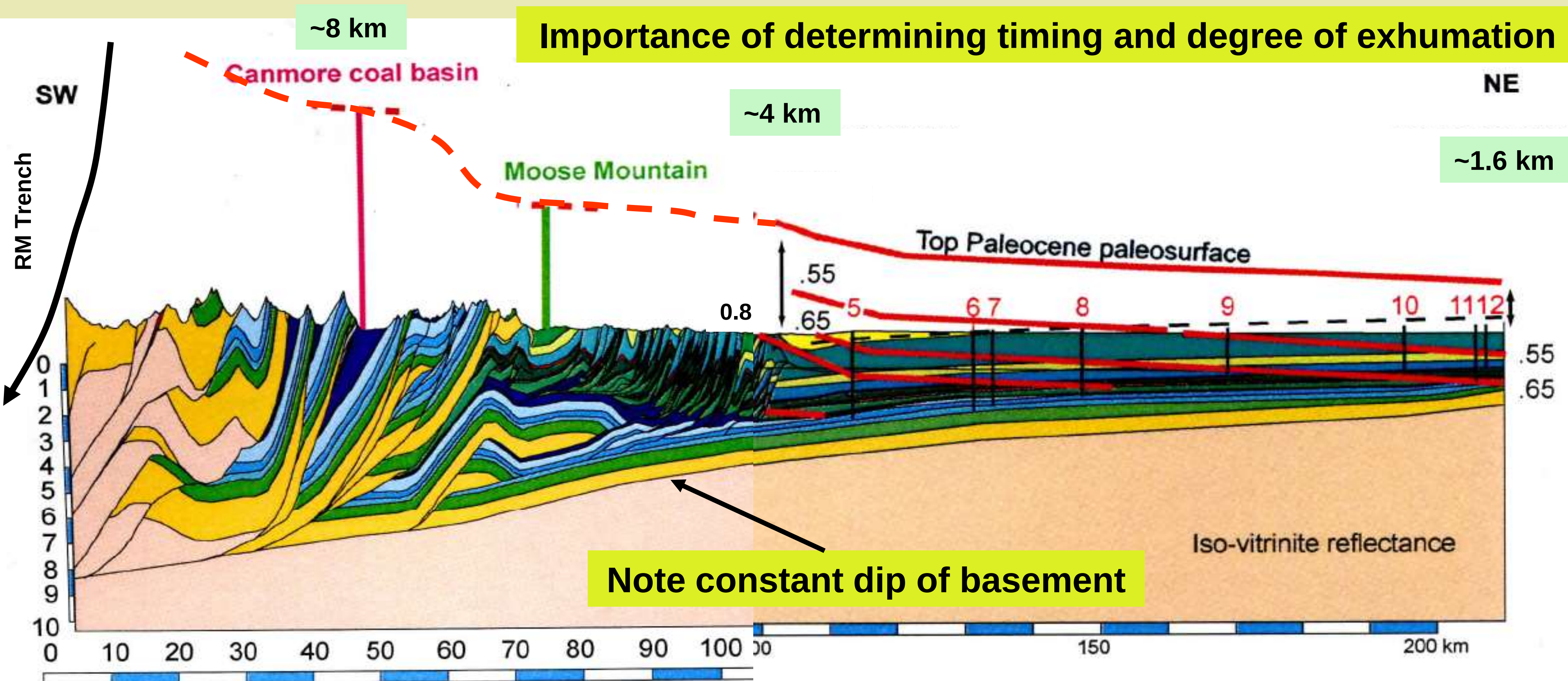
HC in outer (blind) thrusts;
HC richness ~0.1 mmboe / km2

# IFP profile thro' vicinity of Calgary

Importance of determining timing and degree of exhumation




Faure et al, 2004, Rev IFP 59(1)

- Used vitrinite reflectance and AFTA to model extent/amount of removed overburden
- Extensional collapse of FTB core in Eocene (RM trench) led to large (upto 8 km) uplift of E sector of FTB, but effect of uplift is seen >100 km into adjacent foreland basin.

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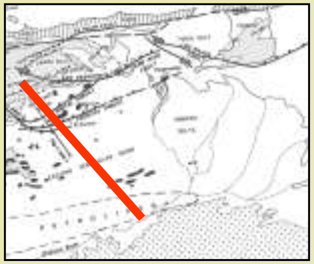
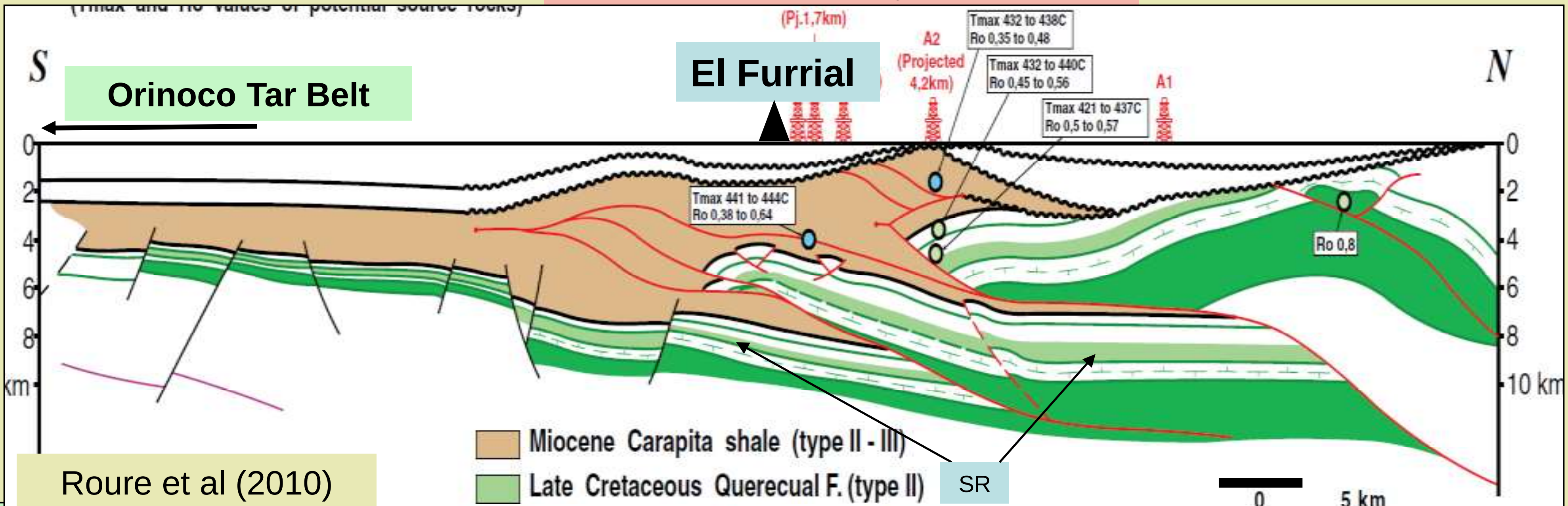
# FTB: fluid flow modelling (IFP)



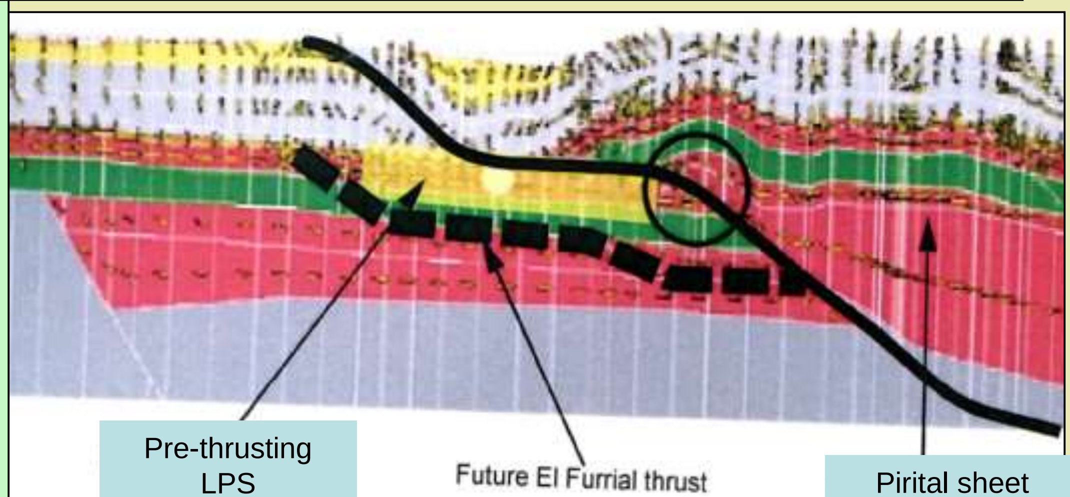
~9 BBO: 28 API at crest, 8 API at OWC




Roure et al (2010)

History of HC charge:

1. 'Squeegee' effect drives oil out of frontal foreland basin updip to charge the oil sands of the Orinoco Tar Belt
2. Charge into El Furrial from underlying / downdip Querecual SR during thrusting.
3. FI study suggests possible early charge from (over-pressured) Pirital sheet as it passes (future) EF sheet



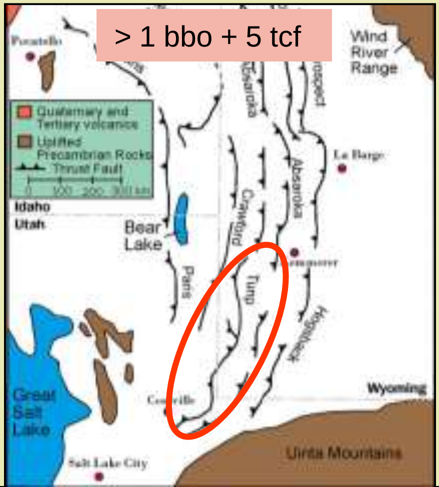
# FTB: Global Studies

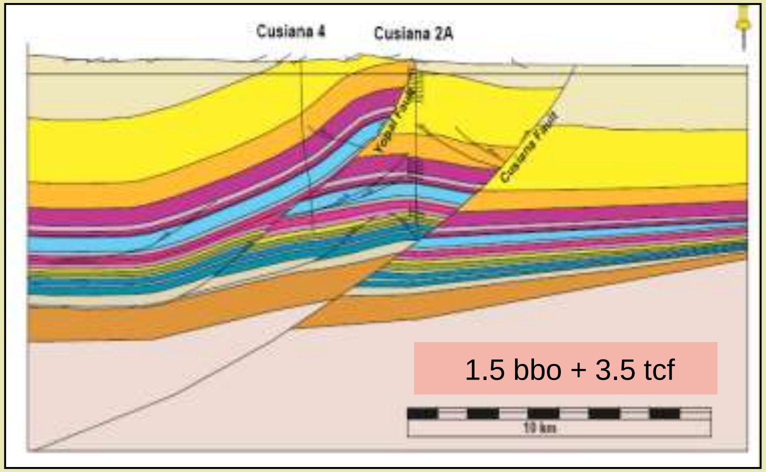
**PJ study (unpublished): Critical success factors (1)**

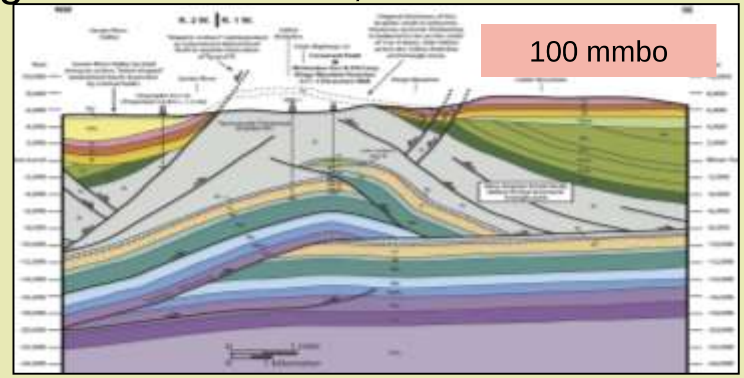
- rich source rock in mature kitchen
- good charge timing vs. trap timing
- 'good' reservoir (but see below)

} given these, any trap style can work

- perseverance
  - Amoco drilled first W. Overthrust discovery on a double farm-out.
  - Triton retained Cusiana despite 2 negative industry farm-out attempts.
  - Wolverine took Covenant prospect and acreage to NAPE twice, without success.




~115 dry holes drilled on trend in ~50 years.

Reservoired in frontal (blind) thrust

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# FTB: Global Studies

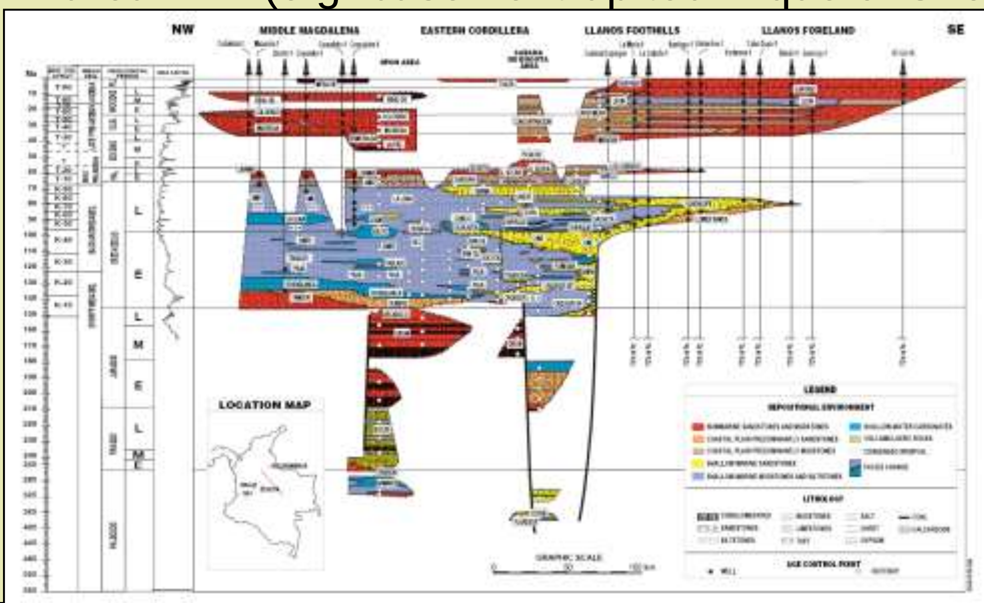
**PJ study (unpublished): Critical success factors (2)**

• integrate detailed surface geological data (including syn-orogenic sediments / ages / patterns with subsurface and geophysical data to construct balanced 3D geometry of FTB

•characterise key source rock horizons

• timing of trap formation vs HC expulsion and drainage areas thro' time, i.e. model timing, sequence and rate of thrusting; co-eval sedimentation; and erosion / unroofing history.

•build regional stratigraphic and tectonic picture and develop key interpretation tool for the area (e.g. basement-up technique of Shell Canada)



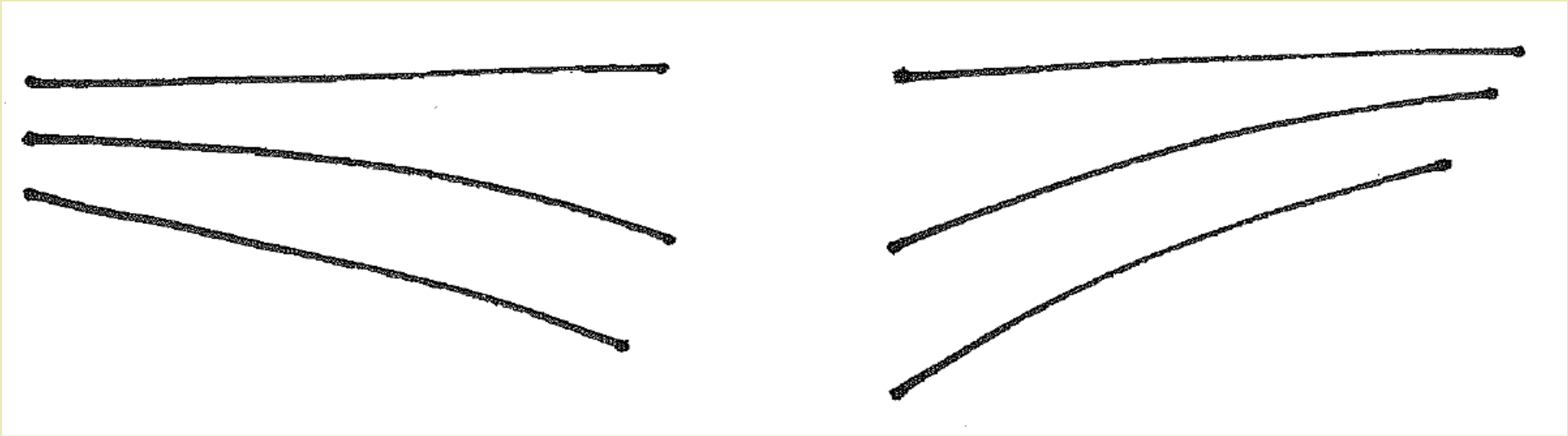

• ability to image traps seismically (tho' PNG shows that geological understanding can make up for very poor quality seismic (high velocity carbonates at surface and very rugged terrain)

**Tectono-stratigraphic summary of Llanos Basin and E. Cordillera, Colombia (BP)**

# FTB: importance of syn-orogenic geometries

Syn-orogenic sediments wedging towards the craton
= age of foreland basin subsidence

Syn-orogenic sediments wedging towards fold belt
= age of uplift / unroofing



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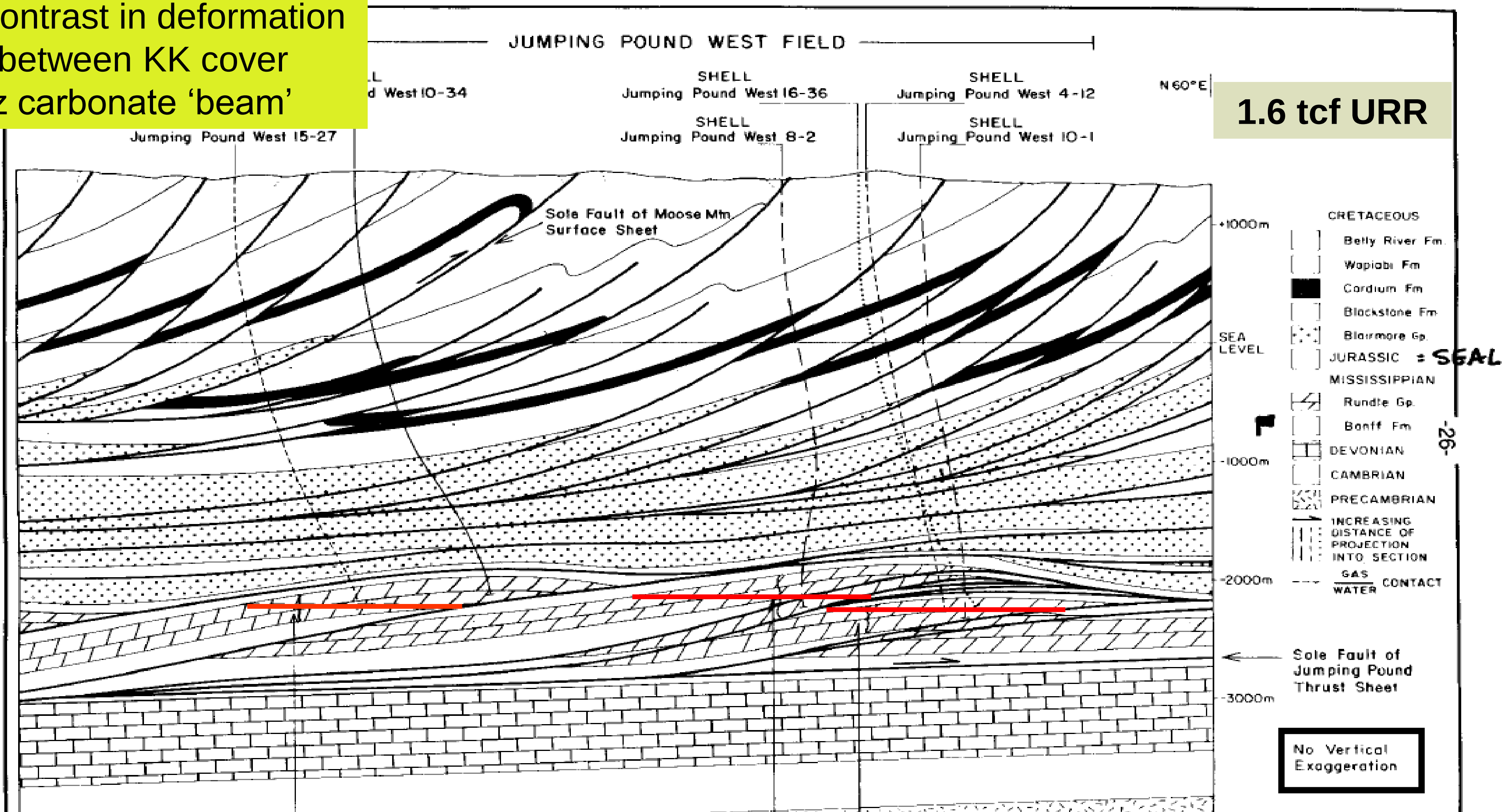
# FTB: typical Canadian Foothills gas field (Jumping Pound West)

Note contrast in deformation styles between KK cover and Pz carbonate 'beam'

1.6 tcf URR




Note constant basement dip

Charge from Exshaw SR 63 – 59 Ma was oil, co-eval with thrusting and dissolution of calcite in resvr. Gas produced later by secondary cracking. Oil only found at shallow depths in outboard (Turner Valley). (IFP)

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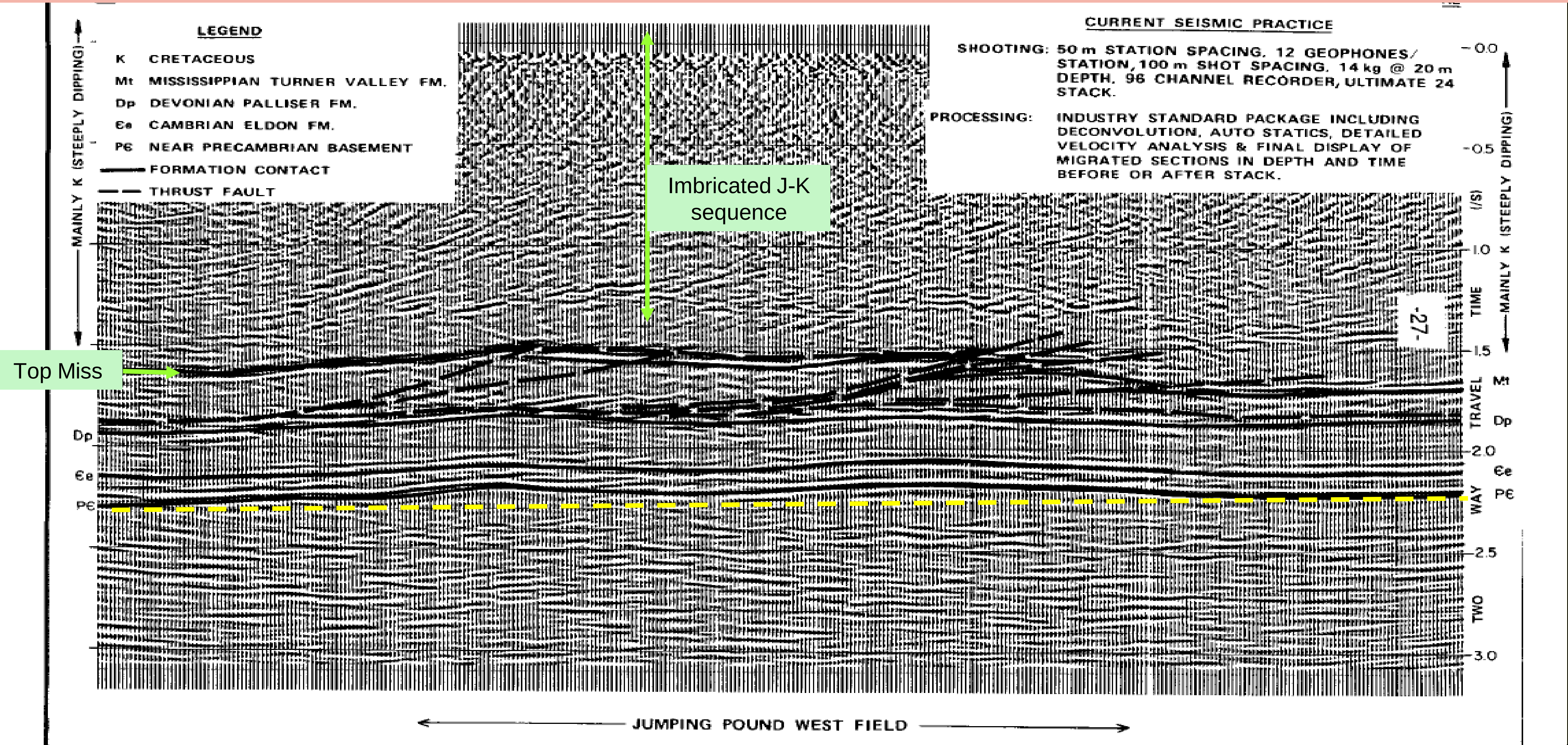
# FTB: the key to the first discoveries

**Typical Shell Canada seismic section (1960s): undulations in Top Basement reflector = velocity pull-ups due to overlying imbricate stacks of high-velocity Pz carbonates. This was the key to the discovery of the first gas fields in the Canadian Foothills.**



# FTB: tectonic control on FTB architecture

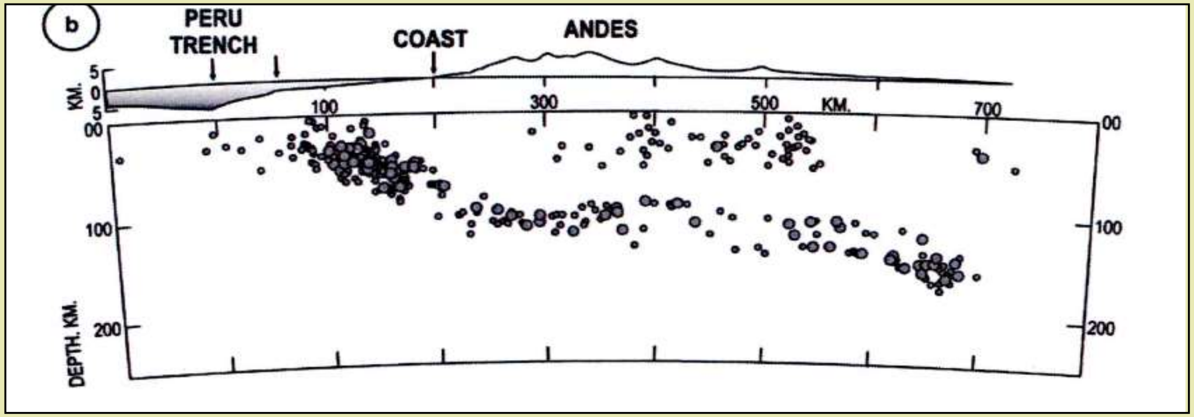
**<u>PJ study (unpublished): rules of thumb (1)</u>**

- structural style is determined largely by:
  - mechanical character of overthrust sequence and/or
  - the dip of the subducting slab and/or
  - nature of inherited (basement) grain
  - nature of decollement horizon (see below)

- presence of evaporites appears to favour development of back-thrusts, and can also cause a dramatic foreland-ward jump in the outer thrust front (e.g. Salt Range, Pakistan)

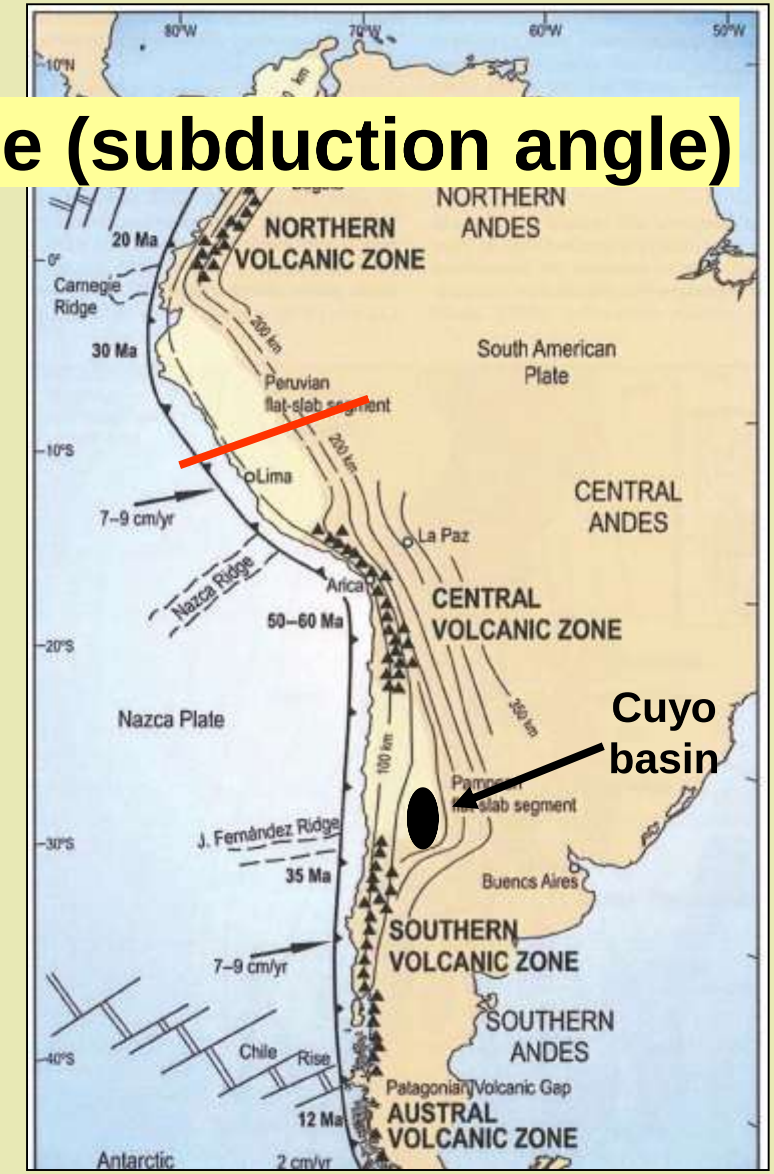
- importance of recognising lateral ramps.

# FTBs: influences on structural style (subduction angle)




Steep dip of Benioff zone correlates well with low-angle sled-runner type deformation e.g. Western North America Fold and Thrust Belts

Shallow-dipping Benioff zone correlates well with high-angle, basement-cored uplifts, e.g. Laramide uplifts of Western USA; Peruvian and Pampean segments of the Sub-Andean Belt.




Ramos and Folguera (2009) GS Sp Pub 327

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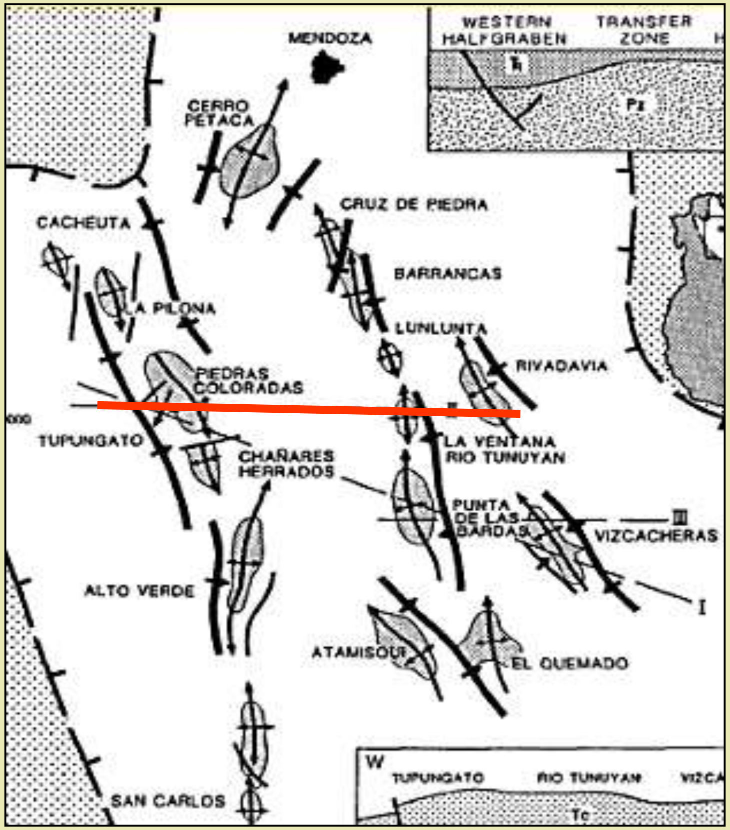
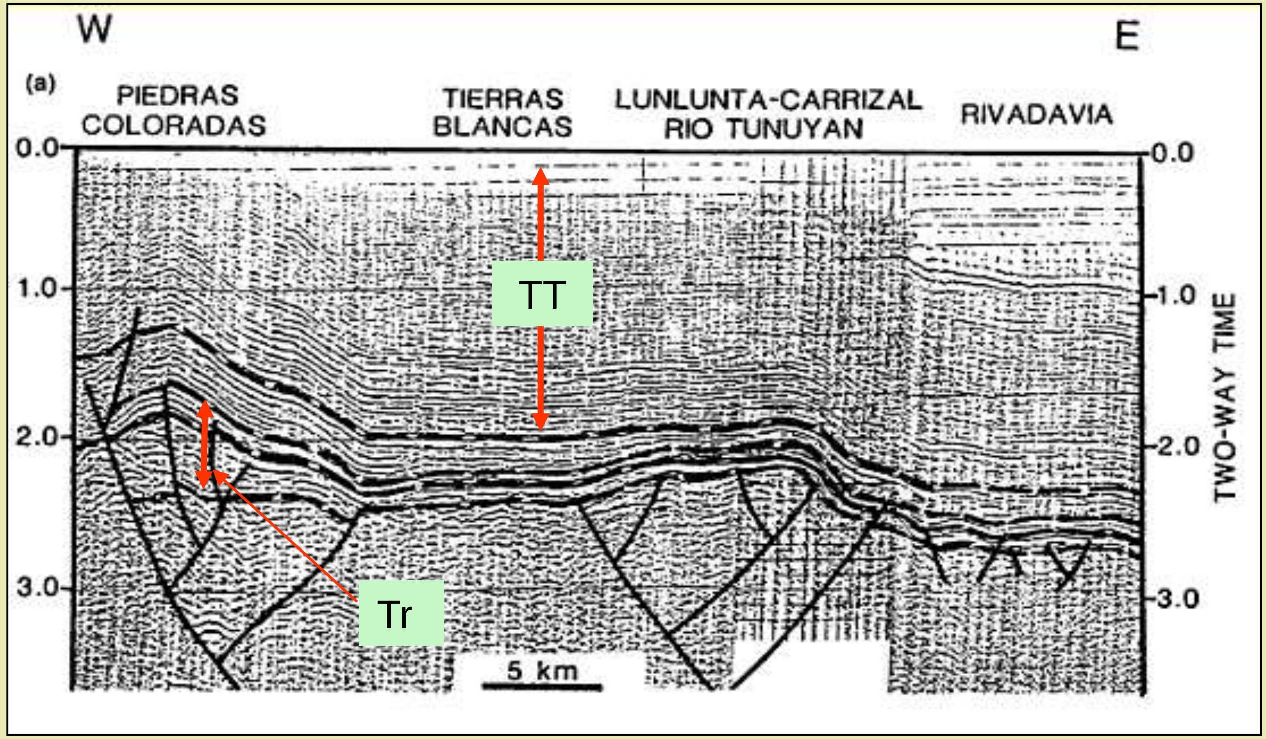
# Inversion of pre-existing rifts, Cuyo Basin, Argentina.

Prospectivity controlled by structure of early passive margin



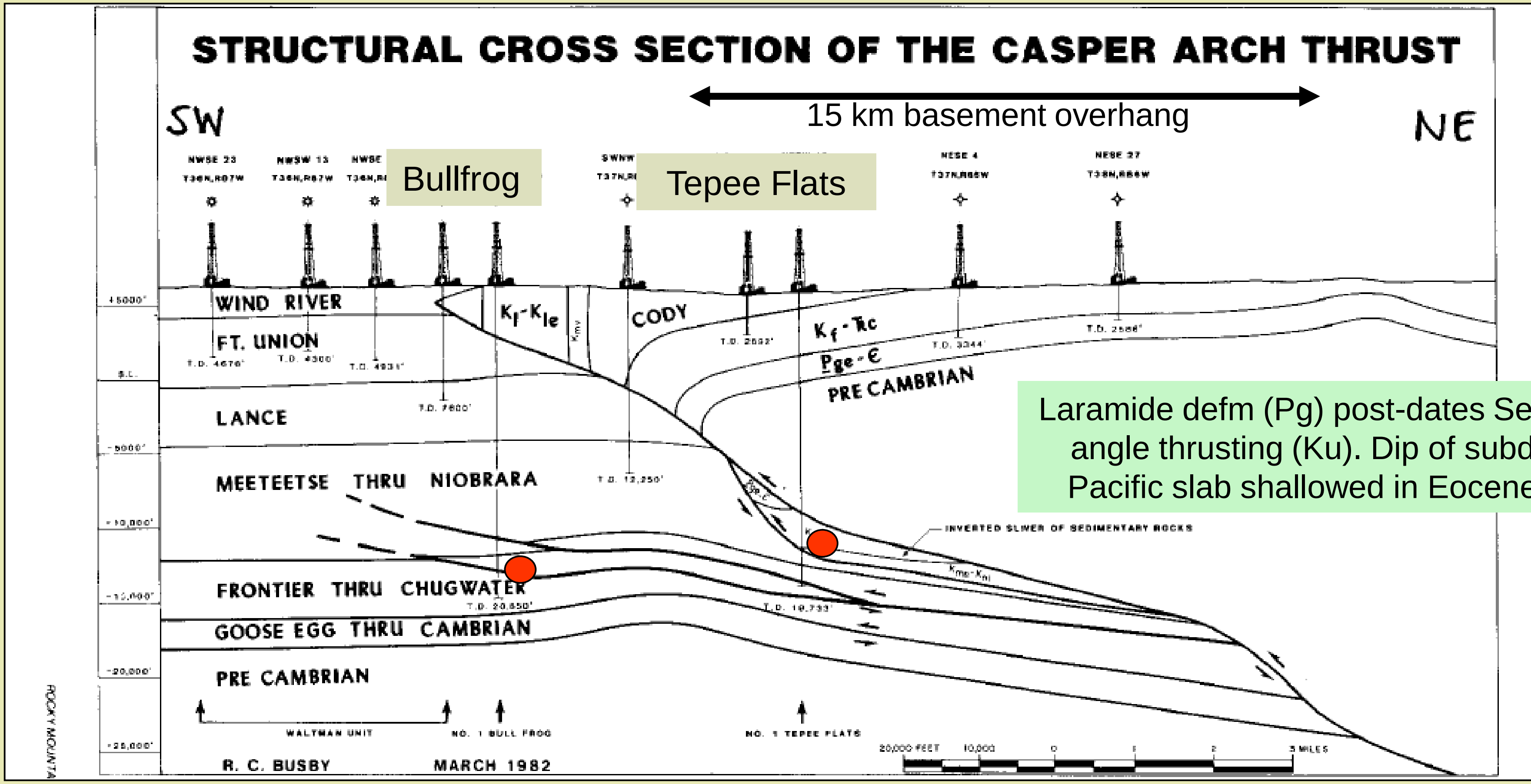




Flat slab subduction induces basement-involved shortening, leading to inversion of Triassic lacustrine source-rock bearing rift basins

Location of existing fields controlled by pattern of Triassic rift basins.

Charge to JJ – KK resvrs comes from syn-rift Triassic lacustrine source rocks.

# Laramide structures in foreland basin, W. USA




By comparison with W. Canada, where the foreland basin is completely unstructured, the Western USA foreland is characterised by massive Laramide uplifts, floored by crust-penetrating reverse faults. These can obscure viable footwall plays.

# Fold and Thrust Belts:
HC prospectivity controlled by structure of early passive margin – New Guinea

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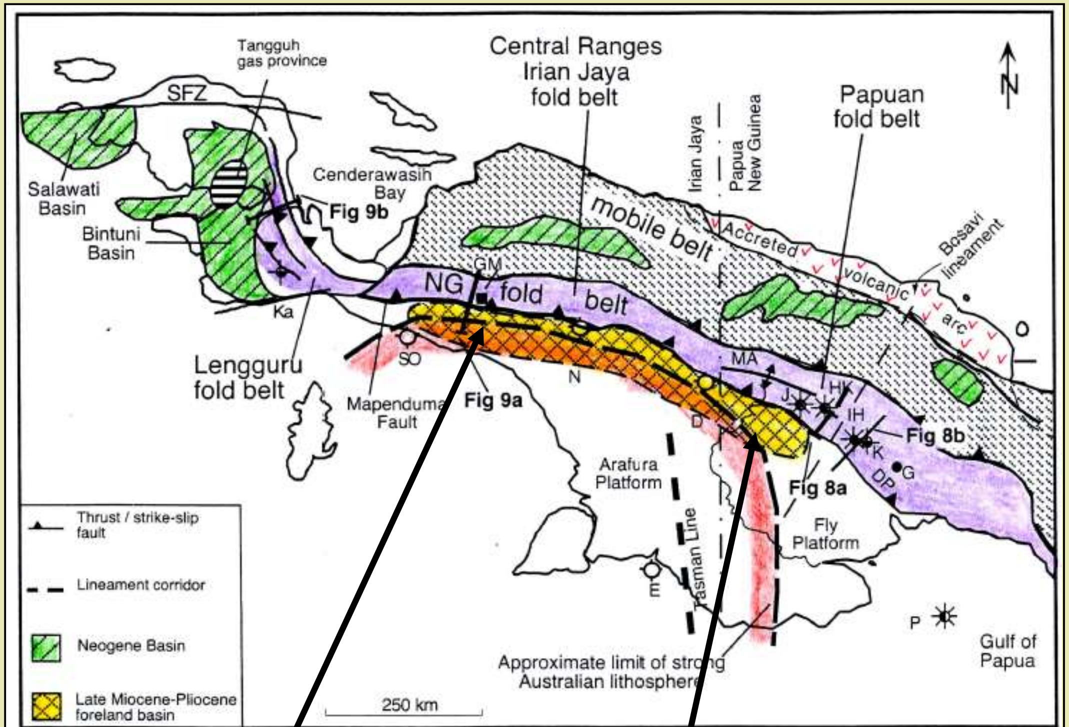
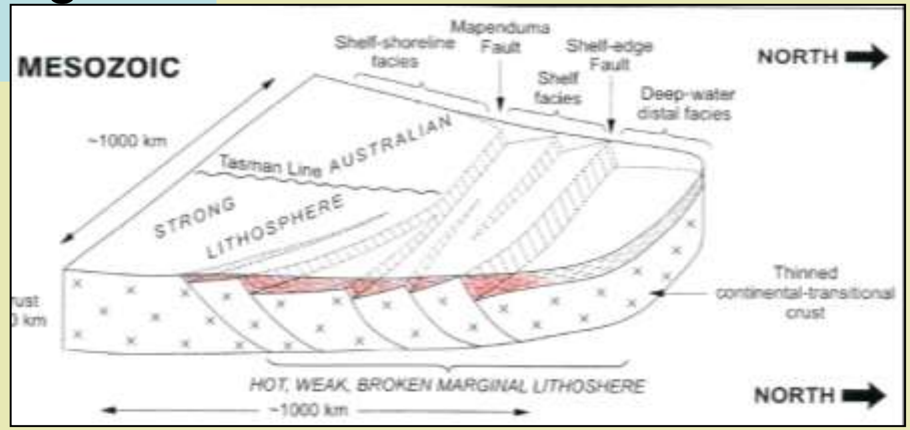
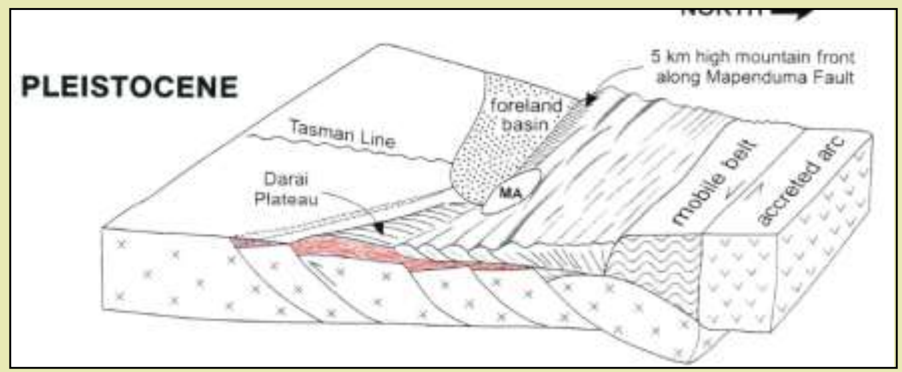



Tr – Jm rifting extends further south in PNG: rift basins host source rocks.




Irian Jaya: Massive uplift (to 5000 km) along inverted, most southerly rift margin, exposes / breaches all traps, and generates deep Ng foreland basin with no source rocks.

PNG: limited uplift, more widespread source-rock bearing rift basins, provides HC charge to FTB.

Deeper foreland in W, hence G/C; shallower foreland in E, hence O/G.

Rift basins all inverted in Irian; less severe defmn in PNG means that rift basins survive under the FTB and yield HCs

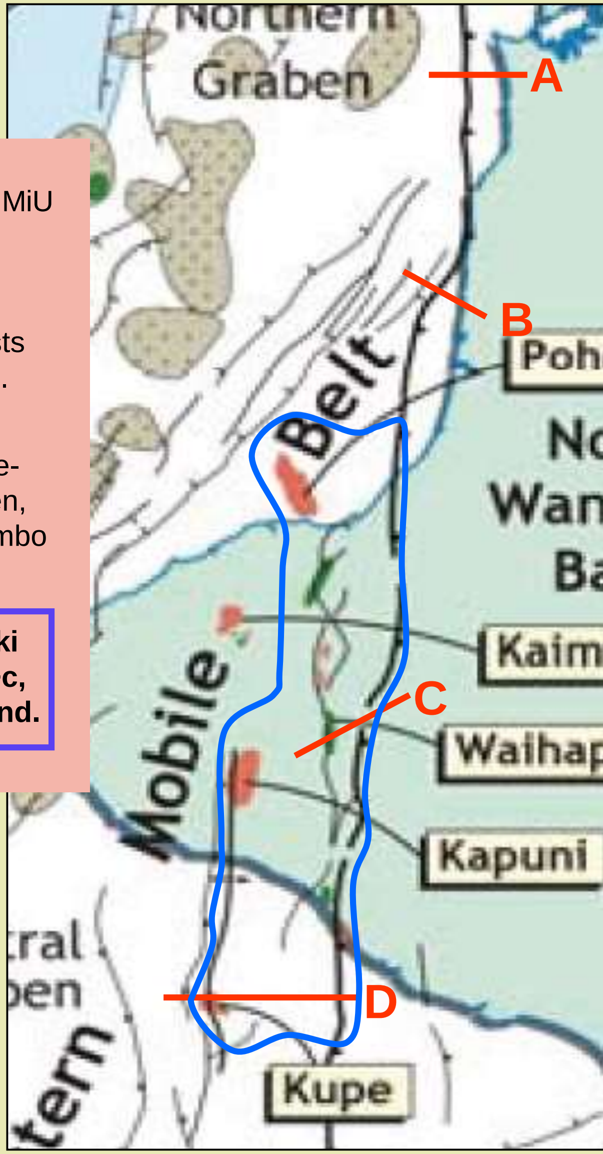
# HC prospectivity controlled by structure of early passive margin – New Zealand

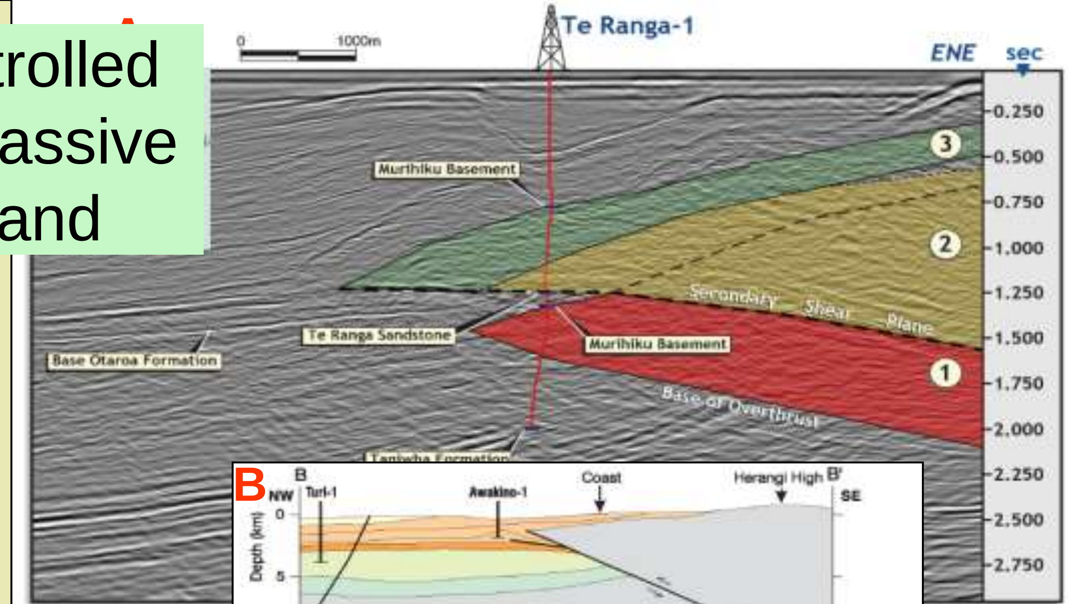
Taranaki FTB: basement hanging wall buried below MiU sediments.

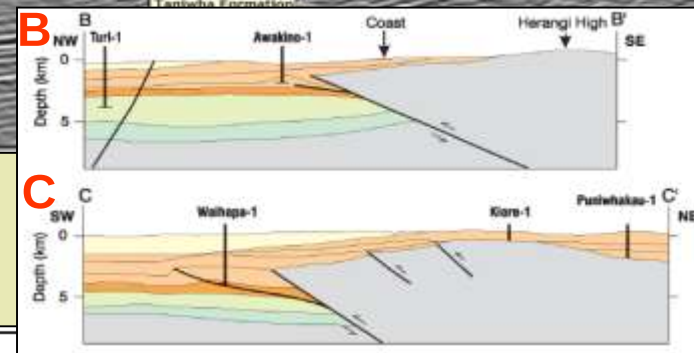
Two fairways:

- eastern – low angle thrusts spalling off thrust front, e.g. Waihapa 24 mmbo
- western – inverted source-rock bearing Pg half-graben, e.g. Kapuni 1.3 tcf + 65 mmbo

**Total reserves of Taranaki FTB = 3 tcf + 230 mmbo+c, with ~80% in western trend.**

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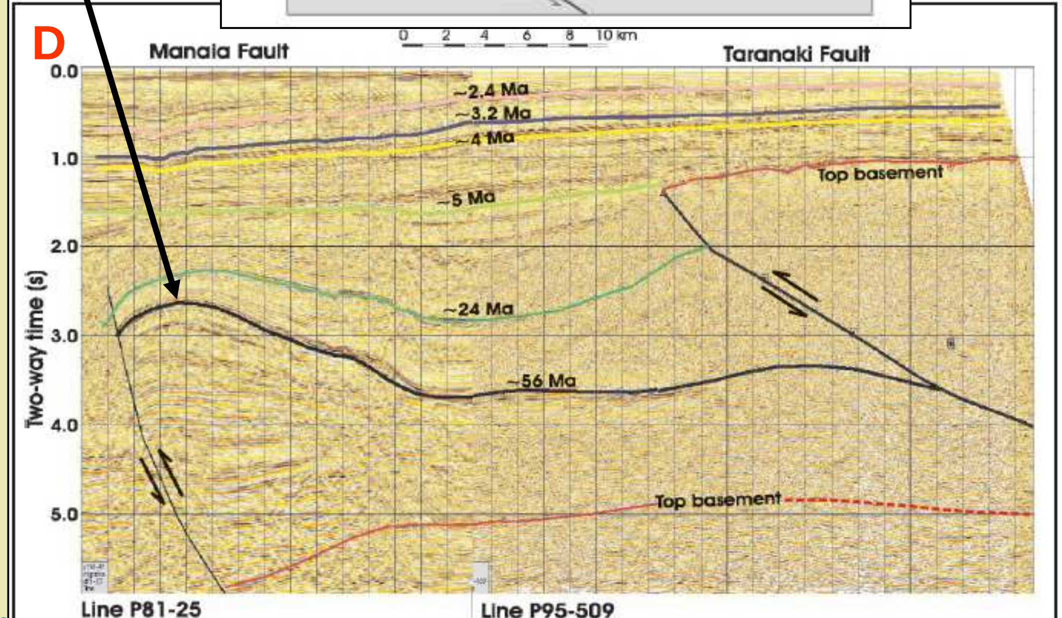
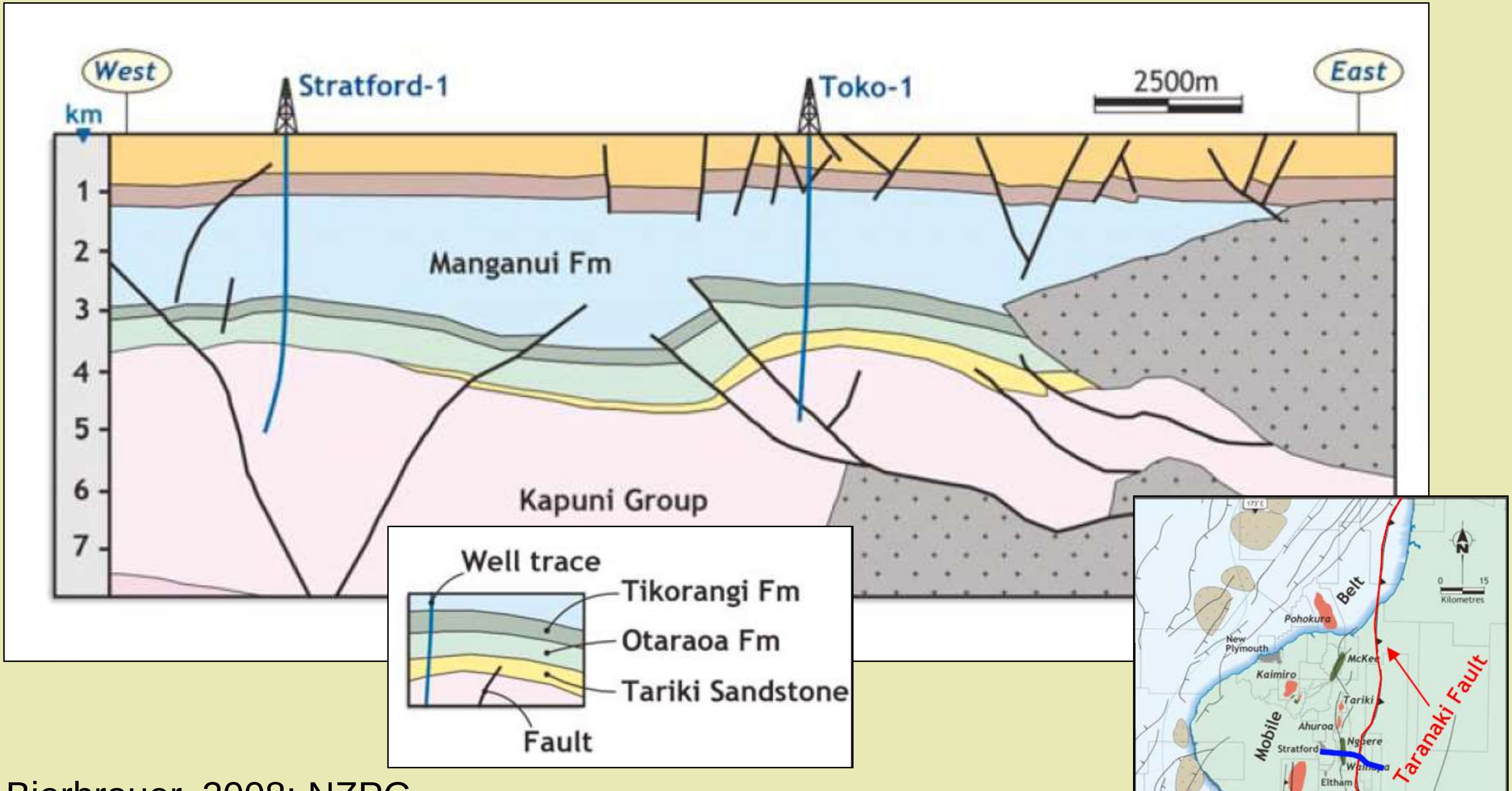


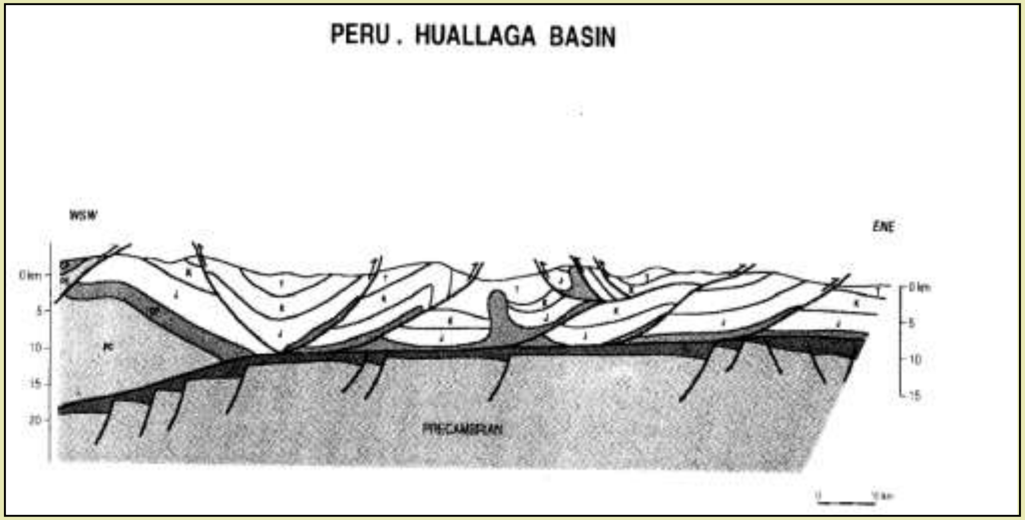

Nicol et al (2004) NZ Petr Conf – www.crownminerals.gov.nz

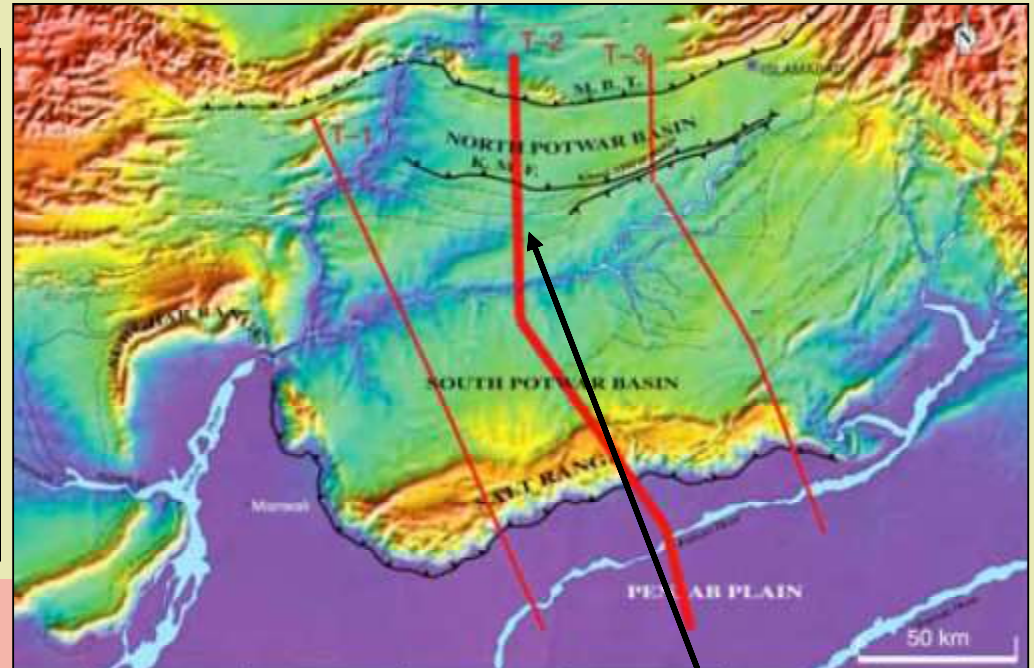
# FTB: further variation in structural style in the Taranaki FTB

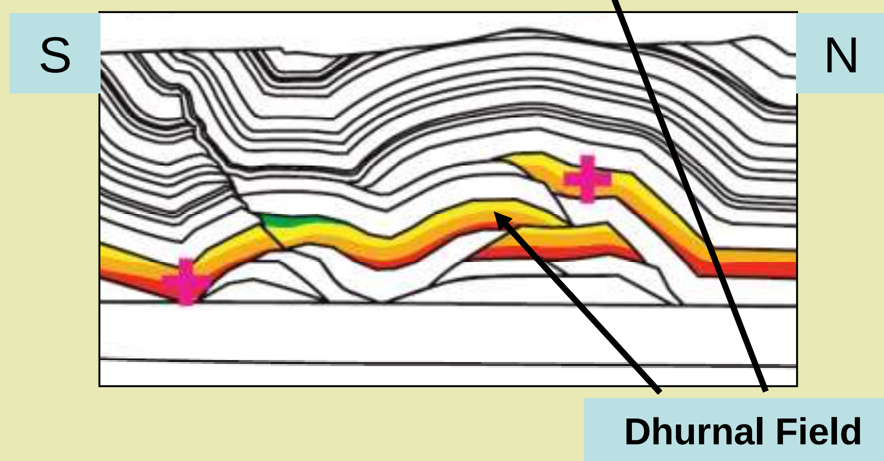



Bierbrauer, 2008; NZPC

# FTBs: influences on structural style (evaporites)



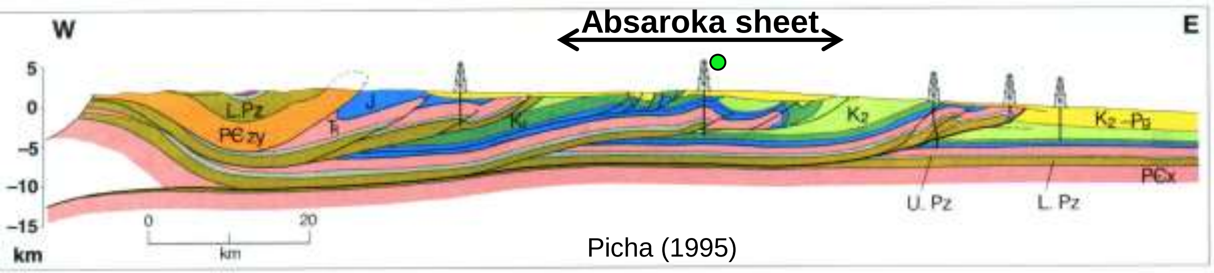




- Foreland-ward jump in thrust front:
  - Salt Range and Trans-Indus Range, Pakistan;
  - Jura, France / Switzerland.
- Evaporites often associated with backthrusts:
  - Utah and Wyoming FTB (Painter, and Covenant Fields)
  - Potwar Basin (Dhurnal Field)
  - Huallaga Basin, Peru

# Fold and Thrust Belts: patterns of HC occurrence

**PJ study (unpublished): rules of thumb (2)**

- charge can be either lateral (from within thrust sheets), or vertical (from footwall)
- the productive fairway is generally limited in width, but may comprise either the outer, frontal thrust (which may be blind), or an interior thrust sheet
- don't be put off by poor reservoir quality in outcrop or in off-structure tests: good reservoirs frequently only found where hydrocarbon bearing

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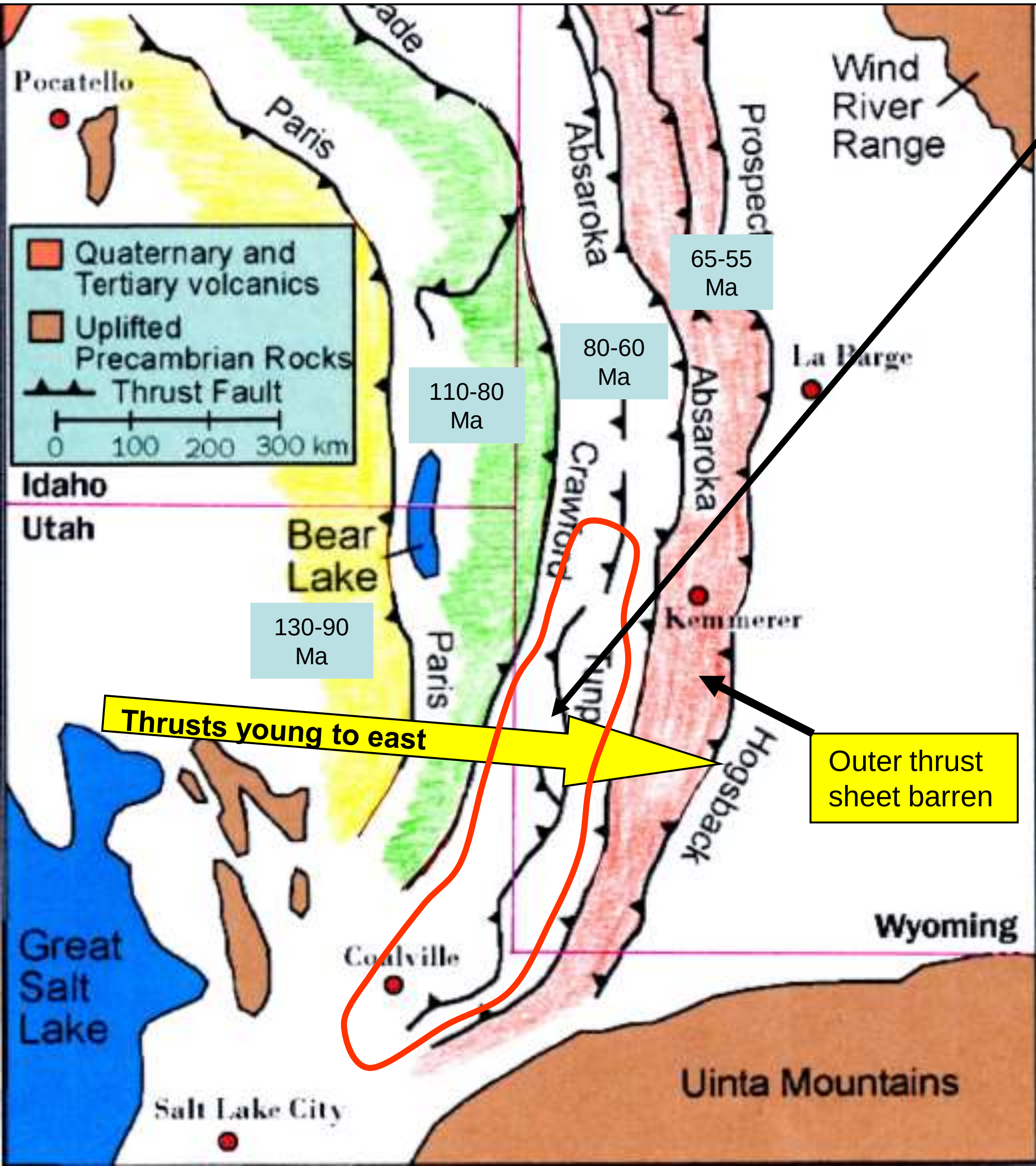
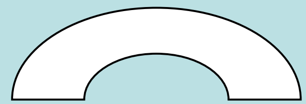
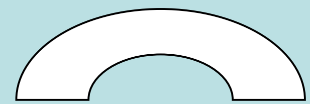
## FTBs: N. Utah - Wyoming




The only significant HC are found in the Absaroka sheet. Total URR ~500 mmbo + 7.5 tcf.
HC richness ~0.1 mmboe / km2

HC hosted in ~25 fields in two separate fairways:

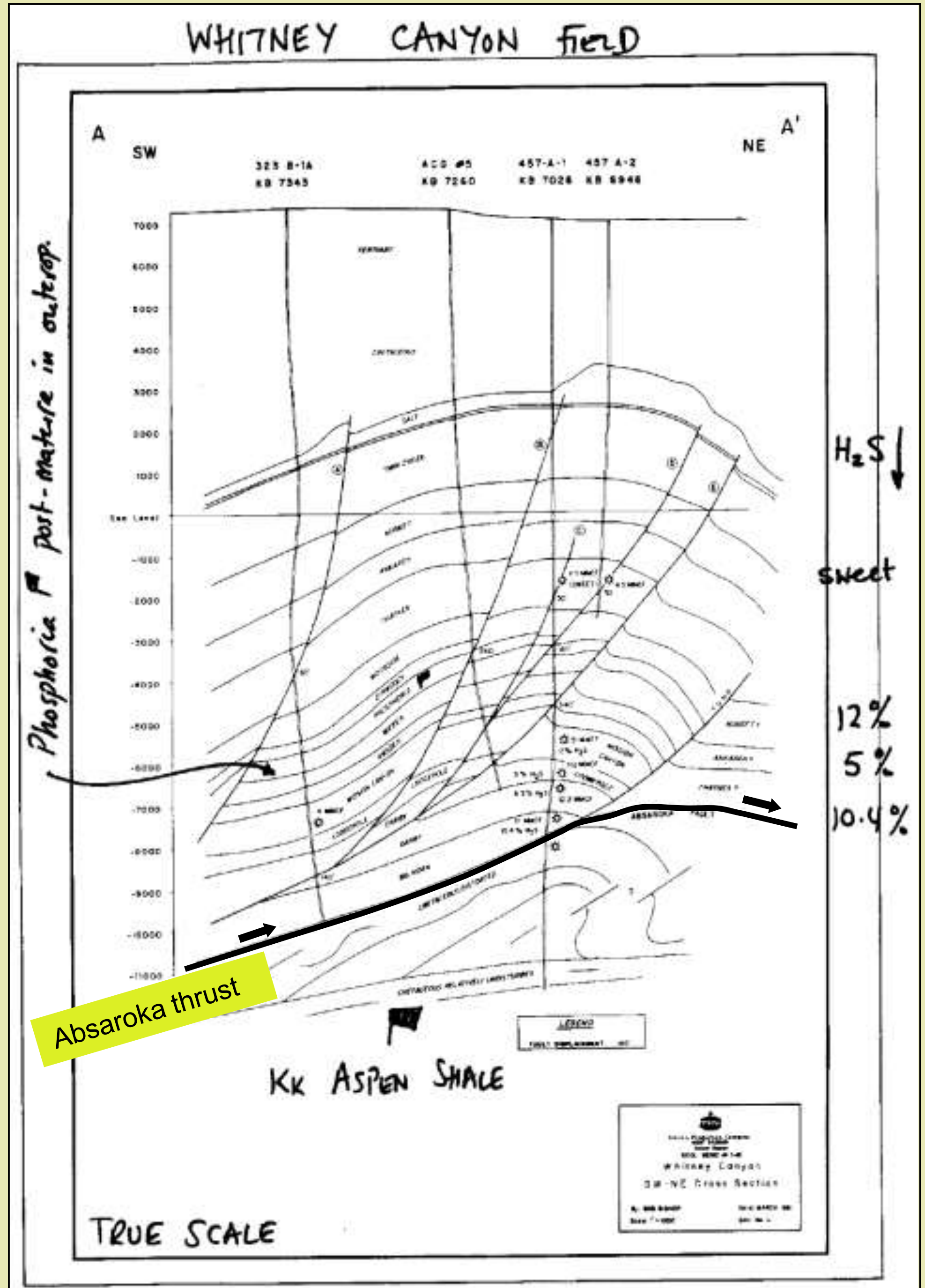
| INBOARD | OUTBOARD |
|---|---|
|  |  |
| Sour wet gas and condensate from Pz resvrs (domin Miss), sealed by intbd anhd. | Sweet light oil and AG from J Nugget resvr sealed by J evaporites |
| Lateral charge from overcooked Pz SR, tho' some vertical charge from gas-prone KK shales (more proximal) | Vertical charge from oil-prone KK shales (distal) in footwall of Absaroka Thrust |
| **Whitney Canyon – Carter Creek 500 mmboe** | **Anschutz Ranch East ~~1 BBOE** |

# FTBs: N. Utah – Wyoming (2)

Inboard trend:

Charge from Phosphoria and Miss source rocks downdip (gas mature, H2S) tho' some contribution from KK source rocks in footwall, which here are more proximal and hence gas-prone than further outboard.

Note (unpredictable) variation in H2S with depth (a common feature of W. Canada / USA)



# FTBs: N. Utah – Wyoming (3)

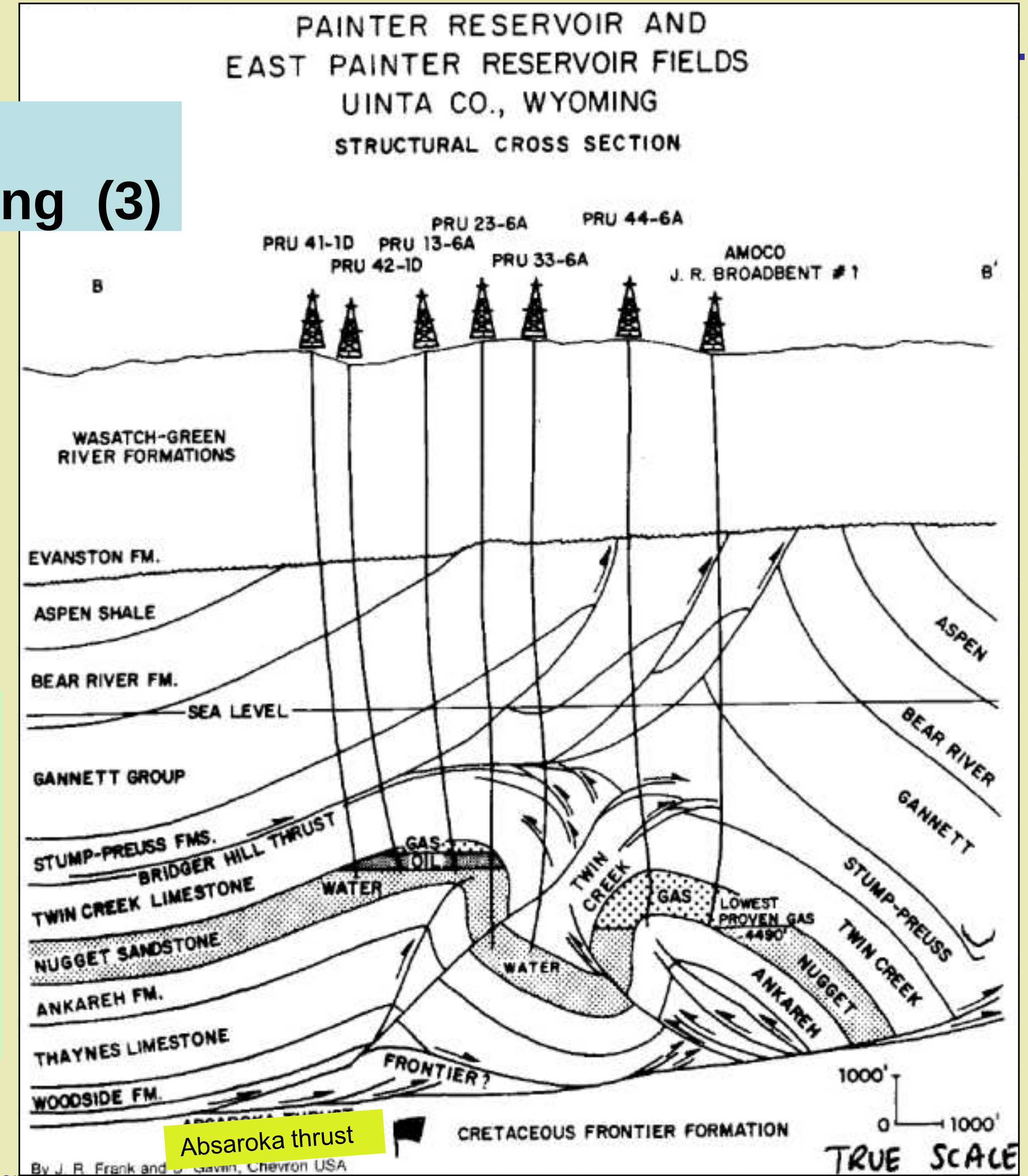
**Note**

a) TT/KK cover → improved seismic imaging
b) mature KK [flag symbol] in footwall
c) presence of evaporites (Ankareh Fm) appears to favour backthrusts ?

Outboard trend:

Light oil and sweet gas in JJ Nuggett aeolian resvr, sealed by Twin Creek shales.

Charged vertically from rich KK type II source rocks in footwall of Absaroka thrust.



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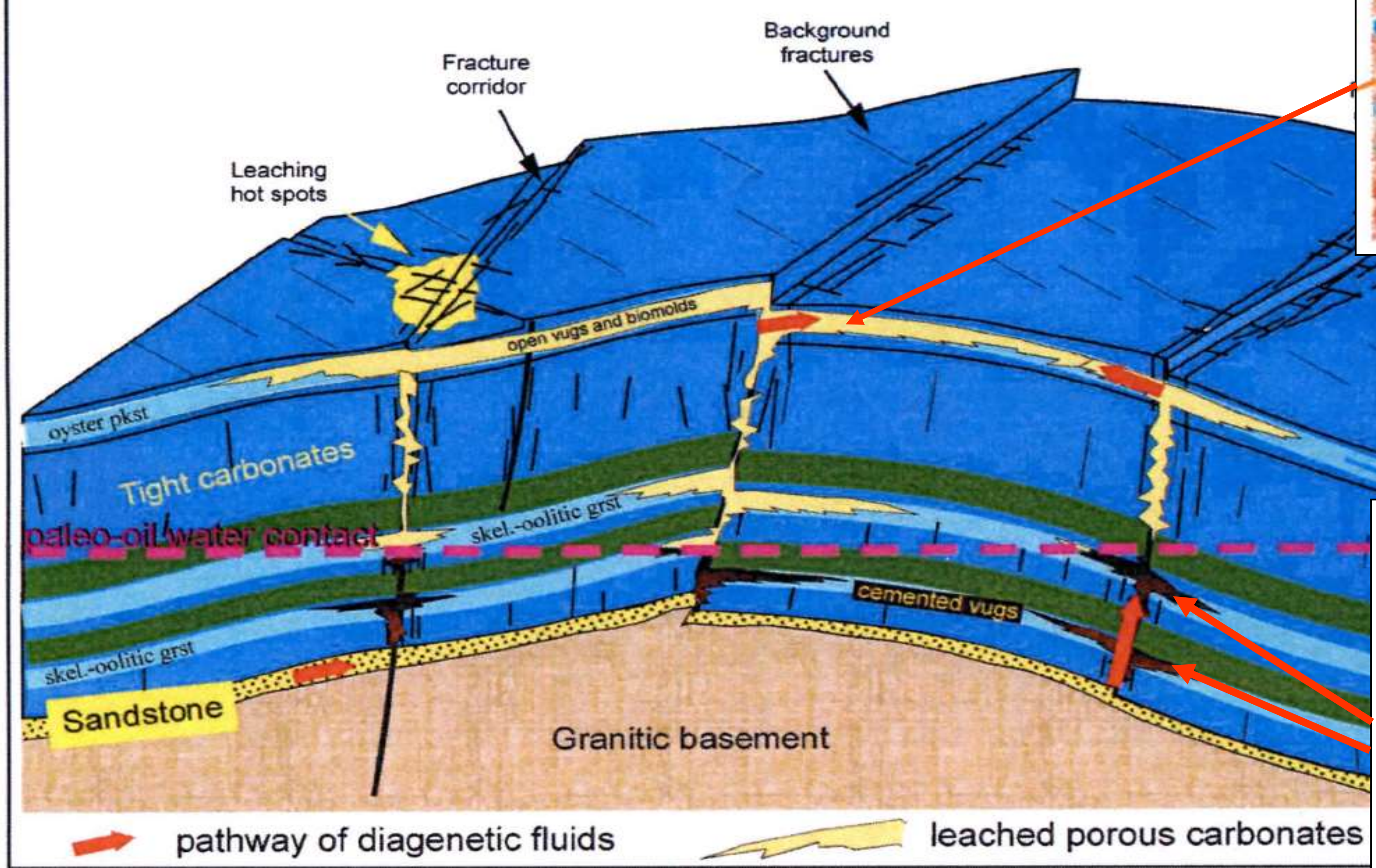
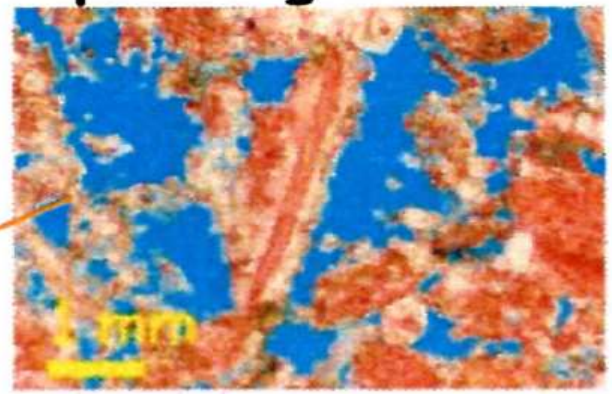
Also seen in W. Canada: average phi 6-8% in HC column.
Little correlation between phi/h and well deliverability.
Below GWC, phi diminishes dramatically.

# Fold and Thrust Belts: preservation of reservoir in HC leg.

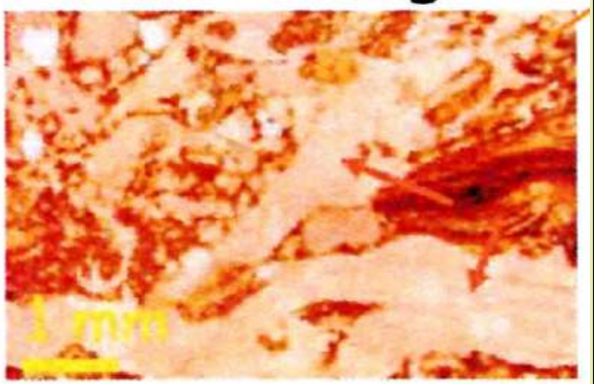
Cogollo resvr, Urdaneta West, Venezuela




Open Vugs




Cemented Vugs

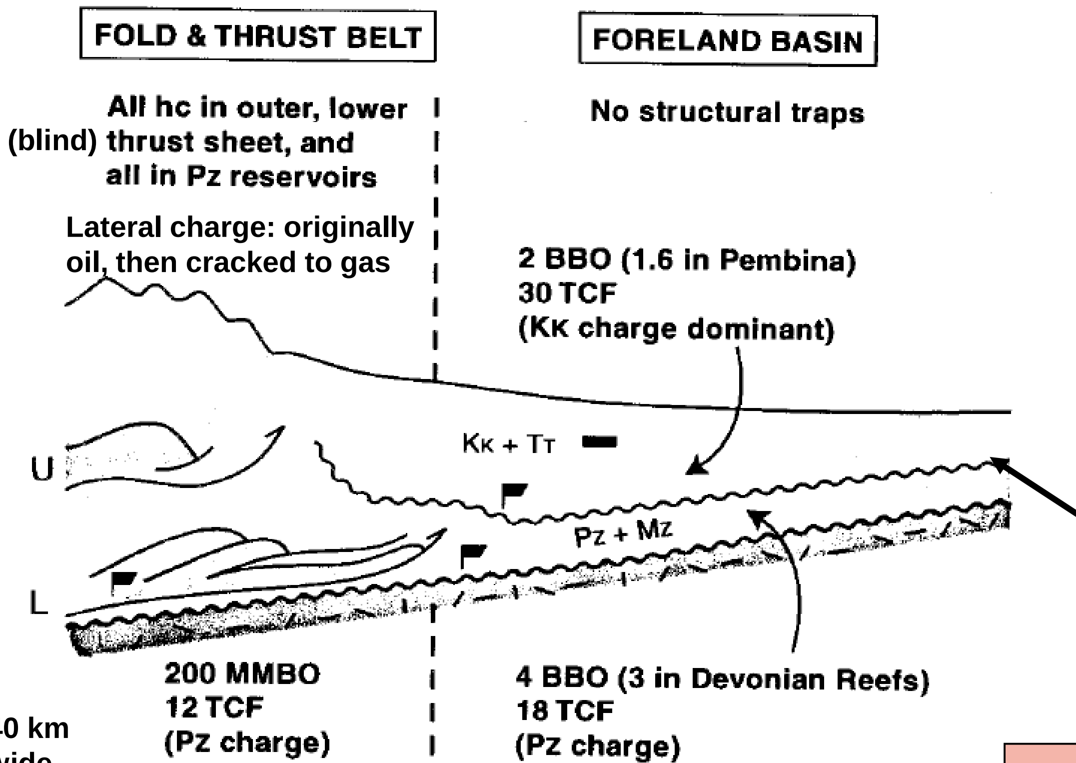


# Fold and Thrust Belts: characterisation of W. Canada FTB (+ FB)

## CHARACTERIZATION OF F & Th B + FB W. CANADA

Shortening ~50%

### THUMB-NAIL SKETCH




40 km wide fairway

Total: 6.2 BBO + 60 TCF

### RESERVE MATRIX

| | F & ThB | FB |
|---|---|---|
| Syn - post Tectonic | - <br> - | 2 BBO <br> 30 TCF |
| Pre - Tectonic | 200 MMBO <br> 12 TCF | 4 BBO <br> 18 TCF |

Figures are ~15 yrs old, but provinces are mature, so significant change in proportions is unlikely

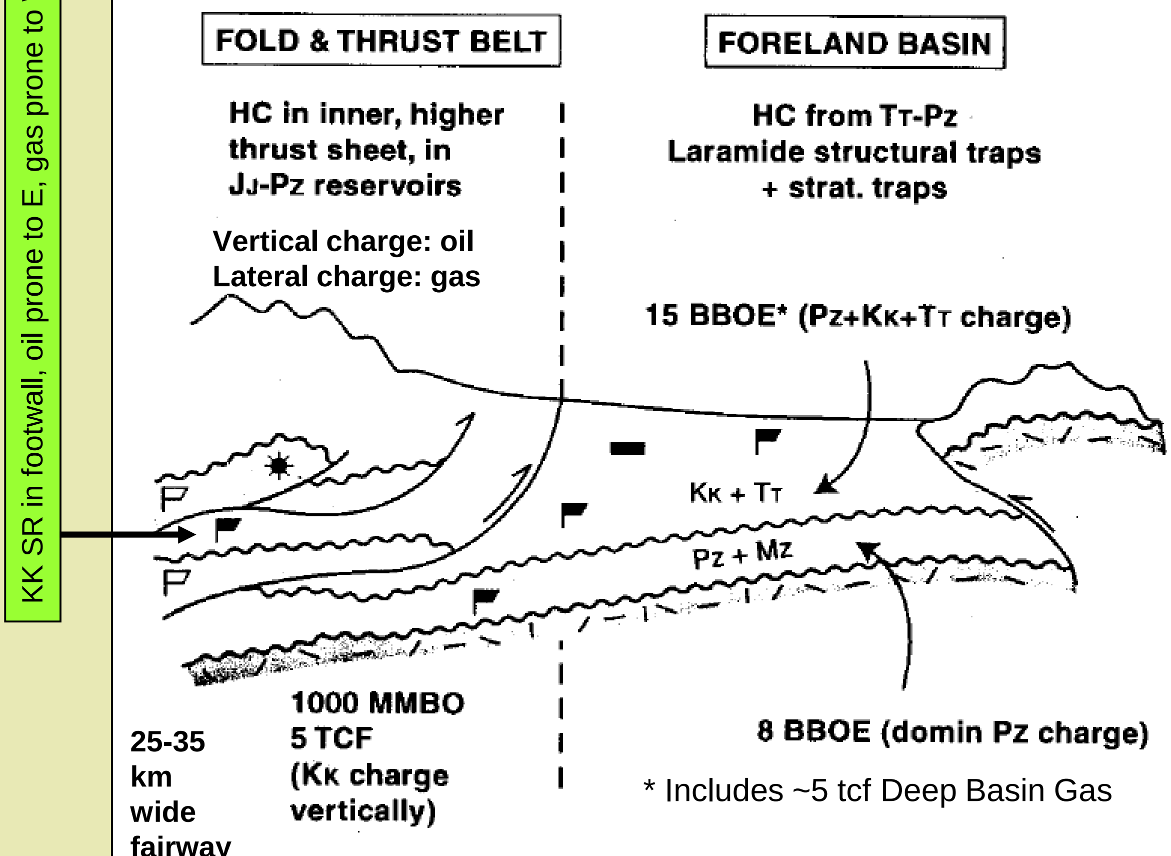
FTB HC richness ~0.1 mmboe.km2

# Fold and Thrust Belts: characterisation of W. USA FTB (+ FB)

## CHARACTERIZATION OF F & Th B + FB
## W. USA

Shortening ~50%

### THUMB-NAIL SKETCH




* Includes ~5 tcf Deep Basin Gas

### RESERVE MATRIX

| | F & ThB | FB |
|---|---|---|
| Syn - post Tectonic | - <br> - | 15 BBOE |
| Pre - Tectonic | 1000 MMBO <br> 5 TCF | 8 BBOE |

Figures are ~15 yrs old, but provinces are mature, so significant change in proportions is unlikely

FTB HC richness ~0.1 mmboe.km2

# Fold and Thrust Belts: more rules of thumb, and good practise

## PJ study (unpublished): rules of thumb (3)

• degree of HC fill bears no relation to the degree to which closure is fault-dependant
• no trend of $H_2S$, $CO_2$, content apparent: can vary up or down with depth (e.g. Panther Field, W. Canada, where upper sheet has 70% $H_2S$; lower sheet has 12% $H_2S$) .
• each thrust sheet carries its own maturity profile (frozen at time of thrusting)
• in a given area, displacement on individual thrusts is constant and cumulative in the dip direction. On a regional scale total displacement will vary, but gradually, along strike
• highest sheet of stack of duplexes generally the best
• 2D seismic @ 1.5 - 2 km spacing, with good surface geology is generally sufficient.

## PJ study (unpublished): Good practise

• serial balanced reconstructions essential, should be made for min, max and mean cases.
• cross sections must be TRUE SCALE, and incorporate all surface and subsurface data
• good subsurface geology – including good dipmeters and good cuttings - essential
• check interpretations by constructing strike-parallel sections and thrust plane maps
• importance of recognizing lateral ramps – potential structure / closure forming;
• locate and analyse all seeps. Integrate with Fluid Inclusion data to give regional charge story
• beware PSDM data - the velocity model may be based on an invalid geological model: always check against normal time migration.

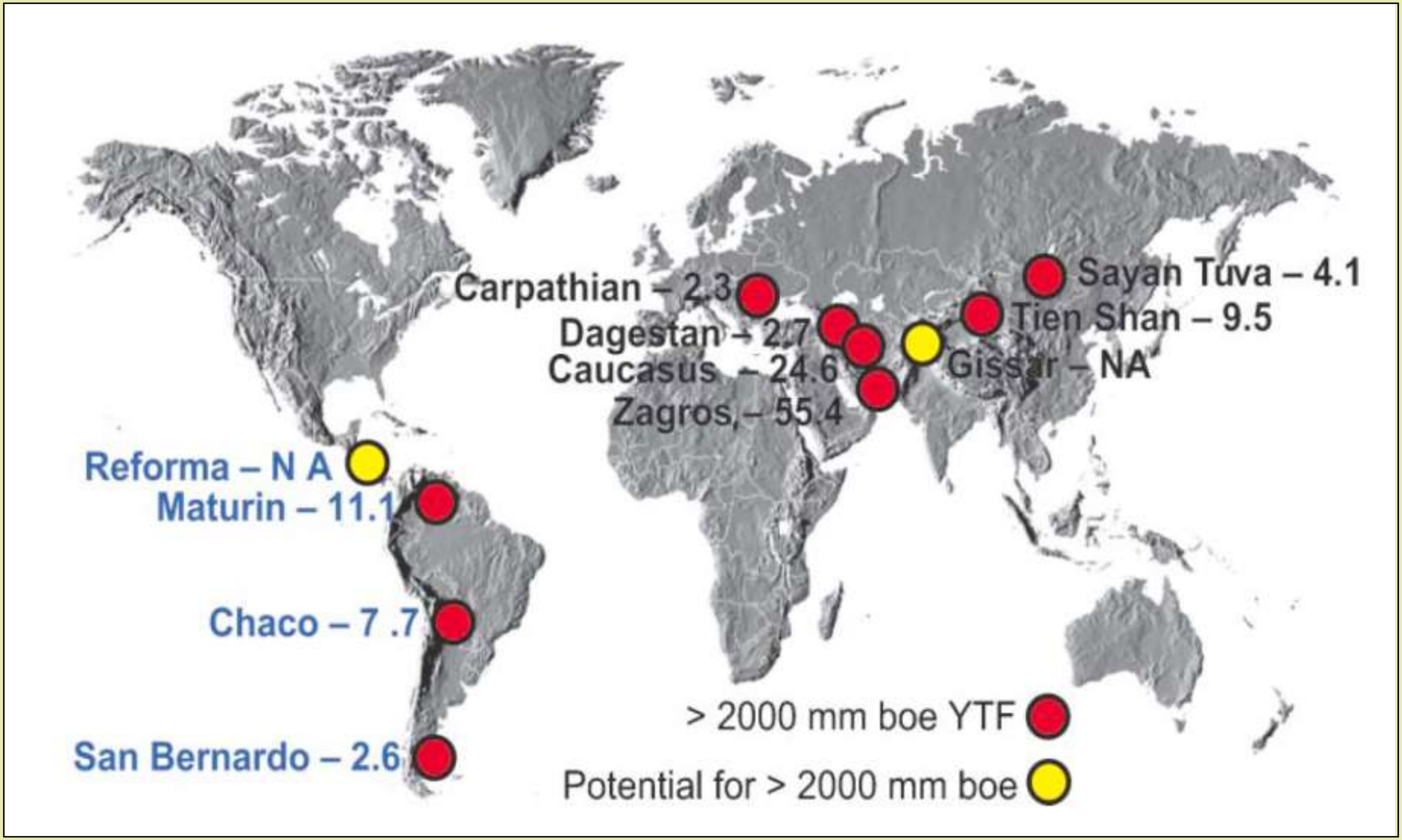
# Fold and Thrust Belts: conclusions

- FTBs are due to be re-visited. Their last heyday was in mid-1970s – late 1980s with discoveries such as Cusiana, Camisea, El Furrial, W. Overthrust

- Exploration then went into Deep Water and no significant return to FTBs has been seen since.

- Many new technologies developed
  - Hi-res radar altimetry and DTMs
  - Hi-res aeromagnetics; hi-res gravity gradiometry
  - Refined age dating (e.g. Ar/Ar) – clay minerals; age of thrusting etc;
  - Refined geochemical techniques – AFTA; fluid inclusion analyses.

# Fold and Thrust Belts: where to go? Potential scope from Cooper (2007)



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