Petroleum Potential of the Jamaican Wagwater Trough: New Insight Obtained from 3-D Basin Modeling*

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Abstract

3D basin analysis constrained by outcrop exposures and gravity basement modeling reveal the 700 km^2 north-northwest trending Cenozoic Wagwater Trough in eastern Jamaica to be a fault-bounded pull-apart graben. The Wagwater Trough underwent three major stages of tectonic development accompanying Jamaica's tectonic interactions along the northern edge of the Caribbean plate: (Stage 1) Paleocene to Middle Eocene fault mechanical rift associated crustal subsidence (66-51 Ma; β=1.66), (Stage 2) Middle Eocene to Middle Miocene gentle thermal subsidence (51-10 Ma), and (Stage 3) Middle Miocene to Holocene crustal shortening (10-0 Ma; β=0.81). The sedimentation in the trough distinguishes these three tectonic episodes. Clastic alluvial fan and fan-delta sedimentation of the Wagwater and overlying Richmond Formations accompanied the rapid subsidence and marine transgression of Stage 1, while the Yellow Limestone and White Limestone Groups were deposited in the continually deepening and transgressing Stage 2. Stage 3 commenced with a Middle Miocene reversal from dextral to sinistral at a constraining bend, the Wagwater Trough experienced negative tectonic subsidence and subaerial exposure.

Two rifting heat flow models were used to bracket the uncertainty of the present heat flow of the basin (0.96 or 40.2 mW/m^2 to 1.4 HFU or 58.6 mW/m^2, respectively) in order to construct thermal maturity models of these three tectonic stages. Both values allow for the shale layers of the Richmond Formation to range from mature enough to be in the early oil and mid oil windows for the 0.96 HFU model to middle and late oil windows and gas window for the 1.4 HFU model. The first in situ oil for the rifting 1.4 HFU model commenced at 52 Ma, while that for the rifting 0.96 H.F.U. model at 49 Ma. First expulsion time was 50 Ma for rifting 1.4 HFU case and was 41 Ma for the rifting 0.96 HFU case.

The Richmond Formation has the best reservoir properties in the Wagwater Trough owing to its sandstone lithology and good sorting. Hydrocarbons sourced from Richmond shales, Type II (submarine turbidite deposits), could potentially accumulate in traps based on two cases using outcrop constrained fault data: the impermeable fault model and the permeable fault model. If faults were impermeable, hydrocarbons would be confined to the individual fault blocks. If permeable, most of the hydrocarbons in the Richmond Formation escaped to the surface, with potential traps in the deeper zones only.

Selected References

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Wagwater Trough Background

- Strikes NNW – SSE
- Measures about 20 km east to west 60 km north to south
- Fault-bounded half-graben
- Presently has a minimum of 6,800 meters of Early Paleogene clastic sediment unconformably overlaying Mesozoic igneous rocks

Mann and Burke, 1990

Location and Physiography

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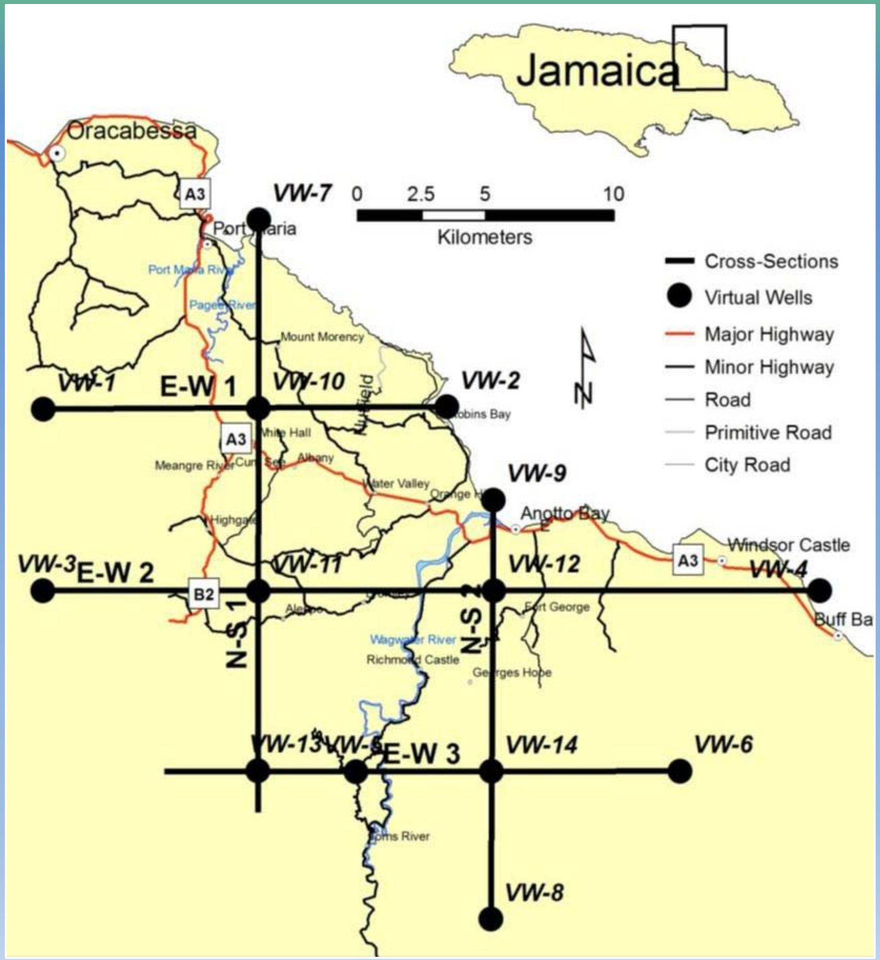
Determining Basement Depth

- For this study a combination of field data, published data, and published maps were used to extrapolate lithologic formations and facies into the subsurface. (Seismic reflection and well data was unavailable)
- Using a regional Bouguer anomaly map the Bouguer anomaly was used to constrain the basement depth for each cross-section and virtual well.
- Using published densities from Wadge et. At (1983) five cross-sections were created with their basements constrained in GYM-SYS(PRO).

Map of Cross-sections and Virtual Wells



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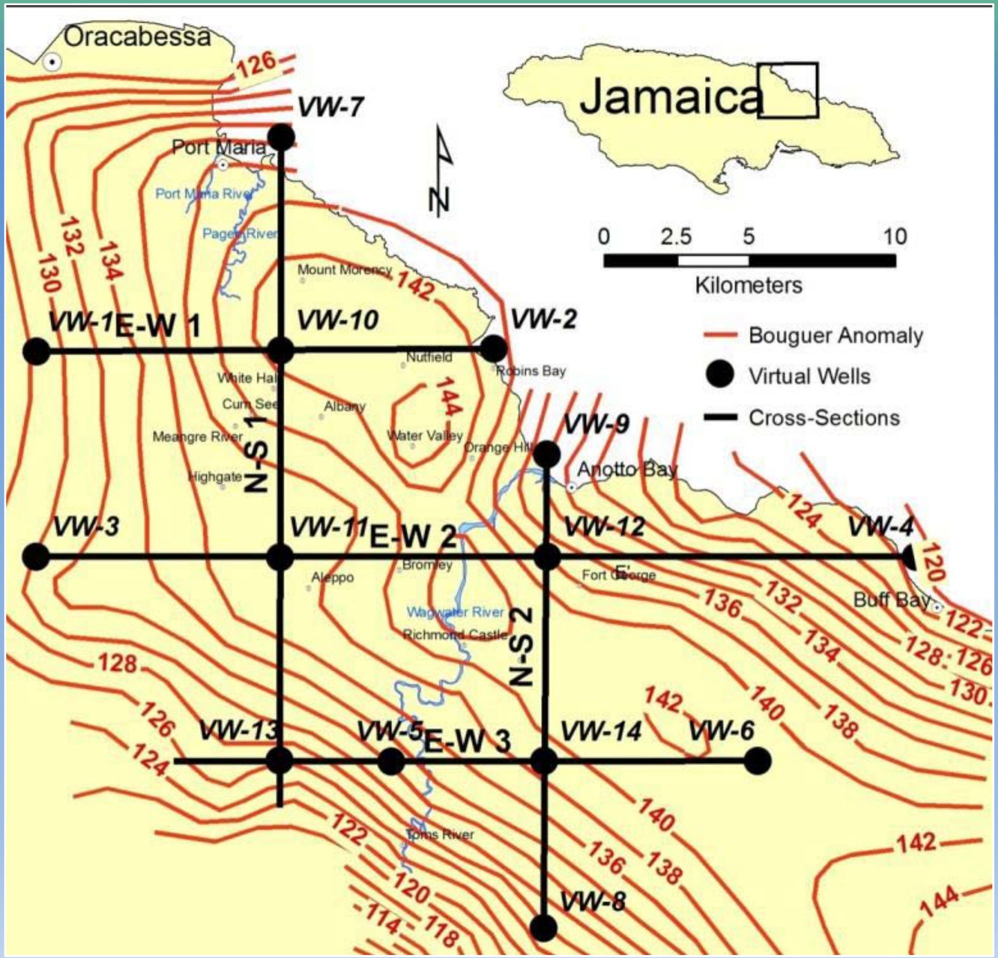
Regional Bouguer Gravity Anomaly



(after Andrew et al., 1992)

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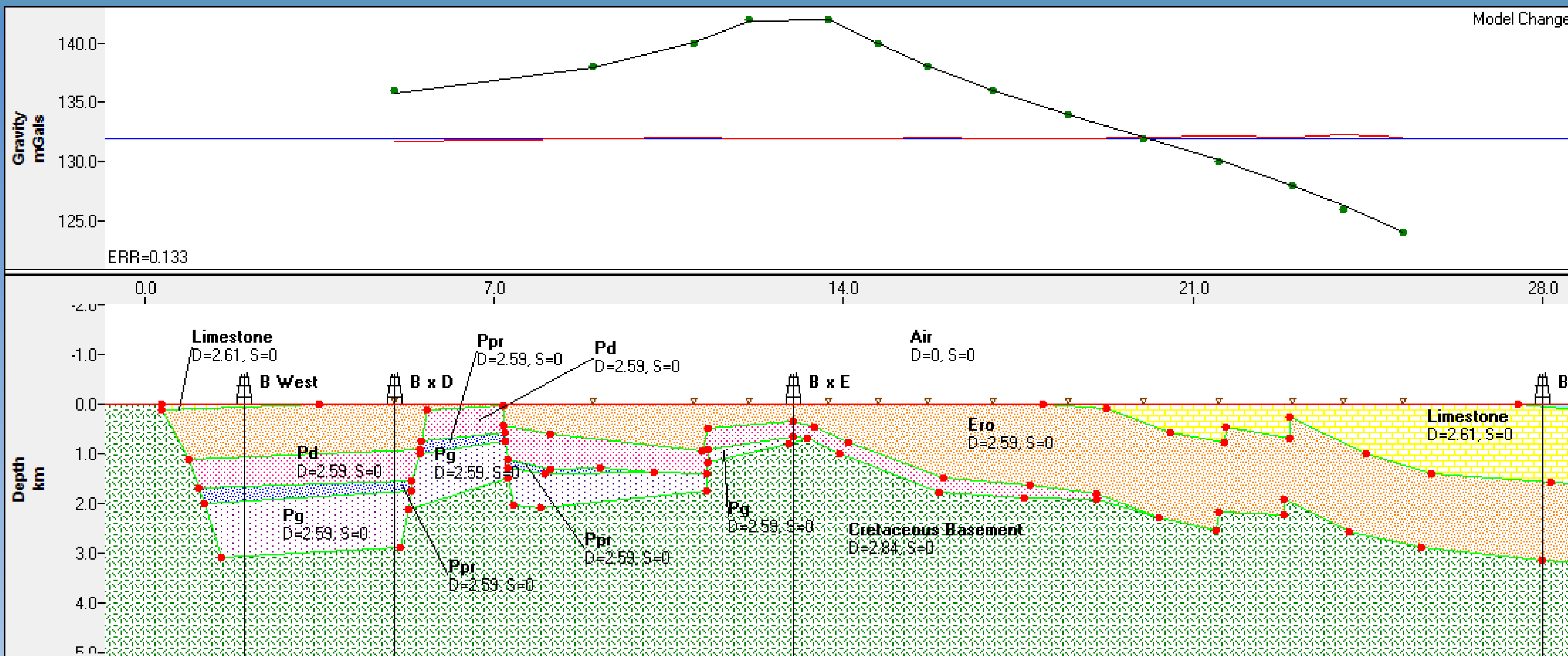
GYM-SYS(PRO)



Model Changed
Gravity mGals
140.0
135.0
130.0
125.0
ERR=0.133
0.0
7.0
14.0
21.0
28.0
Depth km
-1.0
0.0
1.0
2.0
3.0
4.0
Limestone
D=2.61, S=0
B West
B x D
Ppr
D=2.59, S=0
Pd
D=2.59, S=0
Air
D=0, S=0
B x E
Ero
D=2.59, S=0
Limestone
D=2.61, S=0
Pd
D=2.59, S=0
Pg
D=2.59, S=0
Pg
D=2.59, S=0
Pg
D=2.59, S=0
Cretaceous Basement
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Ppr
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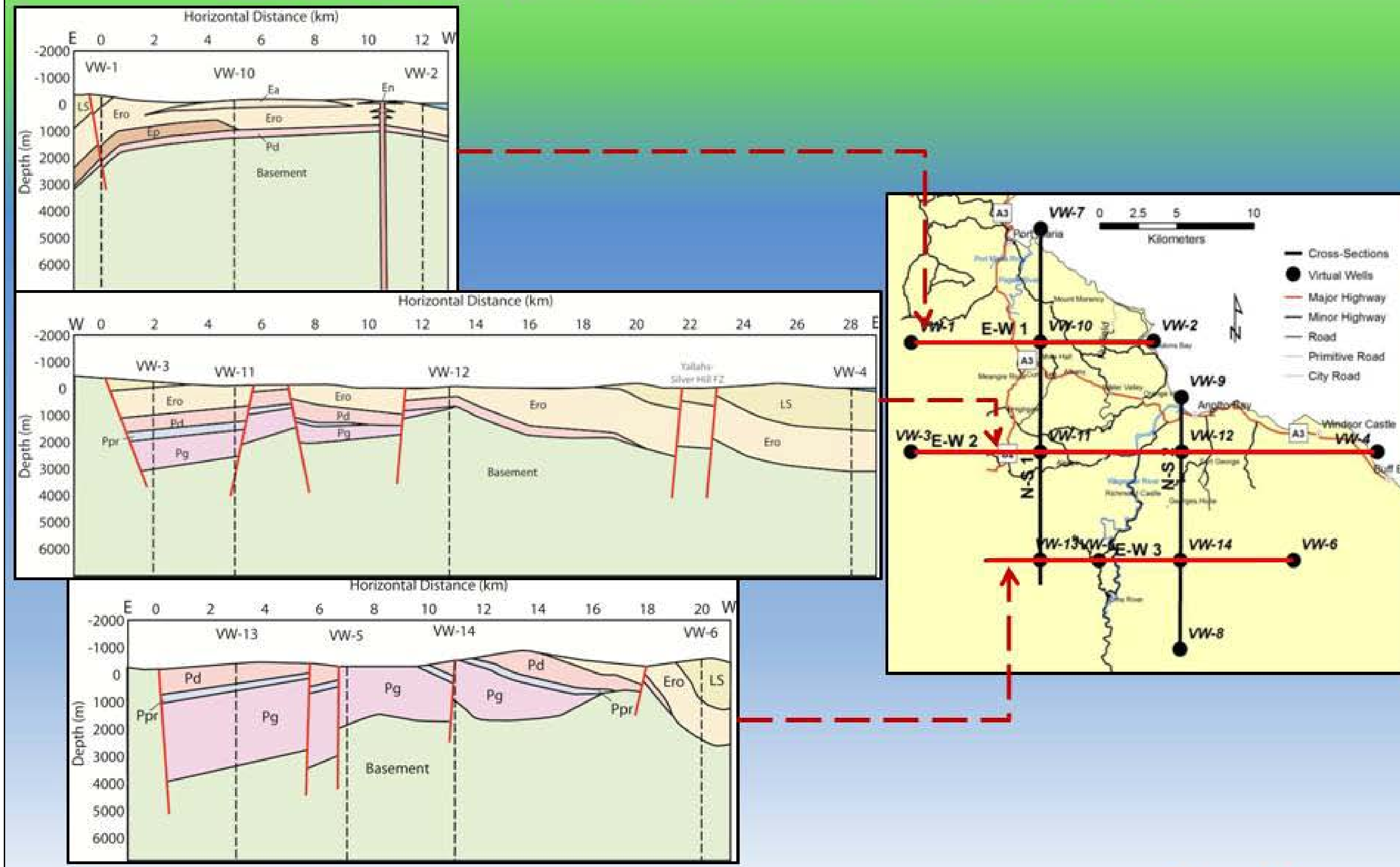
Ppr
D=2.59, S=0

East to West Cross-Sections



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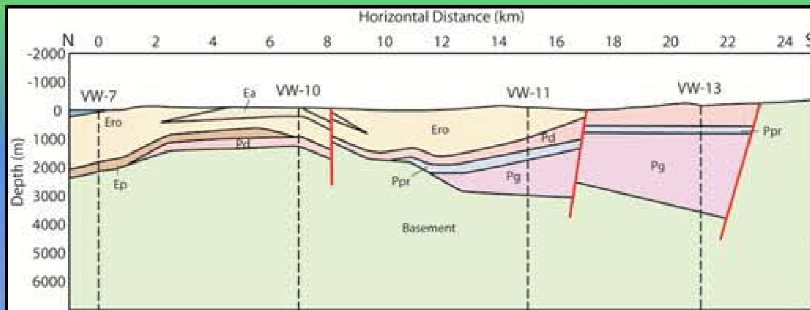
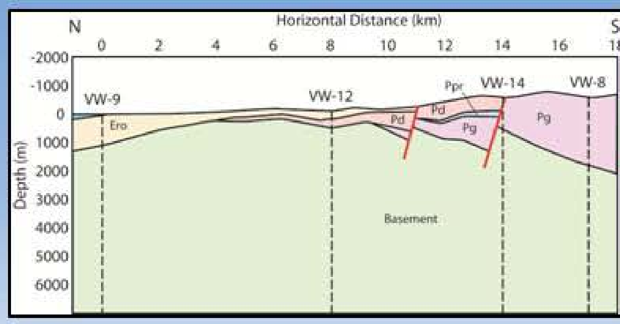
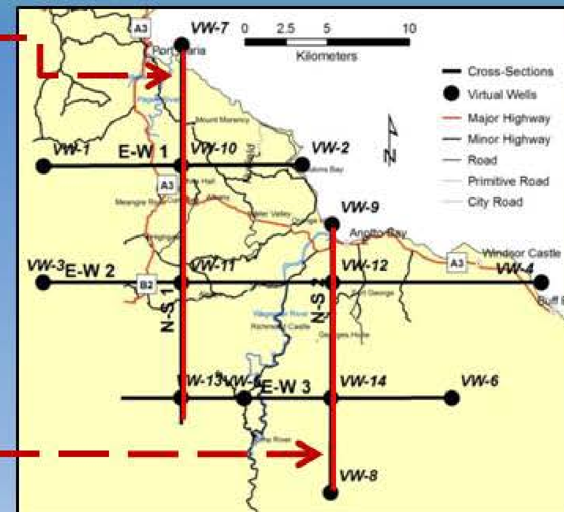
Notes by Presenter: East-west basement-constrained cross-section E-W 1. This cross-section runs across the most northern region between Port Maria and Anotto Bay.

North to South Cross-Sections







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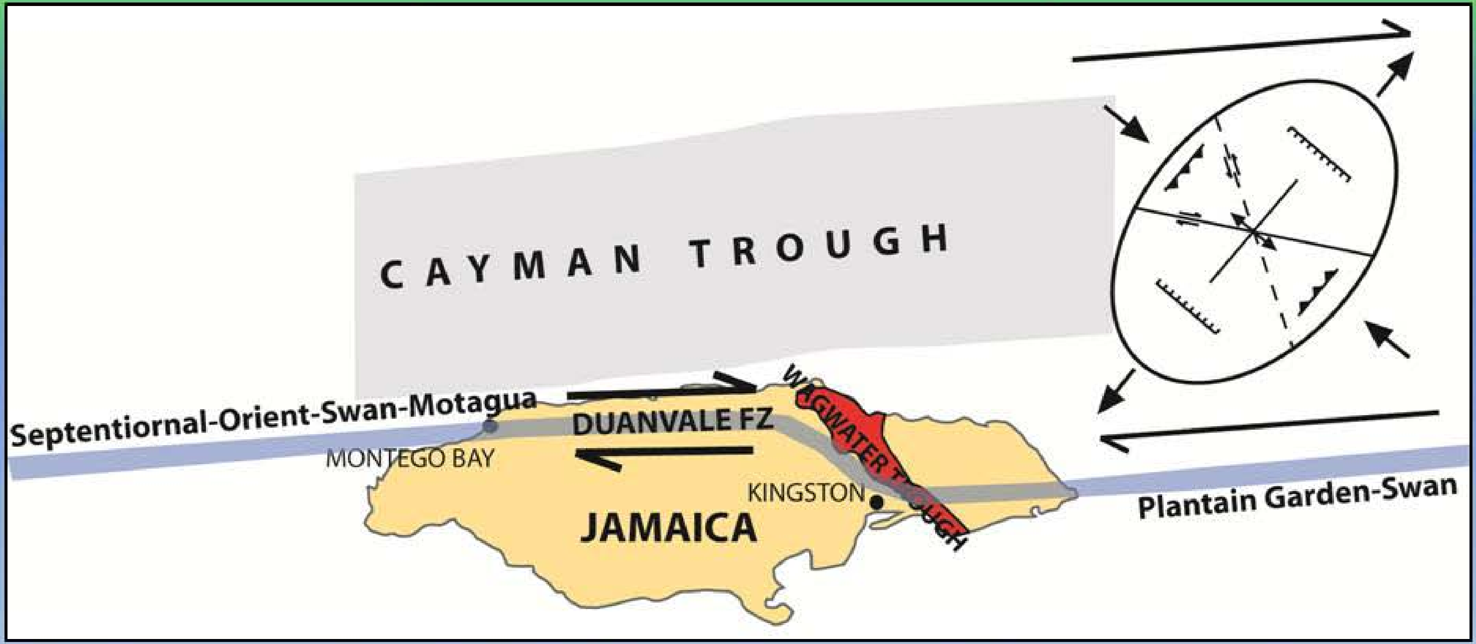
Notes by Presenter: North-south basement-constrained cross-section N-S 1. This cross-section runs west of along the western side of the trough, west of Tom's River to just East of Port Maria.

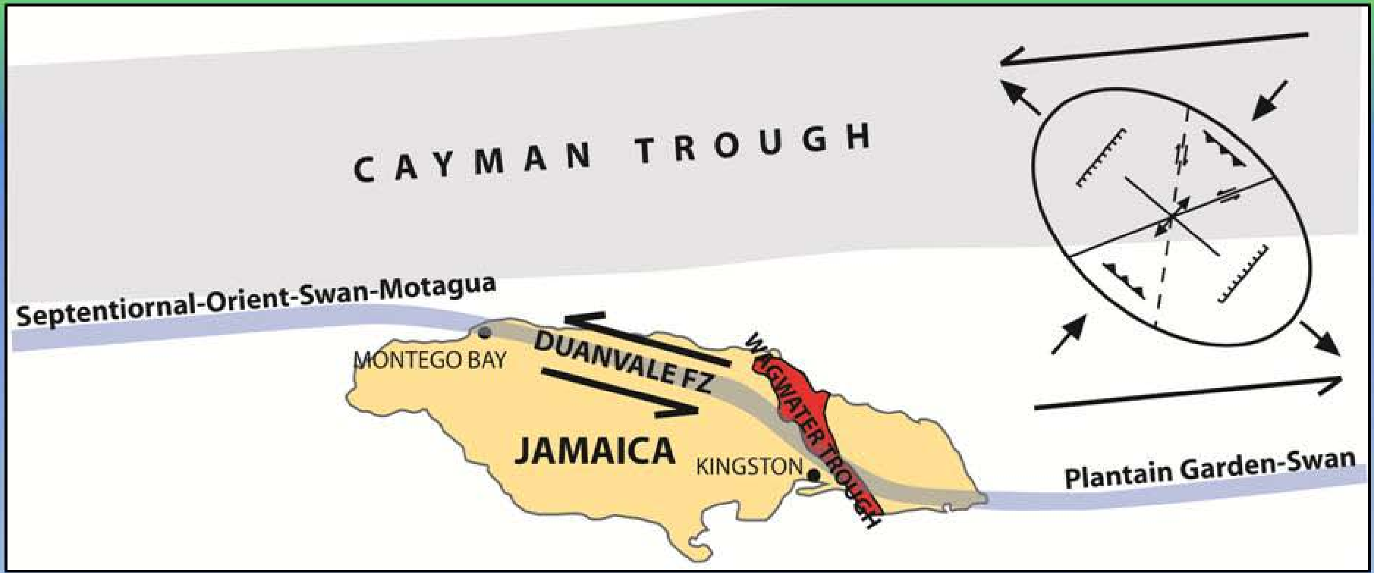
Releasing Bend: Dextral Shear (Paleocene-Eocene)



The Wagwater Trough likely formed as a result of extension along a releasing bend.

Notes by Presenter: Map showing a possible Paleocene position of Jamaica. The Wagwater Trough (Red) formed along a releasing bend in the present-day Septentiornal-Orient-Swan-Motagua and the Plantain Garden-Swan fault systems (Blue).

Restraining Bend: Sinistral Shear (Miocene-Present)



Uplift and exposure of the rock units of the Wagwater Trough occurred during the Miocene as a strike-slip tectonics reversed and the releasing bend became a restraining bend.

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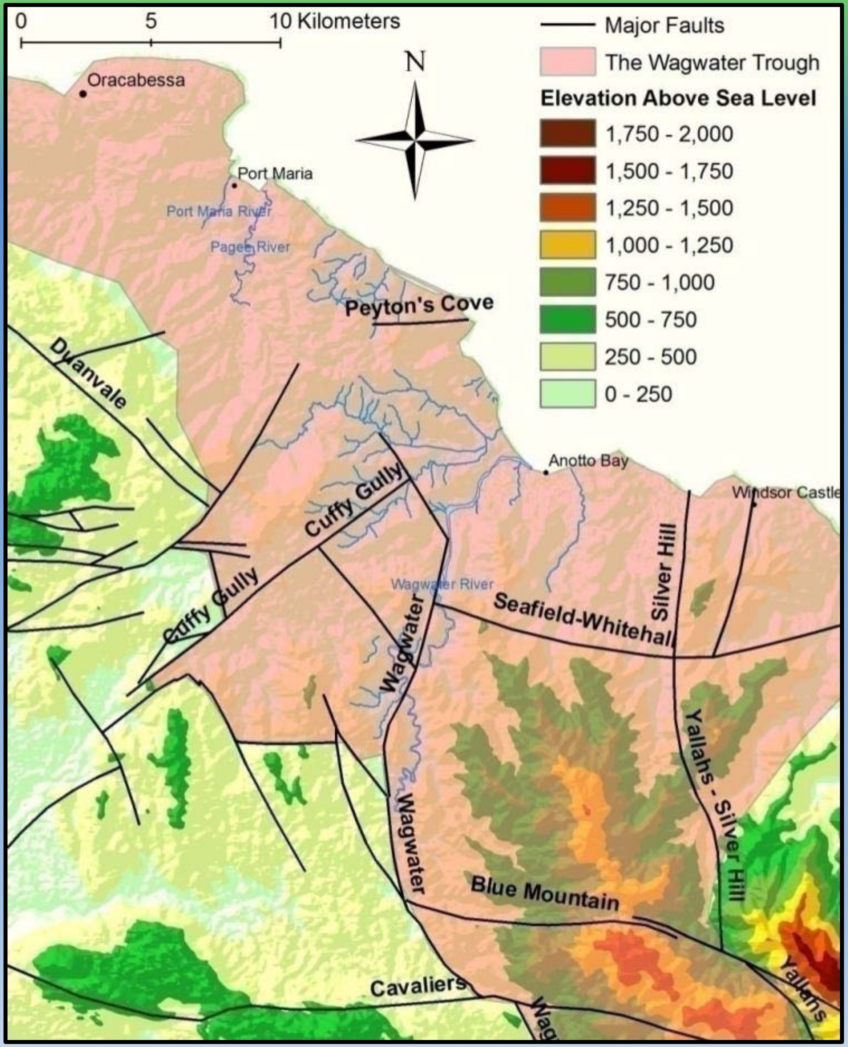
Notes by Presenter: Map showing the present-day Septentiornal-Orient-Swan-Motagua and the Plantain Garden-Swan fault systems connecting at a restraining bend (Blue). These fault systems separate the Cayman Trough (Light Grey) from the Caribbean Plate. The restraining bend is directly over the Wagwater Trough (Red), and as a result significant uplift and faulting has occurred (after Mann and Burke, 1990).

Click to View Notes by Presenter

Major Fault zones in the Wagwater Trough



(after Mann and Burke, 1990)

Notes by Presenter (for previous slide):

Map showing the major faults in the northern Wagwater Trough region. In order to simplify the model, only the major faults will be included in the modeling process. Faults trending northwest to southeast were original basin-forming faults that were reactivated as reverse faults during the Late Miocene. West to East trending faults formed during the Late Miocene as left-lateral strike-slip faults.

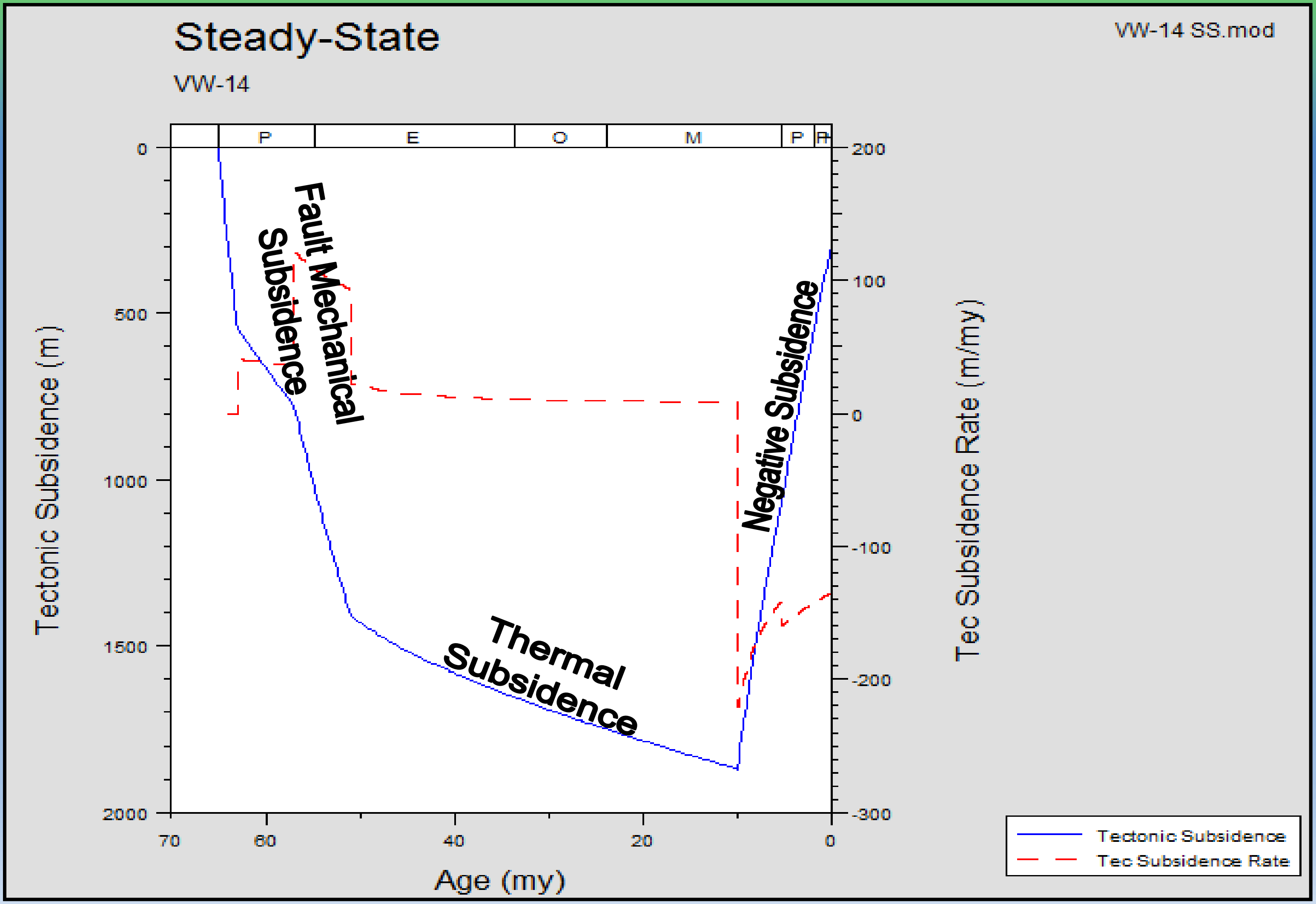
The major basin bounding faults are:

- The Wagwater Fault on the west
- The Yallahs-Silver Hill Fault on the east.
- These faults trend northwest to southeast.

Basin Subsidence Analysis

- Three-Phase Subsidence History
  - Early Fault Mechanical Subsidence or rifting
    - (66 – 51 Ma)
  - Widespread Thermal Subsidence
    - (51 – 10 Ma)
  - Negative Subsidence or Shortening
    - (10 Ma – Present)
    - Erosion and exposure of sediments at the surface

Stages of Subsidence



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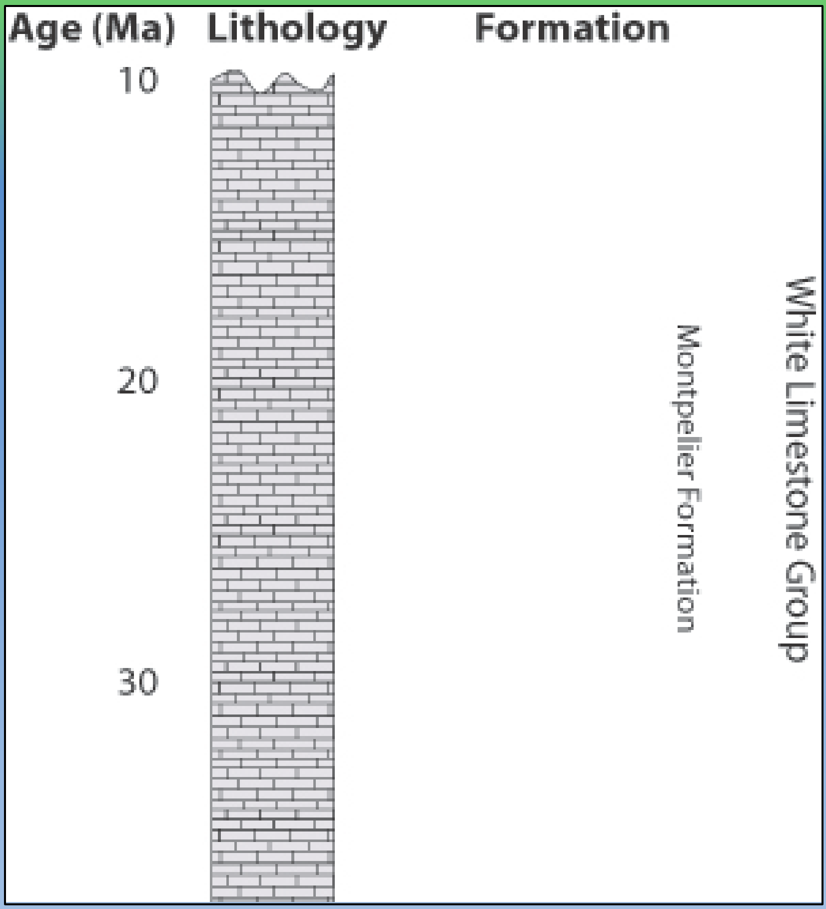
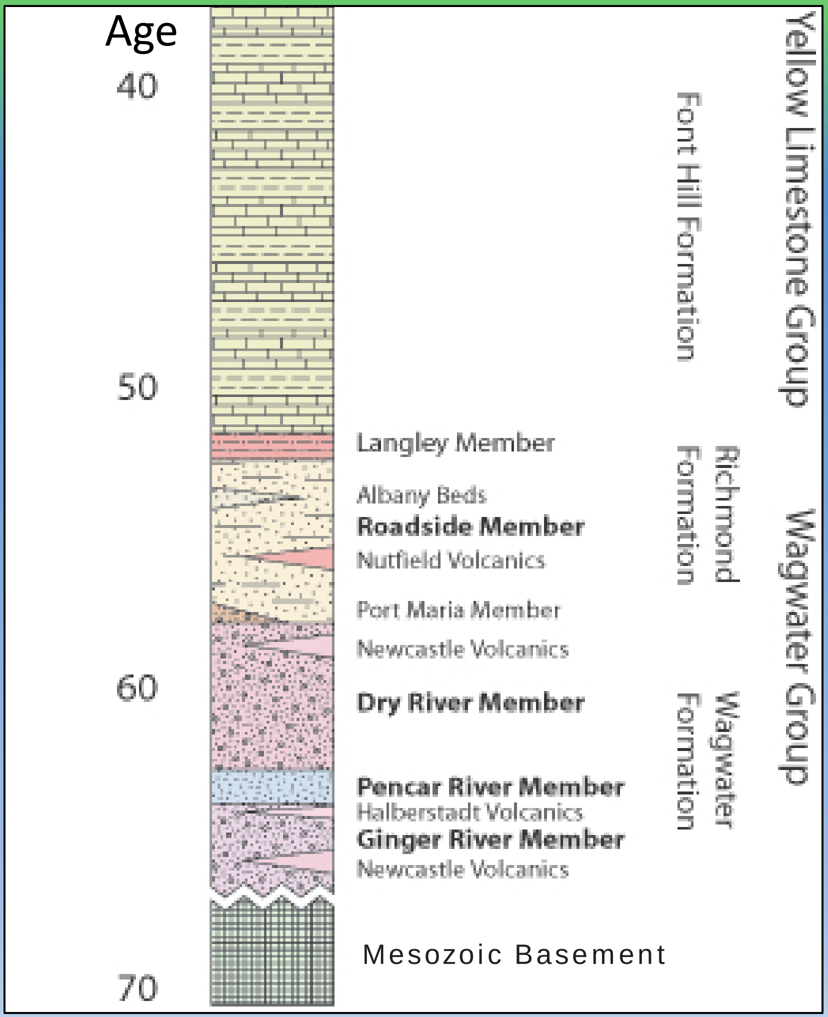
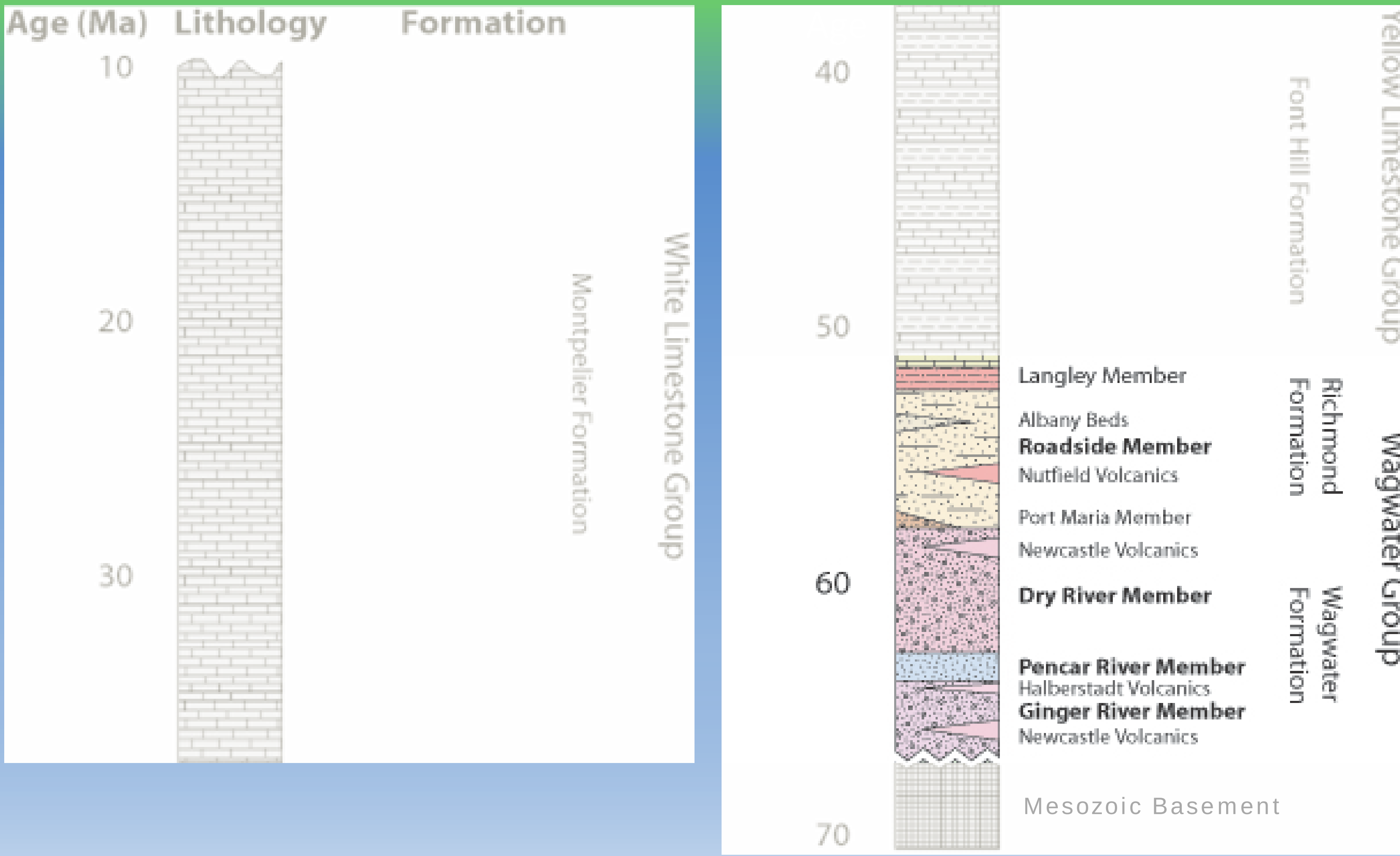
Stratigraphy





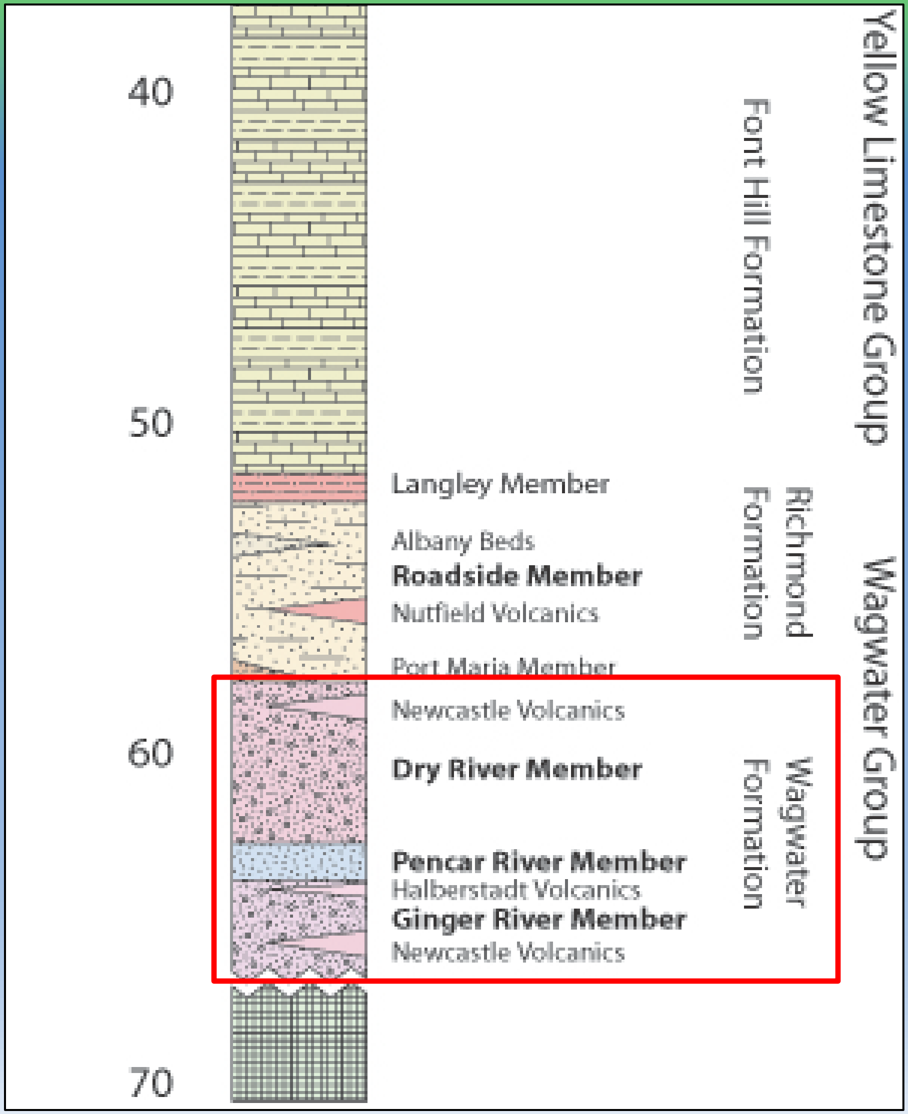
(after Mann and Burke, 1990)

Formations Deposited During Period of Fault Mechanical Subsidence



(after Mann and Burke, 1990)

Wagwater Formation



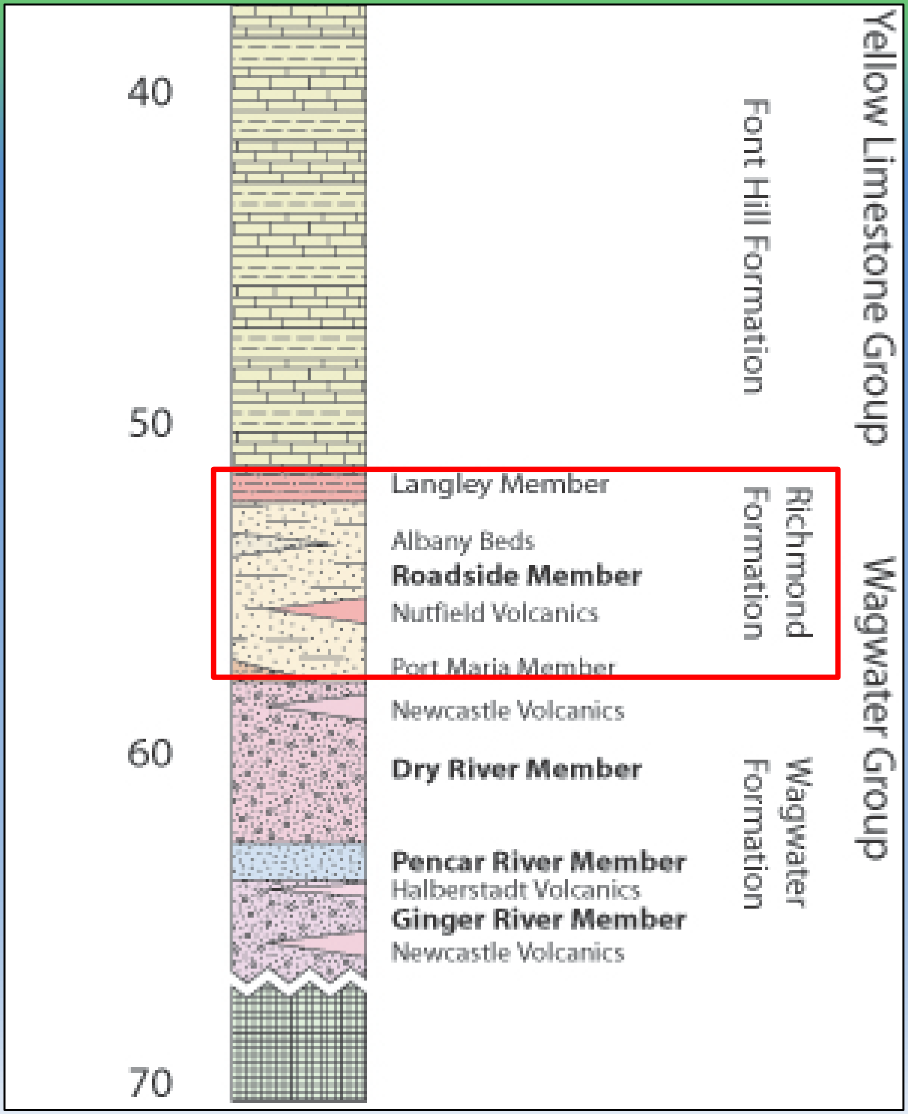
(after Mann and Burke, 1990)

Fault Mechanical Subsidence Deposits: Wagwater Formation

- **Age:** Paleocene to Early Eocene (about 66 – 57 Ma)
- **Members:**
  - **Ginger River:** Very poorly sorted purple conglomerate with metamorphic and volcanic rock fragments
  - **Pencar River:** Coarse dark gray to green sandstones and conglomerates
  - **Dry River:** Poorly sorted purple conglomerates with volcanic and plutonic rock fragments
  - **Newcastle Volcanics:** Five massive flows of porphyritic andesite and dacite
- **Environment:** As rifting initiated, massive alluvial fans formed adjacent to the scarps of the Wagwater fault zone. Sandstones and finer conglomerates were then deposited during a brief landward transgression of sea water. Then as the sea receded, alluvial fans and shallow fan-deltas formed. Another transgression of sea water appeared near the end of deposition of the Wagwater Formation, representing a transition from subaerial to marine deposition.

(Mann and Burke, 1990; Wescott and Ethridge, 1983).

Richmond Formation



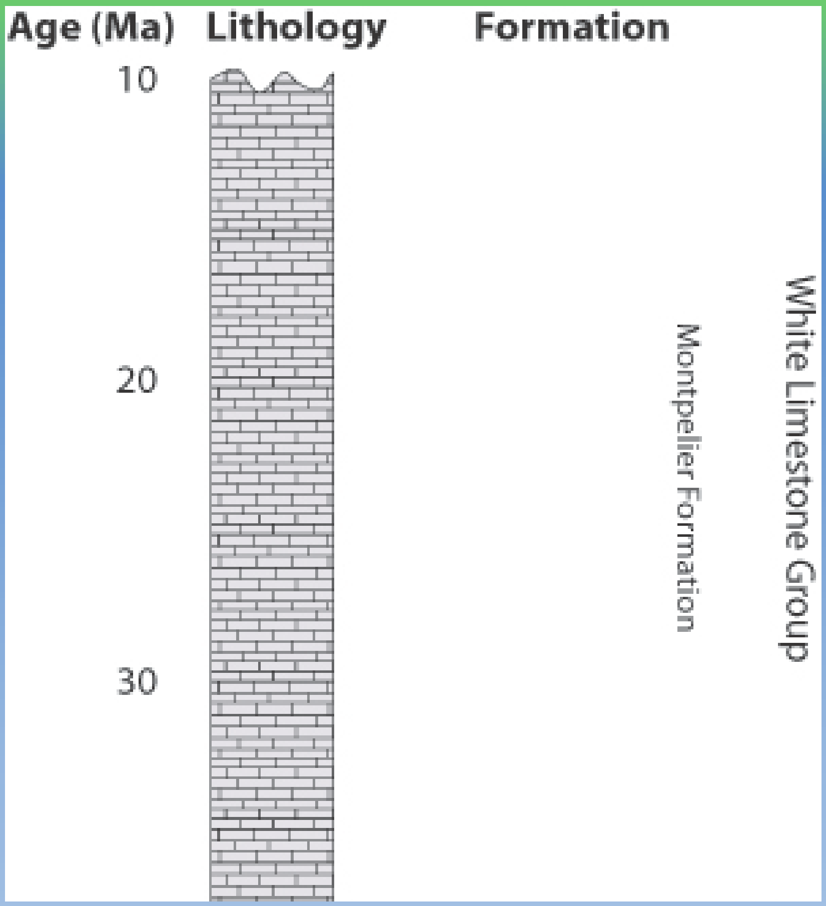
(after Mann and Burke, 1990)

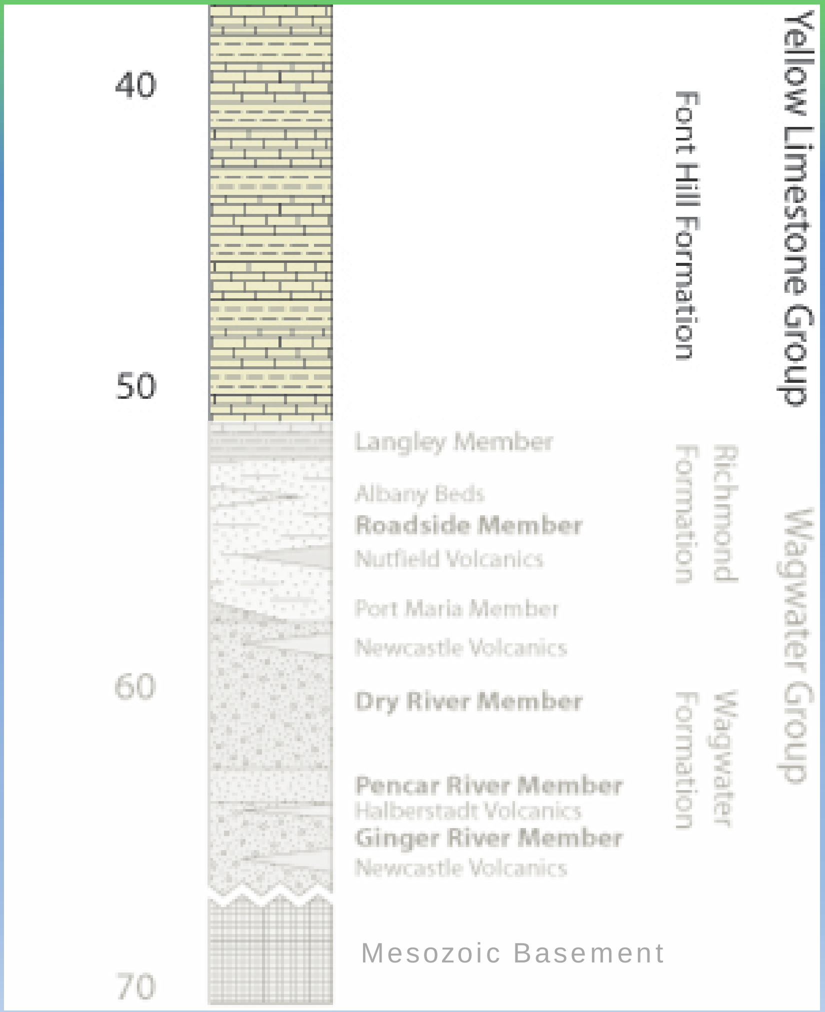
Fault Mechanical Subsidence Deposits: Richmond Formation

- **Age:** Eocene (about 57 – 51 Ma)
- **Members:**
  - **Port Maria:** Calcite cemented brown conglomerate beds and massive inter-bedded sandstone and silt layers containing rudist and mollusk fragments
  - **Albany:** Very poorly sorted clast-supported conglomerate beds containing coral and mollusk fragments
  - **Roadside:** Thin inter-bedded lenticular amalgamated sandstone layers than fine upward into siltstone and mudstone layers
  - **Langley:** Evenly bedded alternating mudstone and siltstone layers
  - **Nutfield Volcanics:** A sheet of basaltic pillow lava conformably overlain by a dacite flow
- **Environment:** Submarine slope deposits consisting of the turbidite flows of the Roadside member and slump deposits of the Port Maria and Albany members topped by a waning flow deposit of the Langley member.

(Mann and Burke, 1990; Wescott and Ethridge, 1983).

Formations Deposited During Period of Thermal Subsidence





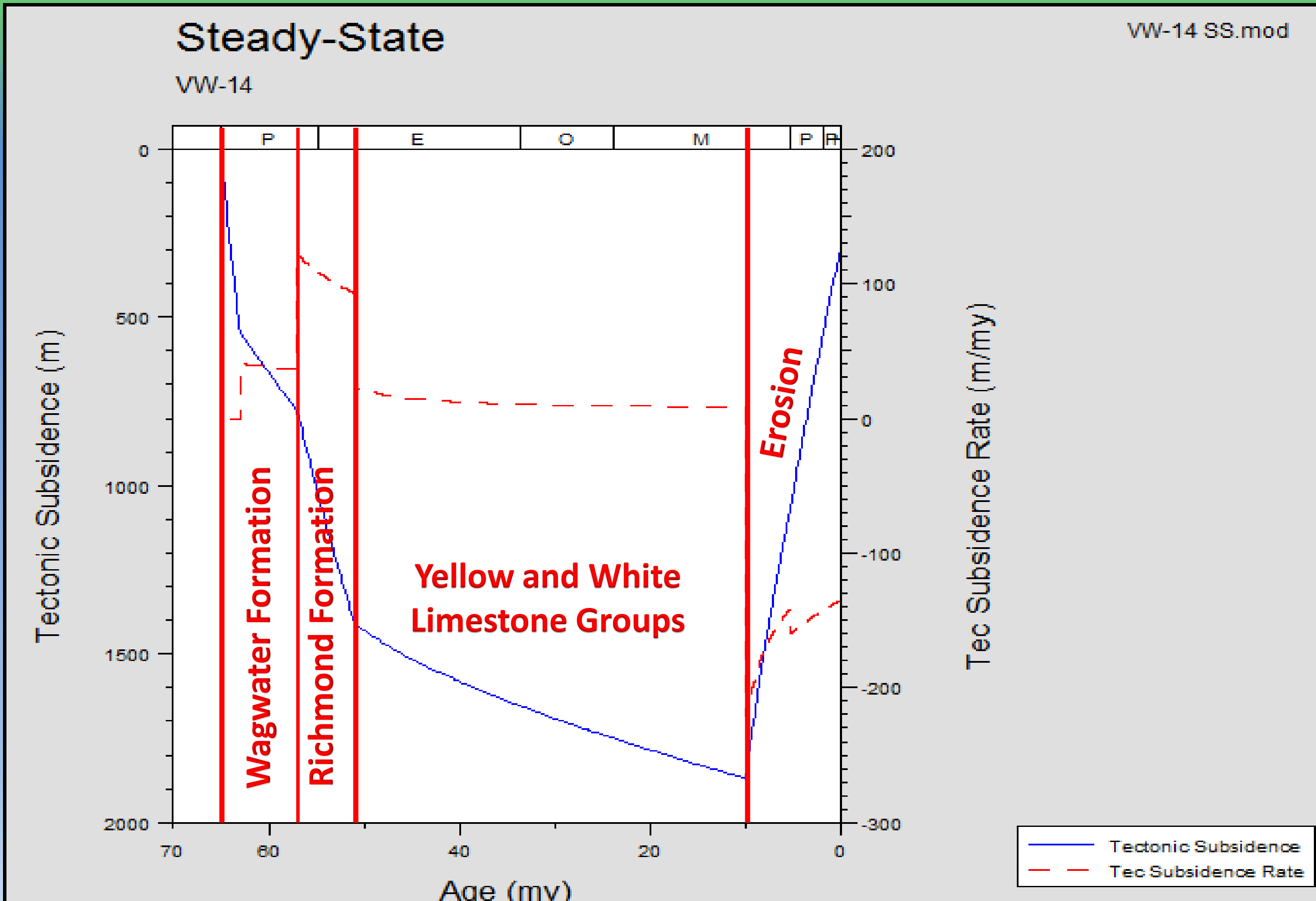
(after Mann and Burke, 1990)

Yellow and White Limestone Groups

- **Age:** Eocene to Miocene (about 51 – 10 Ma)
- **Description:** Biomicrites that are bioclastic at the base.
- **Environment:** Deep-marine environments deposited post-Wagwater rift during a period of gradual subsidence.

(Mann and Burke, 1990 and Robinson, 1974)

Stages of Subsidence

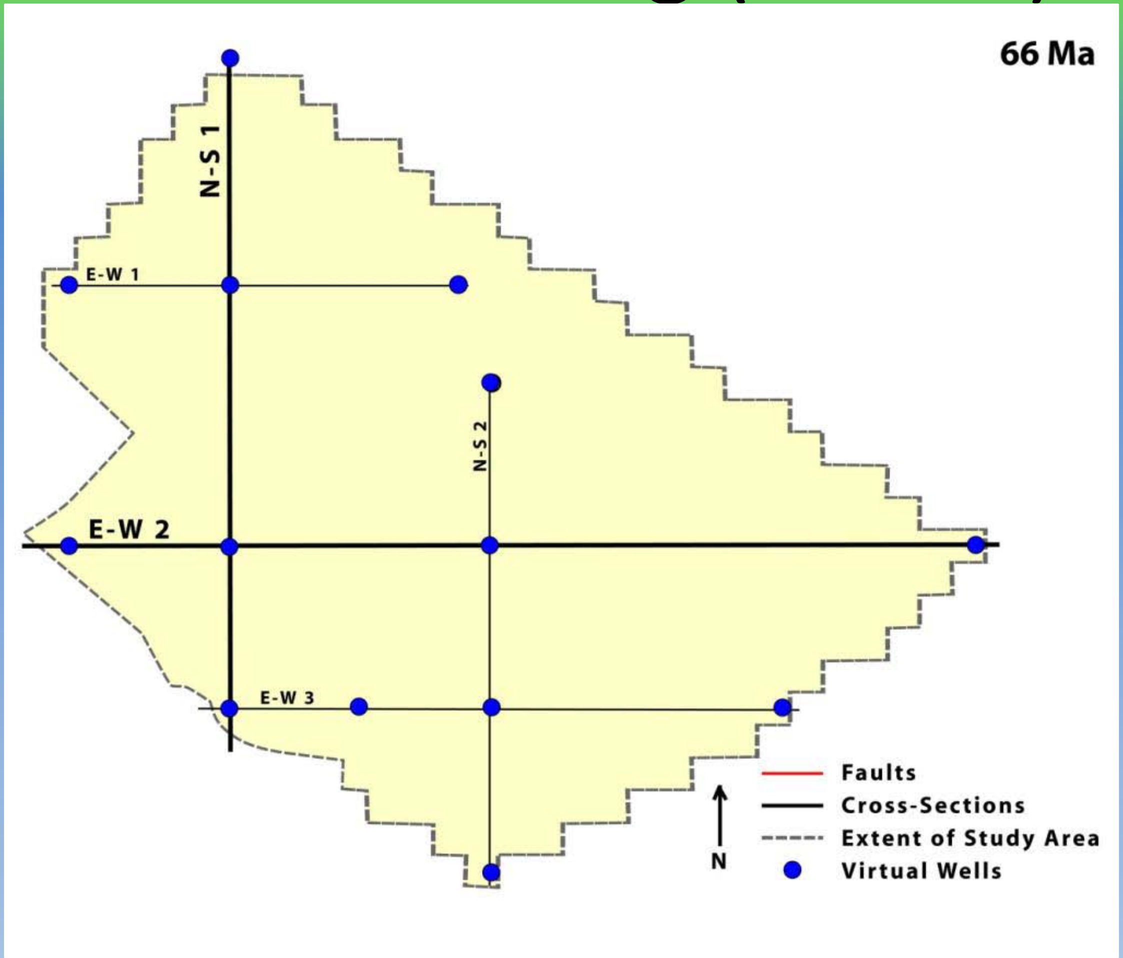


Stretching Factor (Beta)

Model	Beta 66-51 Ma (Fault Mechanical Tectonic Subsidence)	Beta 10-0 Ma (Negative Subsidence)
1-D	1.53	0.66
2-D	1.42	0.86
3-D	1.66	0.81

- The betas calculated for the 1-D, 2-D and 3-D models are similar. The 3-D modeled beta is assumed most accurate, because it uses basin volumes to determine beta.
- The Wagwater Trough experienced significant basin growth as it enlarged 1.66 times during the period of fault mechanical subsidence.

3-D Map showing Basement Structure Prior to Rifting (66 Ma)



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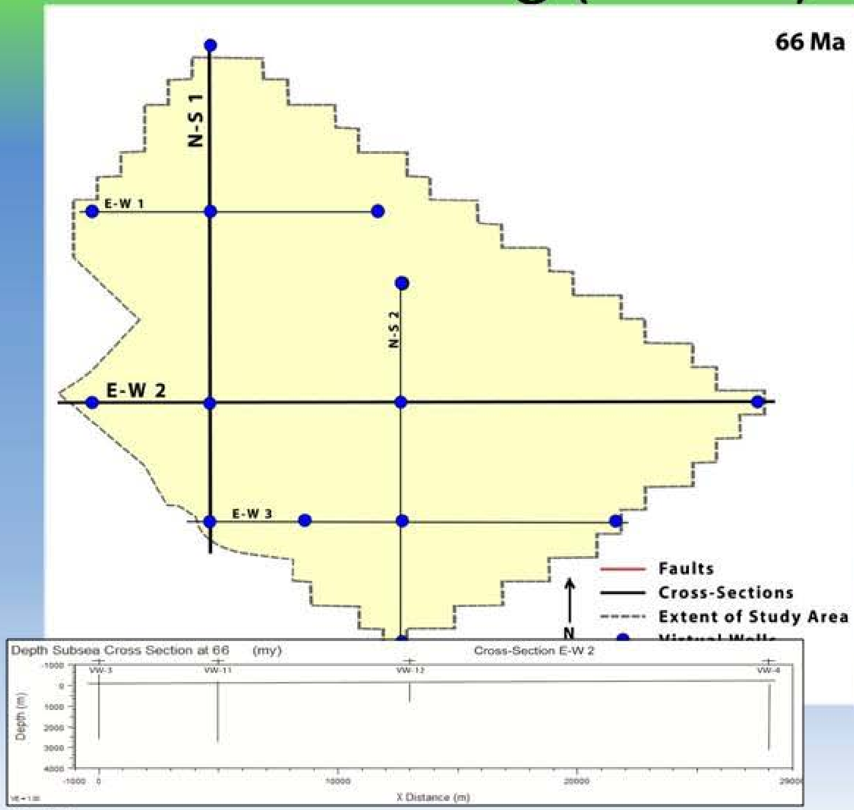
3-D Map showing Basement Structure Prior to Rifting (66 Ma)



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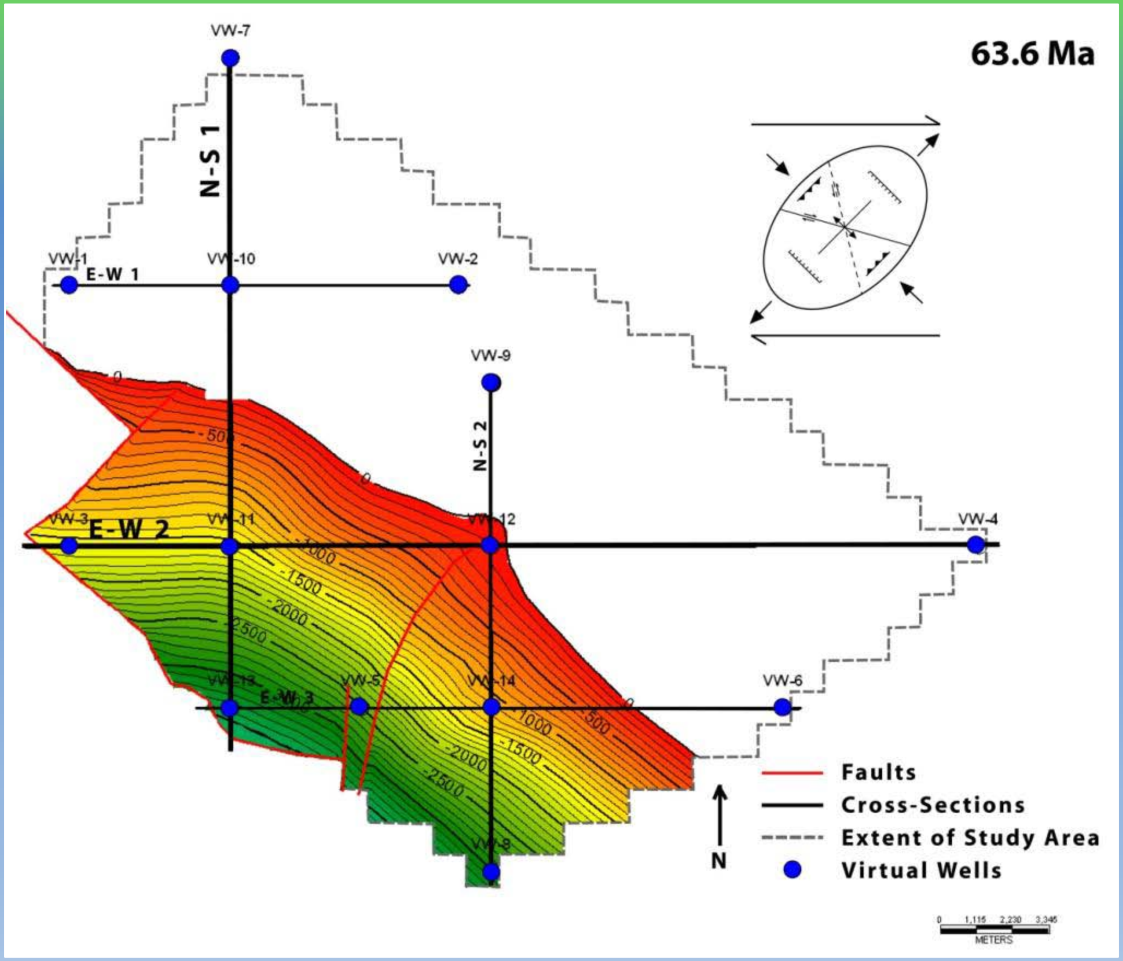
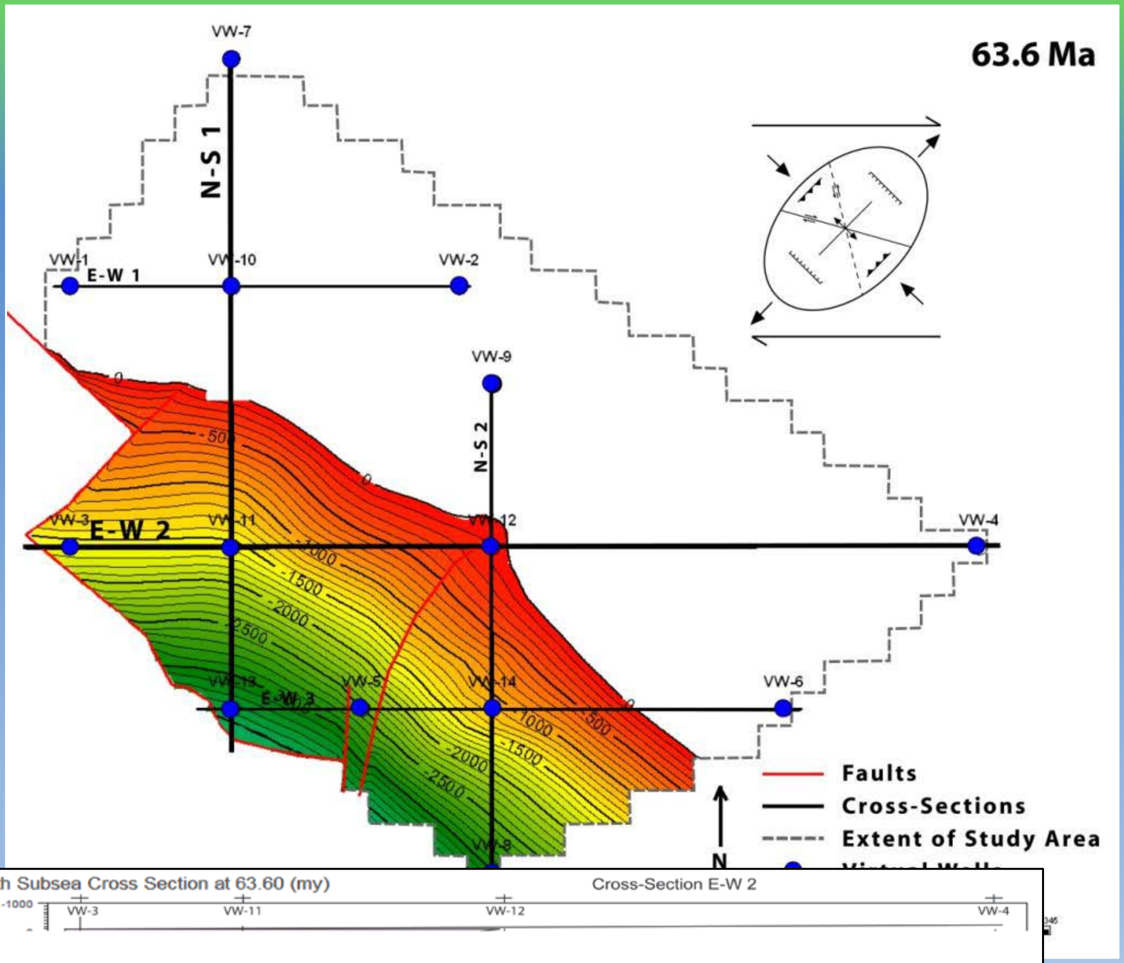
Notes by Presenter: At 66 Ma, the rifting in the trough was just commencing. This period of time represents the unconformity between the Mesozoic Rocks of the region and Ginger River Member deposited in the Wagwater Trough. This is a map and two cross-sections E-W 2 and N-S 1 showing structural depth to basement in meters subsea at 66 Ma. Elevation is currently zero, because the figure represents the period just before rifting.

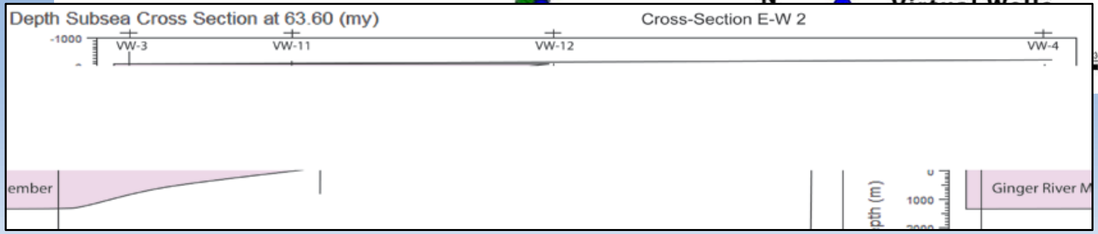
Basement Structure After Deposition of the Ginger River Member (63.6 Ma)



Basement Structure After Deposition of the Ginger River Member (63.6 Ma)

Click to View Notes by Presenter





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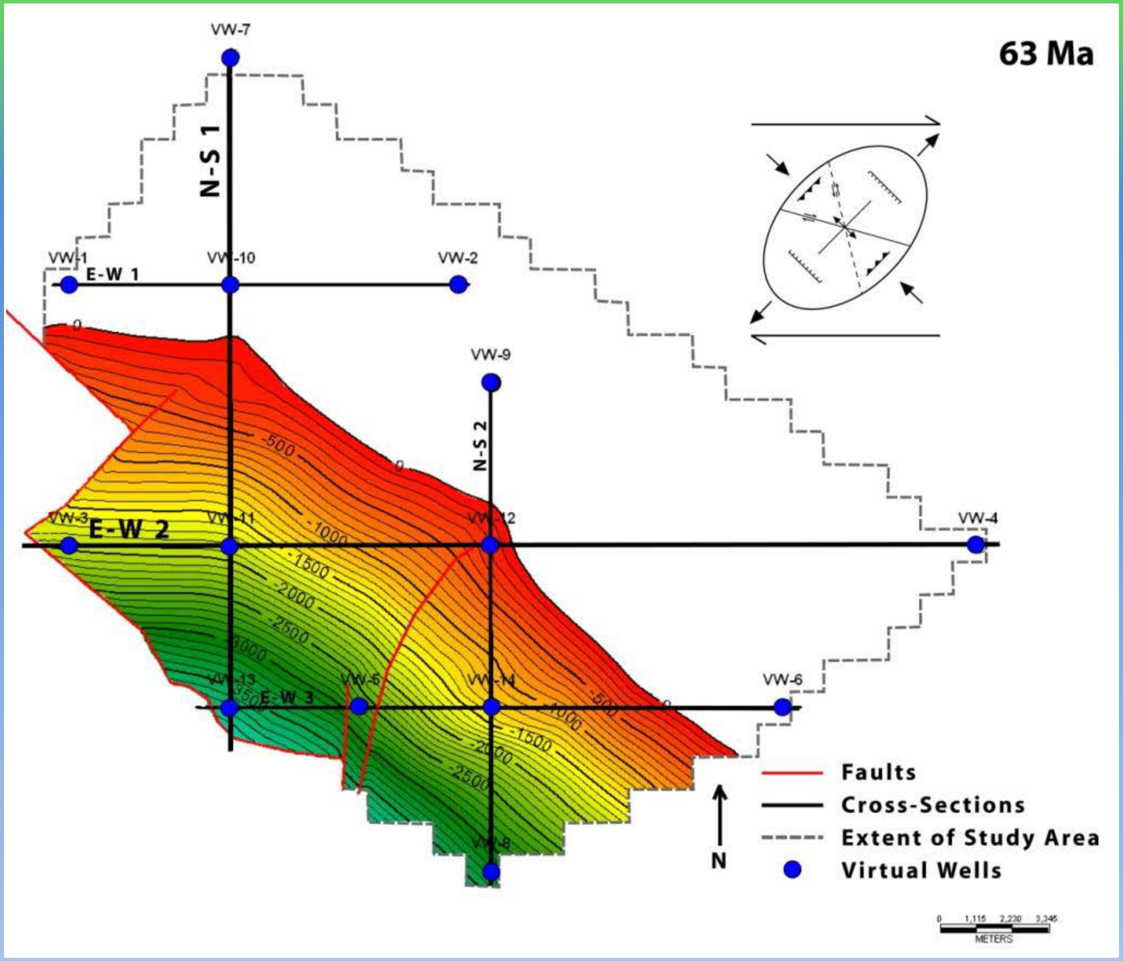
Notes by Presenter (for previous slide):

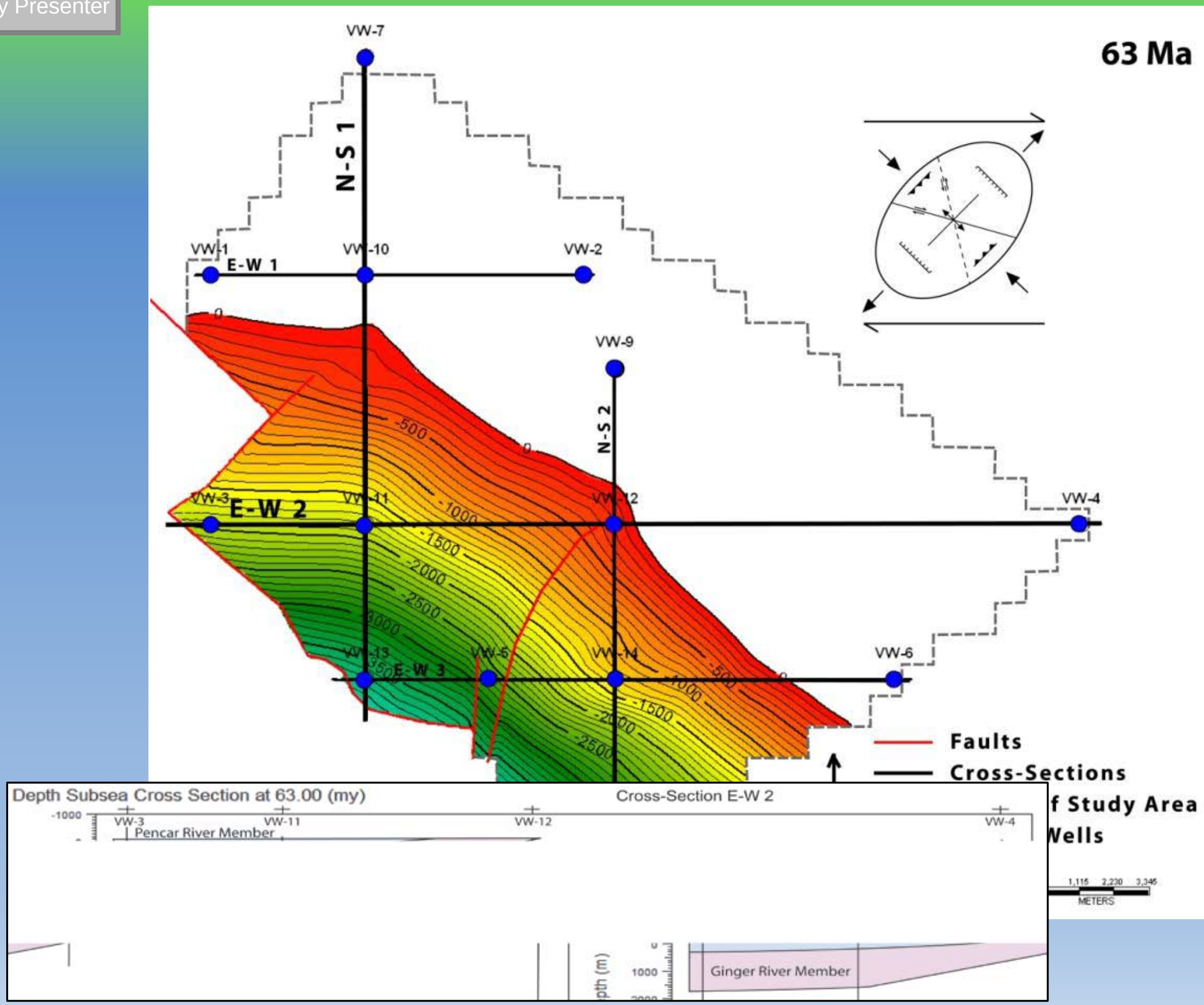
From 66 Ma to 63.6 Ma the basin initiated fault mechanical subsidence as a half graben with northeast to southwest extension owing to simple dextral(?) shear in a releasing bend along the Septentiornal-Orient-Swan-Motagua, Duanvale, and Plantain Garden-Sway fault zones. During this period, the Ginger River Member of the Wagwater Formation was deposited as subaerial alluvial fan conglomerates shed from the southwest Cretaceous inlier. This is a map and two cross-sections E-W 2 and N-S 1 showing structural depth to basement in meters subsea at 63.6 Ma.

Basement Structure After Deposition of Pencar River Member (63 Ma)



Basement Structure After Deposition of Pencar River Member (63 Ma)

Click to View Notes by Presenter



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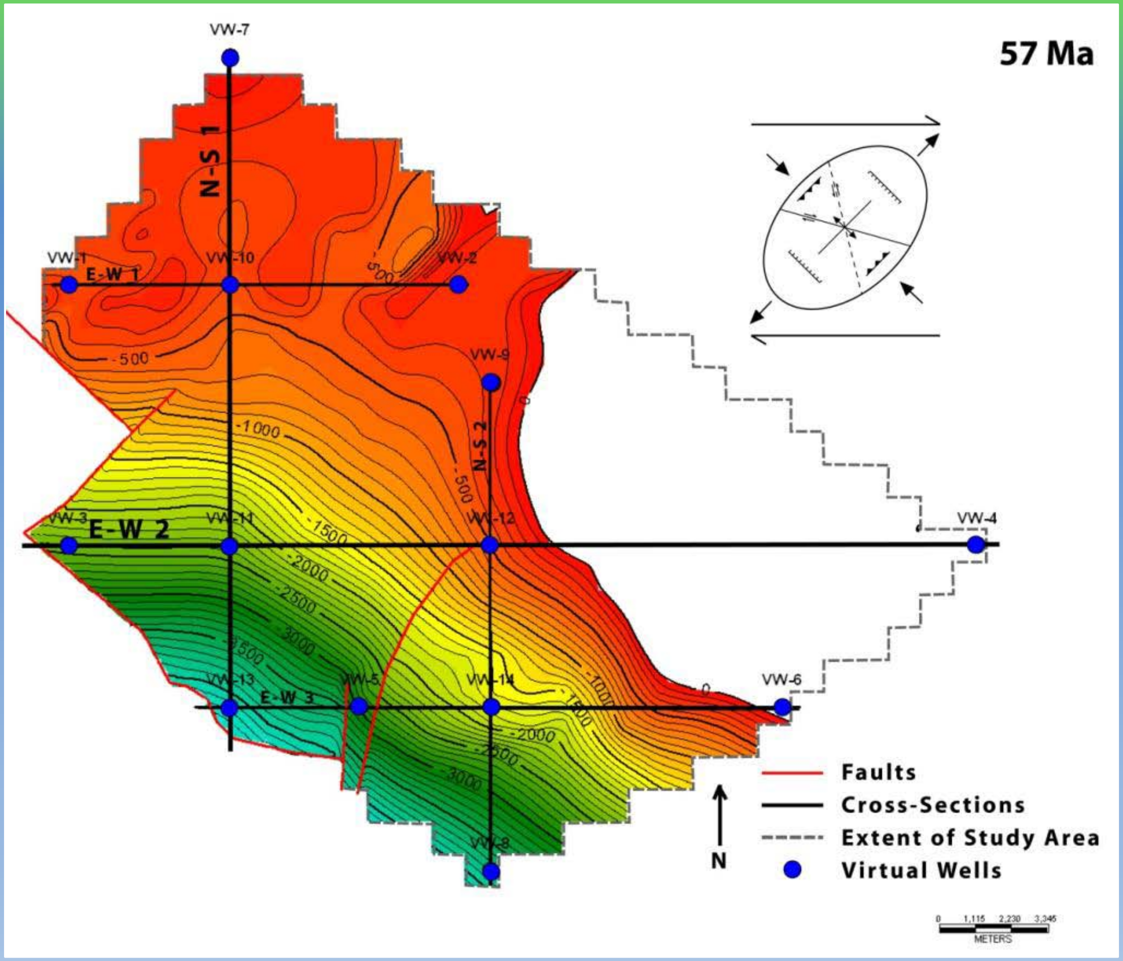
Notes by Presenter (for previous slide):

From 63.6 Ma to 63 Ma, the basin continued fault mechanical subsidence as a half graben with northeast to southwest extension owing to simple dextral(?) shear in a releasing bend along the Septentiornal-Orient-Swan-Motagua, Duanvale, and Plantain Garden-Sway fault zones. This period marks a transgression of seawater into the basin, and the Pencar River Member of the Wagwater Formation was deposited as deltaic sandstones conglomerates shed from the southwest Cretaceous inlier. Figure 7.2.17 is a map and two cross-sections E-W 2 and N-S 1 showing structural depth to basement in meters subsea at 63 Ma.

Basement Structure After Deposition of Dry river Member (57 Ma)



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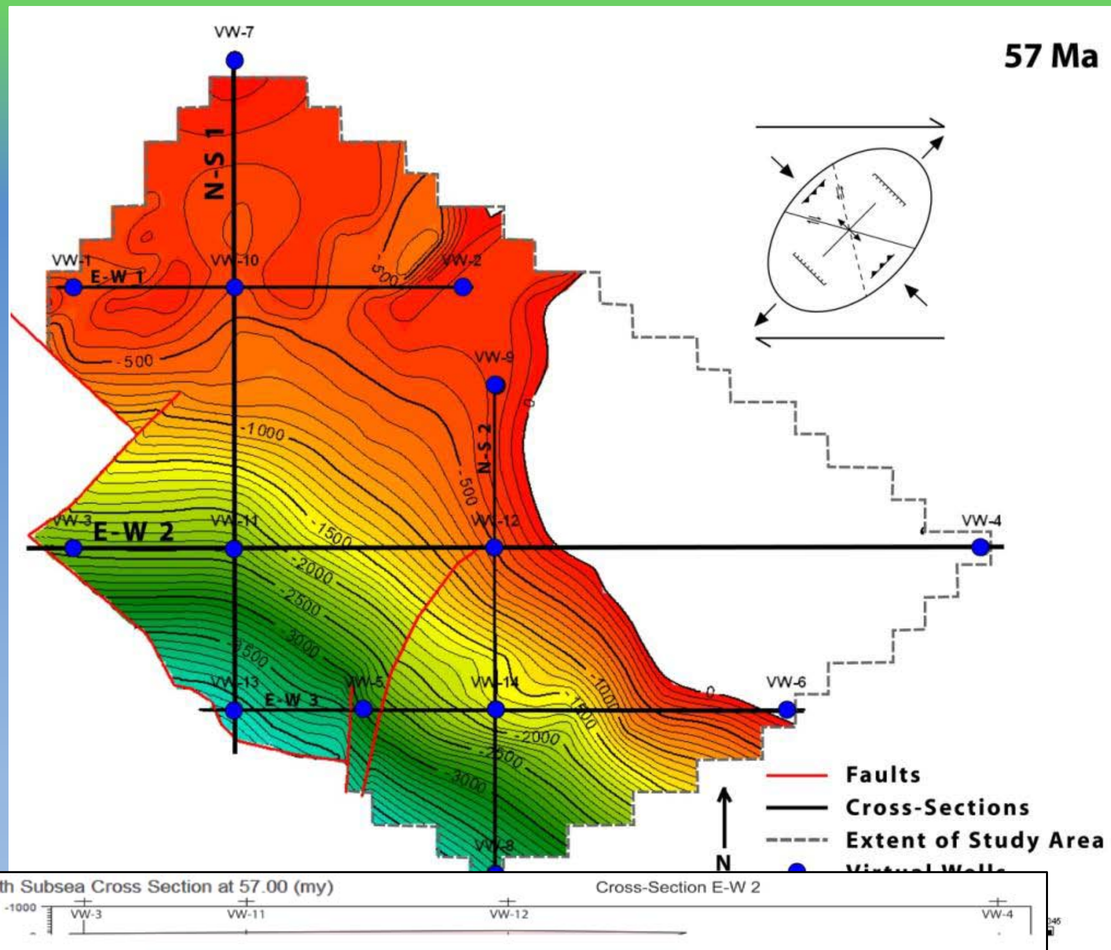
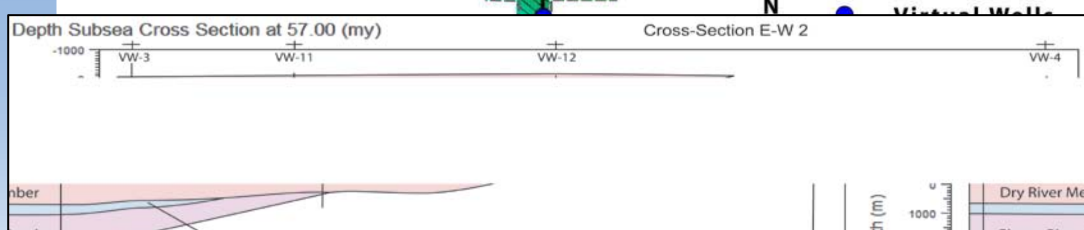
Basement Structure After Deposition of Dry river Member (57 Ma)

Click to View Notes by Presenter





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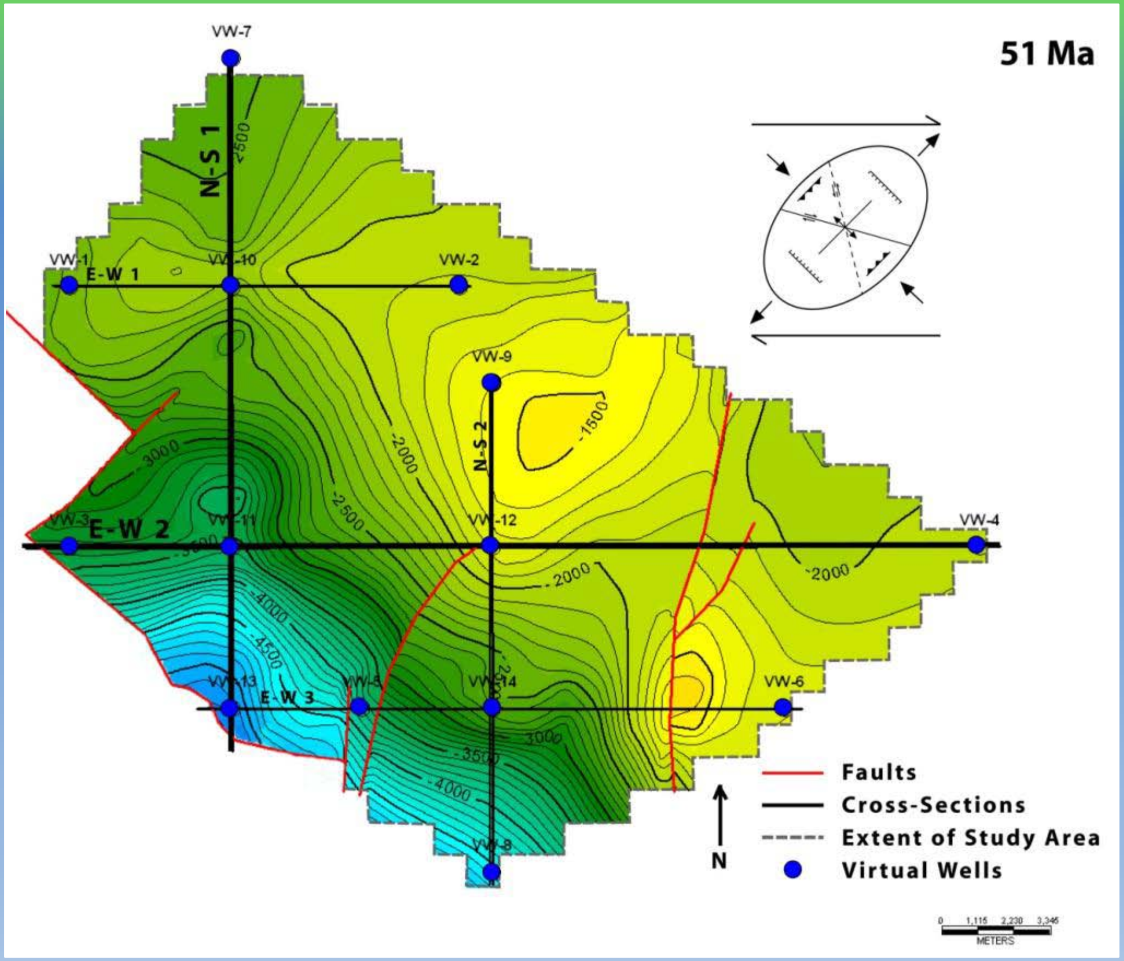
Notes by Presenter (for previous slide):

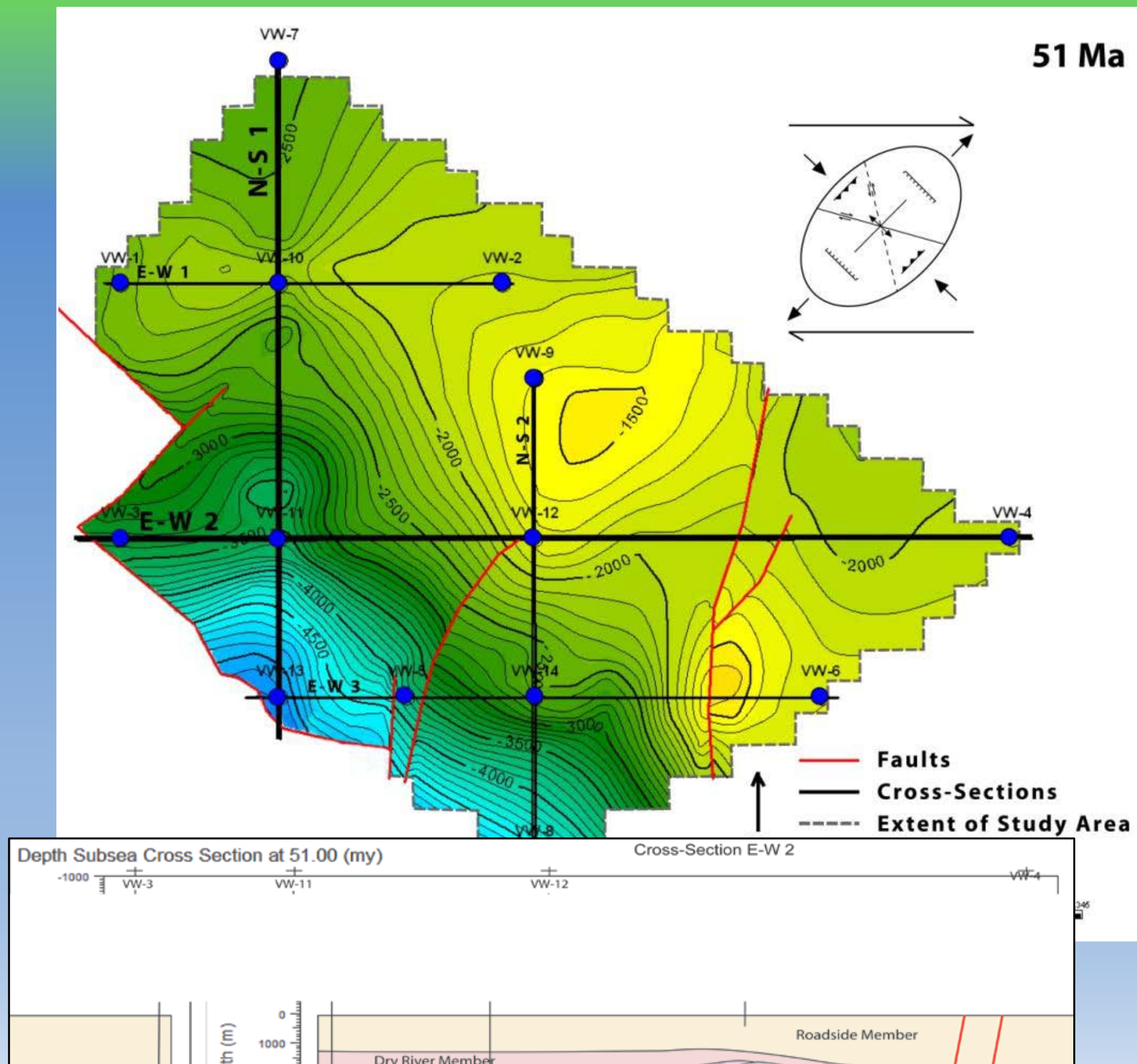
From 63 Ma to 57 Ma, the basin continued fault mechanical subsidence as a half graben. However, toward the end of this period, subsidence began in the north as well. The brief transgression of seawater during the Pencar River time (63.6 – 63 Ma) regressed out of the basin, and the Dry River Member of the Wagwater Formation was deposited as subaerial alluvial fan and fan-delta conglomerates shed from the southwest Cretaceous inlier. This is a map and two cross-sections E-W 2 and N-S 1 showing structural depth to basement in meters subsea at 57 Ma.

Basement Structure After Deposition of the Richmond Formation (51 Ma)



Basement Structure After Deposition of the Richmond Formation (51 Ma)

Click to View Notes by Presenter



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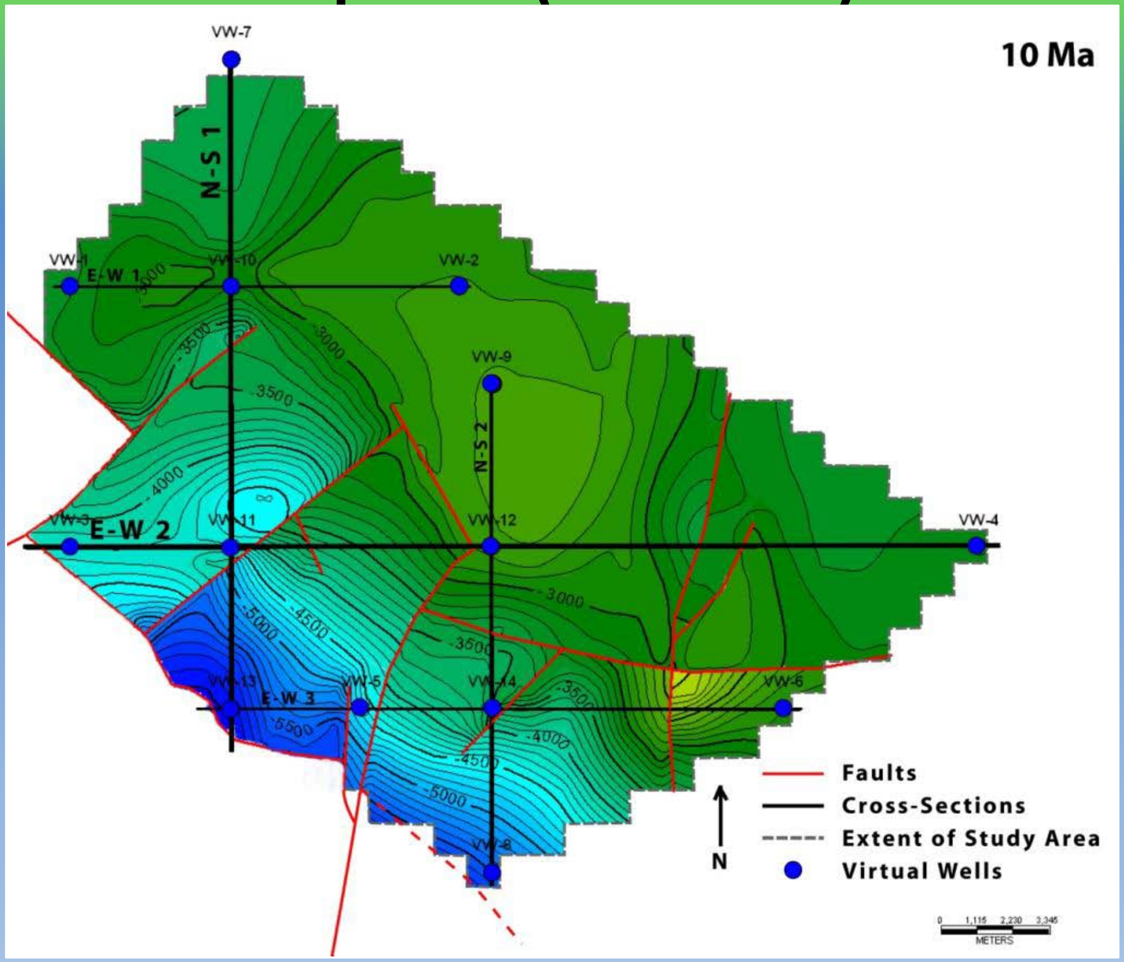
Notes by Presenter (for previous slide):

From 57 Ma to 51 Ma, the basin continued fault mechanical subsidence. During this period, subsidence continued throughout the region and the Yallahs-Silver Hill Fault Zone activated as westward-dipping normal faults. A transgression of seawater during this period produced sediments in the Richmond formation as deltas, fan-deltas, marine shelf, and marine slope sandstone, shale, and conglomerate deposits. This is a map and two cross-sections E-W 2 and N-S 1 showing structural depth to basement in meters subsea at 51 Ma.

Basement Structure at Time of Initial Uplift (10 Ma)



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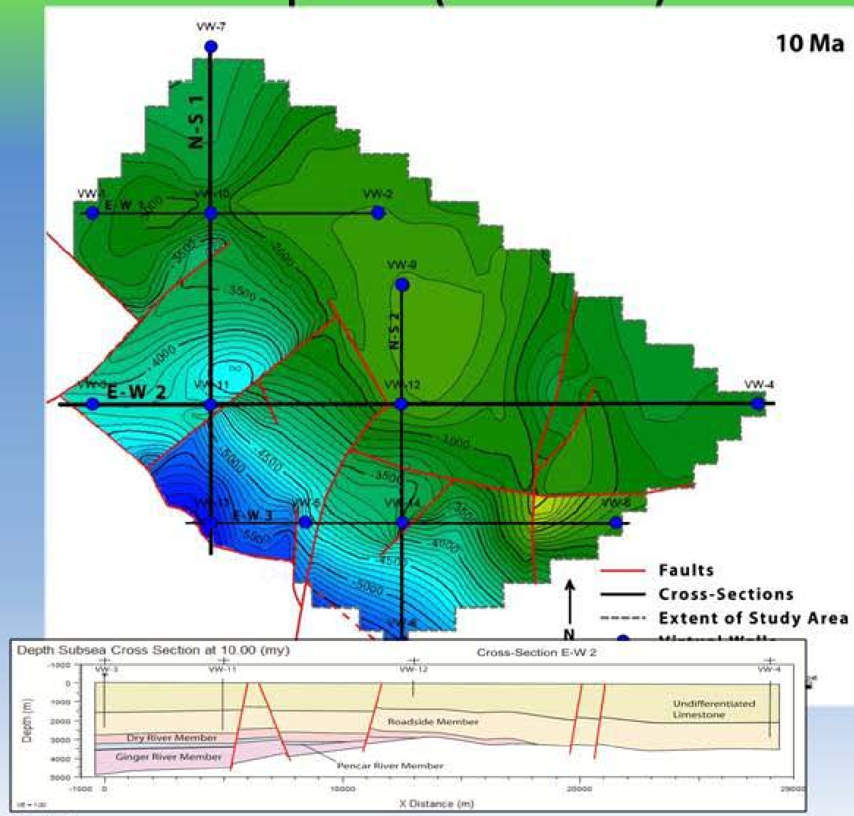
Basement Structure at Time of Initial Uplift (10 Ma)



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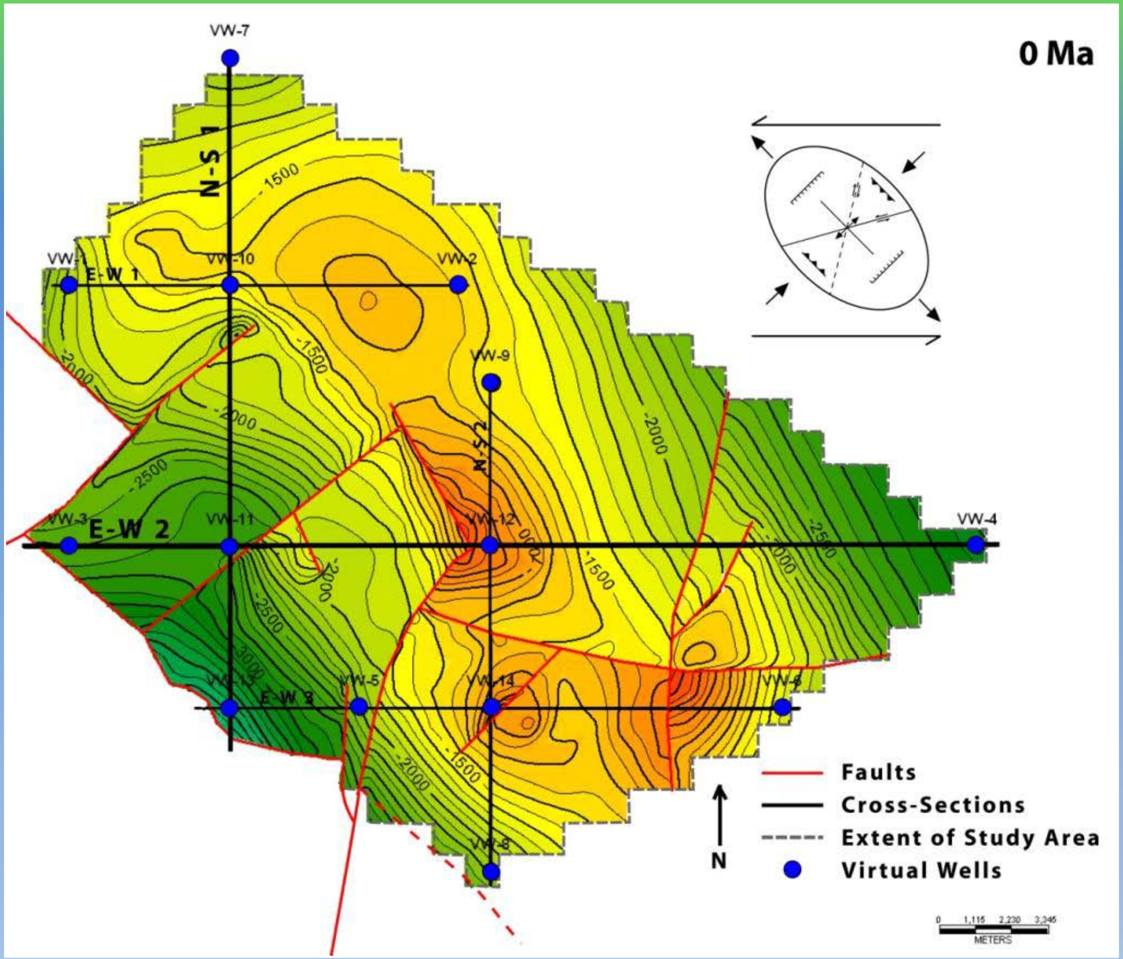
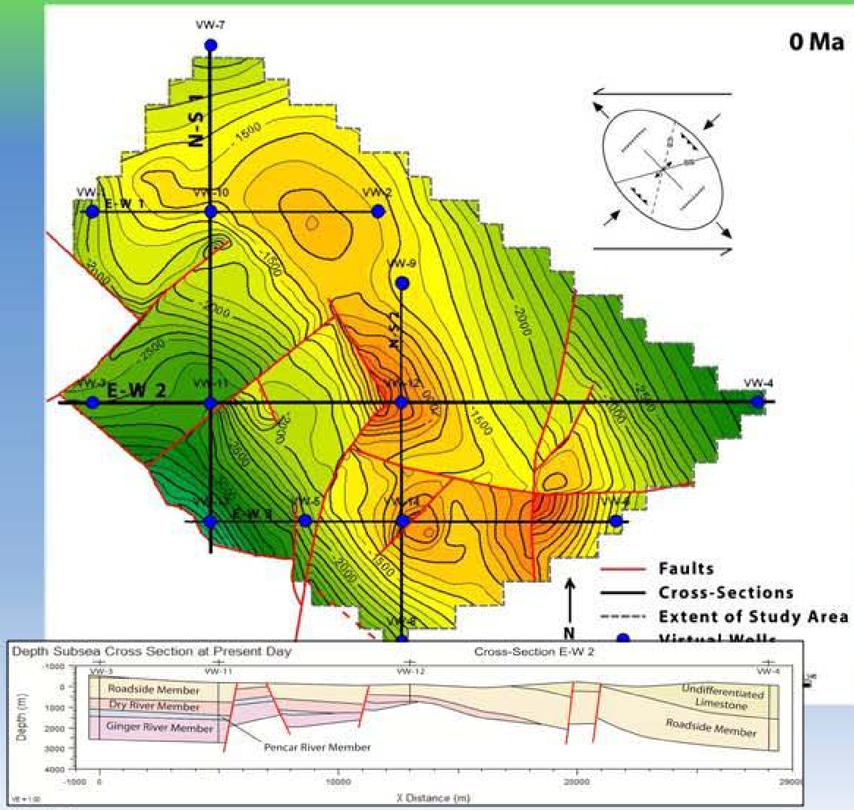
Notes by Presenter: From 51 Ma to 10 Ma, the basin ceased fault mechanical subsidence and thermal tectonic subsidence became the main drive for basin subsidence. During this period, the Yellow and White Limestone Groups were deposited as deep-water shelf bank and slope deposits. This is a map and two cross-sections E-W 2 and N-S 1 showing structural depth to basement in meters subsea at 10 Ma.

Present-day Basement Structure



Present-day Basement Structure



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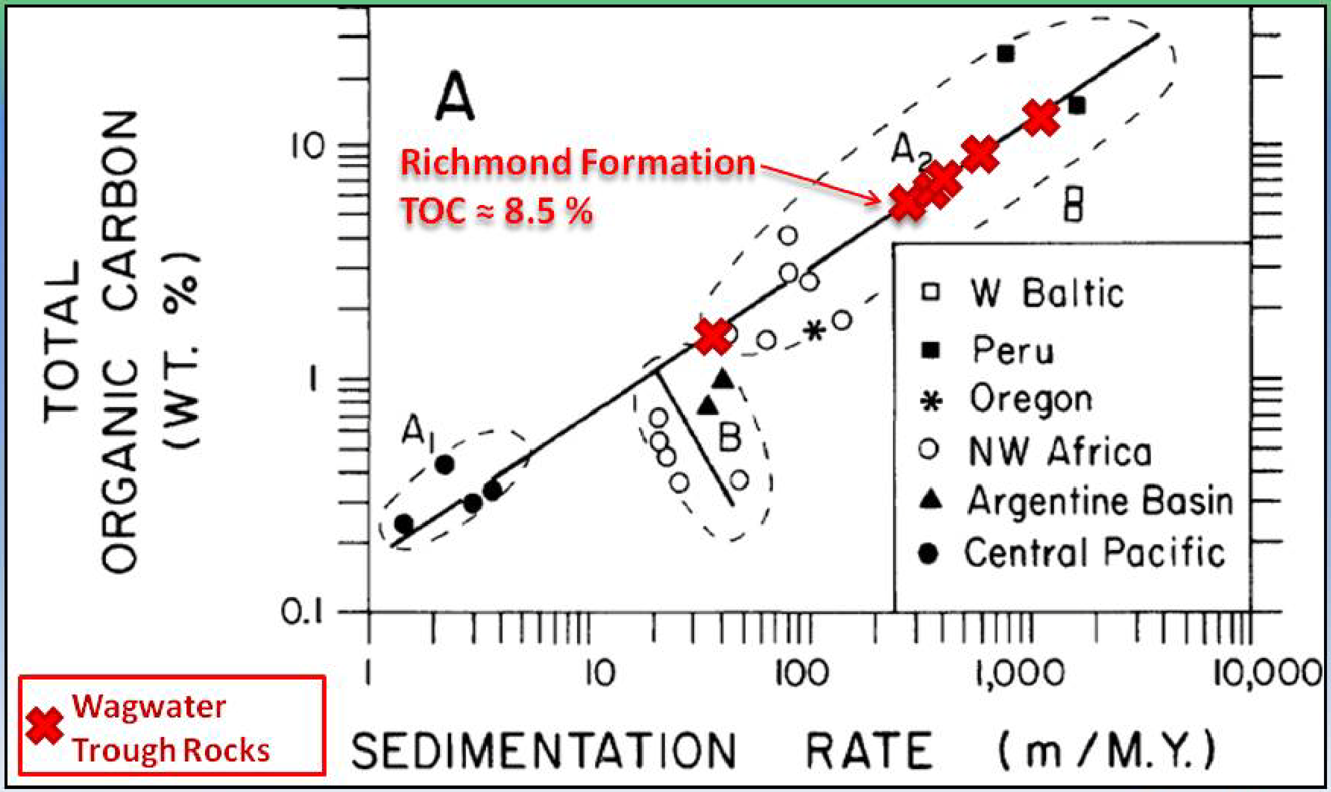
Notes by Presenter: From 10 Ma to 0 Ma, the basin ceased subsidence and uplift and shortening, with a beta of 0.81, occurred along the basin faults. Erosion removed the majority of the Yellow and White Limestone Groups and exposed the members of the Richmond and Wagwater Formations at the surface. This is a map and two cross-sections E-W 2 and N-S 1 showing structural depth to basement in meters subsea at present.

Total Organic Carbon (TOC)

- The primary potential source rocks are the shale layers of the Richmond Formation.
- While the primary potential reservoir rocks are the sandstone layers of the Richmond Formation.
- Due to a lack of measured TOC in the Wagwater Trough, estimates were made using a correlation between sedimentation rate and TOC developed by Johnson-Ibach (1982).

Total Organic Carbon (TOC)



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(after Johnson-Ibach, 1982)

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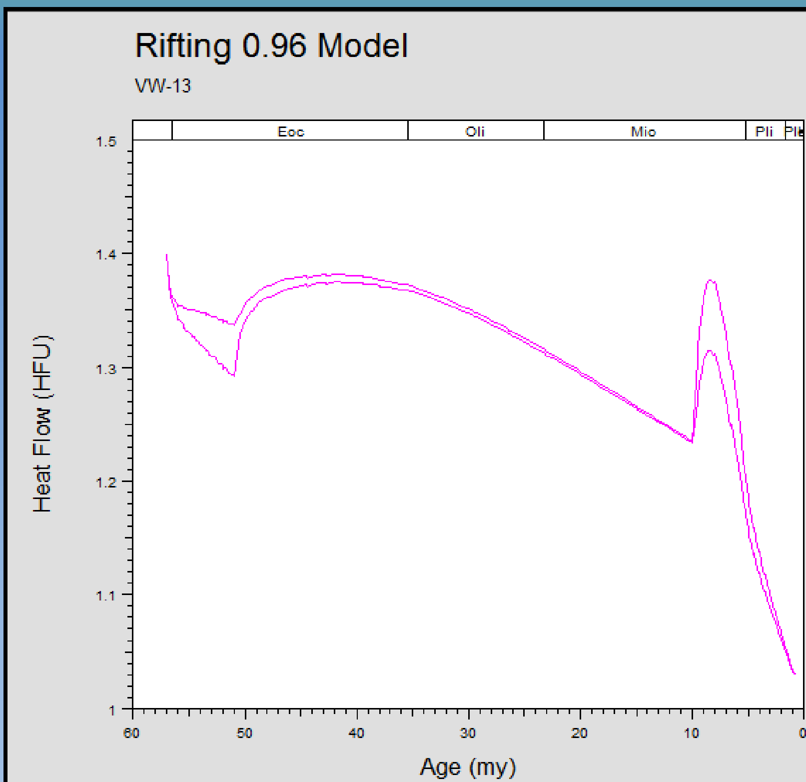
Notes by Presenter: Assuming Clastic deposition in the Wagwater Trough was continuous the average sedimentation rates range from 37 m/MY in Font Hill Limestone to 1,051 m/MY in the Ginger River Member (Wagwater Formation). The average sedimentation rate for the Richmond Roadside Member is 325 m/MY producing a TOC of 6.0%.

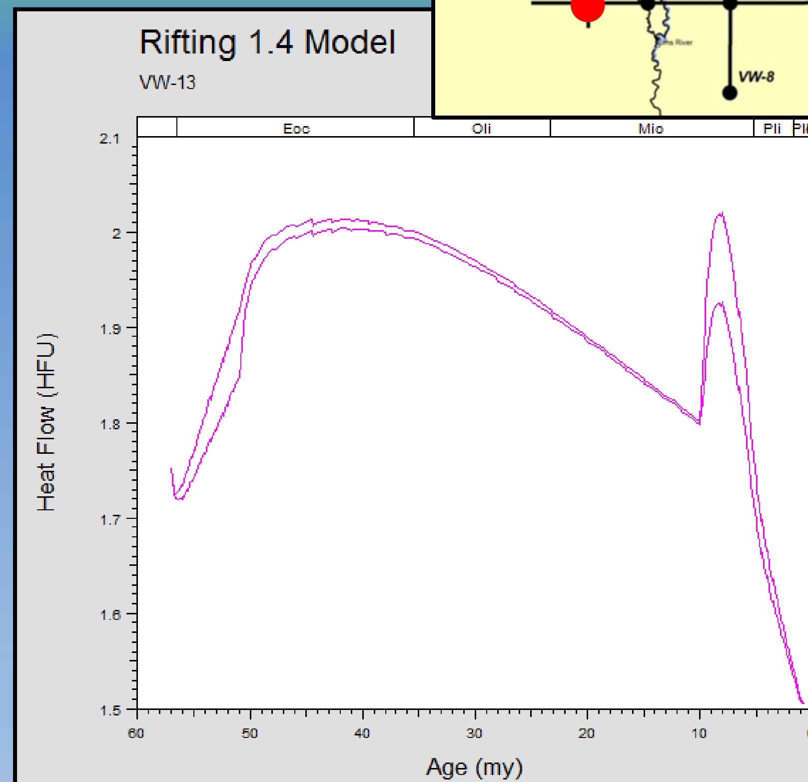
Heat Flow

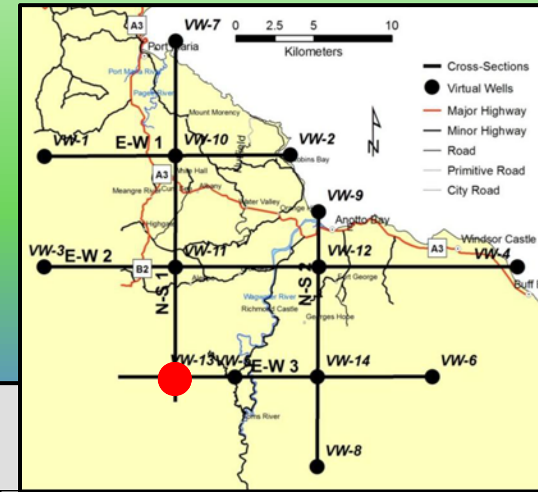
- Heat Flow declines from 2.25 H.F.U. in the Mid-Cayman Spreading center to about 1.4 H.F.U. off the north coast of Jamaica (Perry, 1984).
- O'Neal (1984) calculated heat flow in well Windsor #1, west of the Wagwater Trough, to be 0.96 H.F.U.
- Since no heat flow measurements have been taken within the Wagwater Trough, the 0.96 and 1.4 H.F.U. were used to bracket the present-day heat flow for the Wagwater Trough.

Heat Flow

Virtual Well #13







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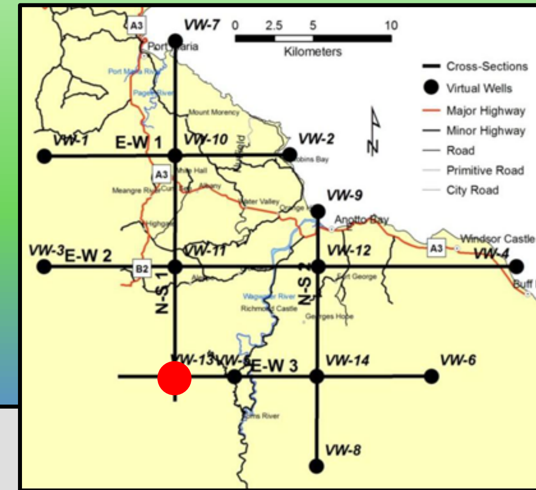
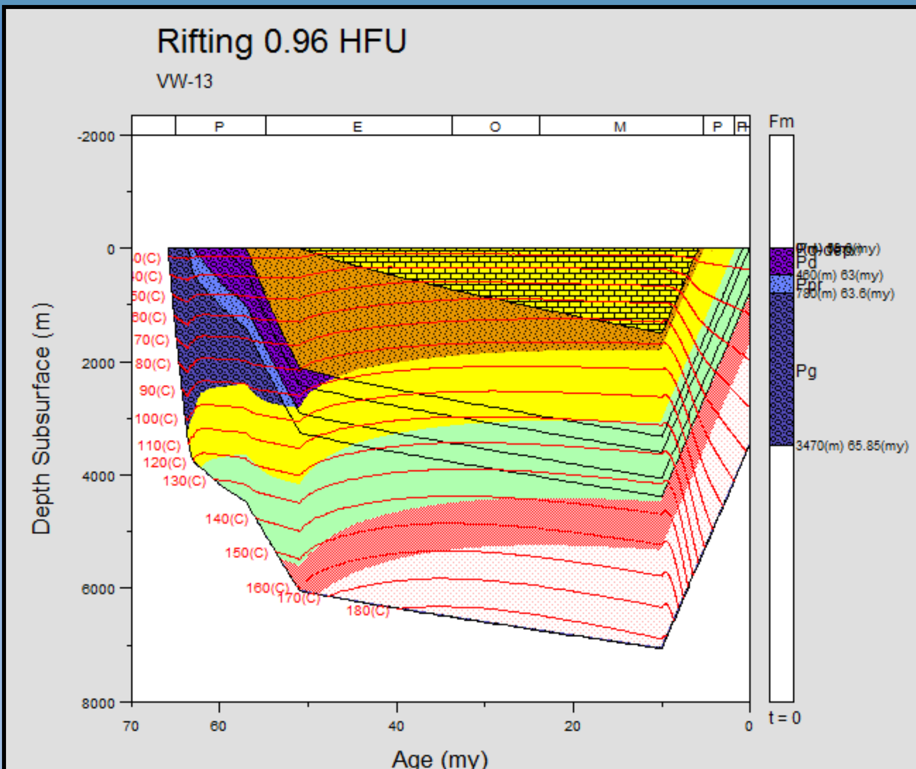
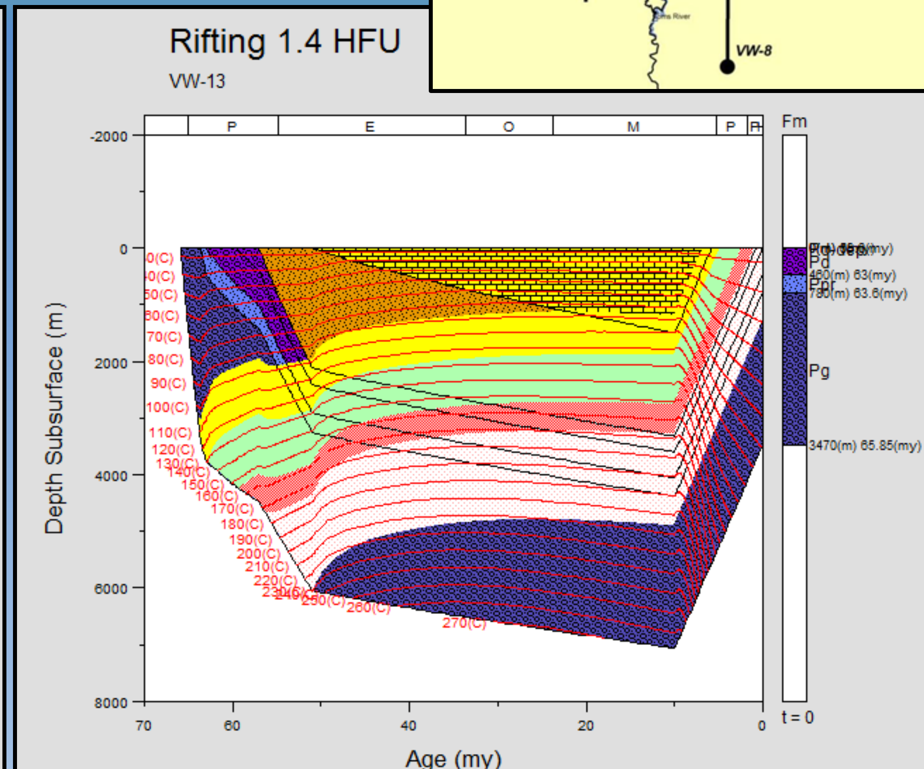
Maturity Analysis VW-13







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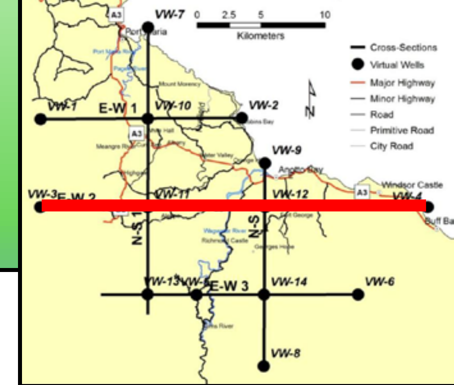
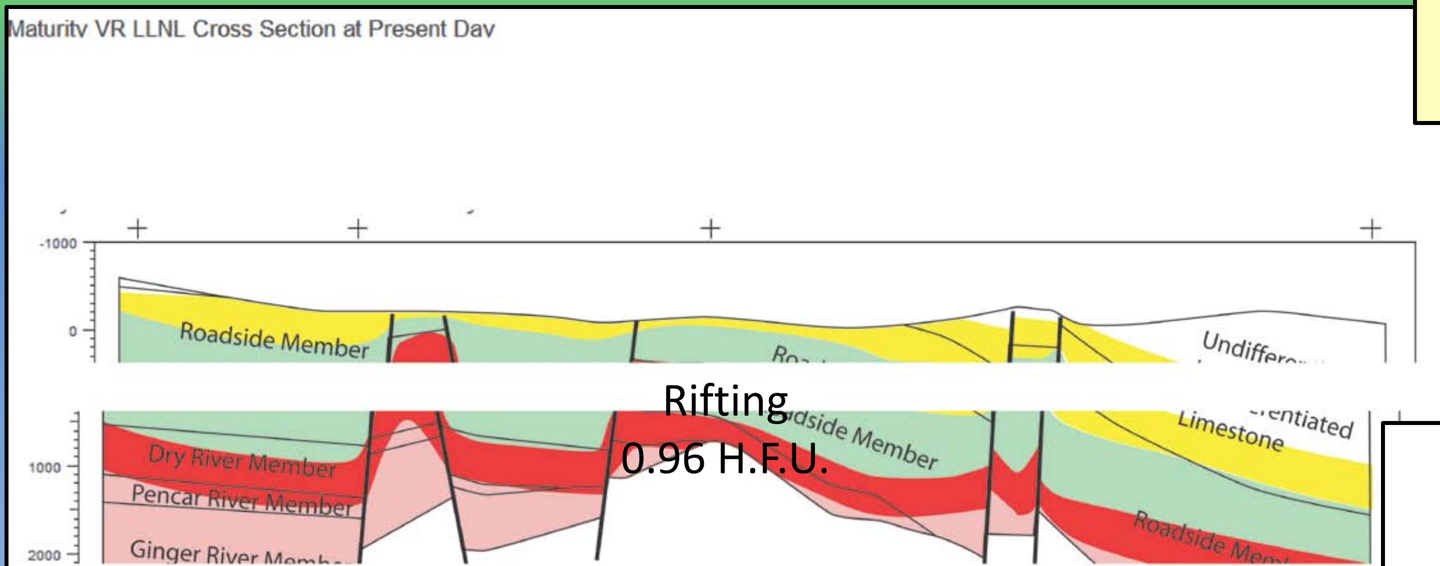
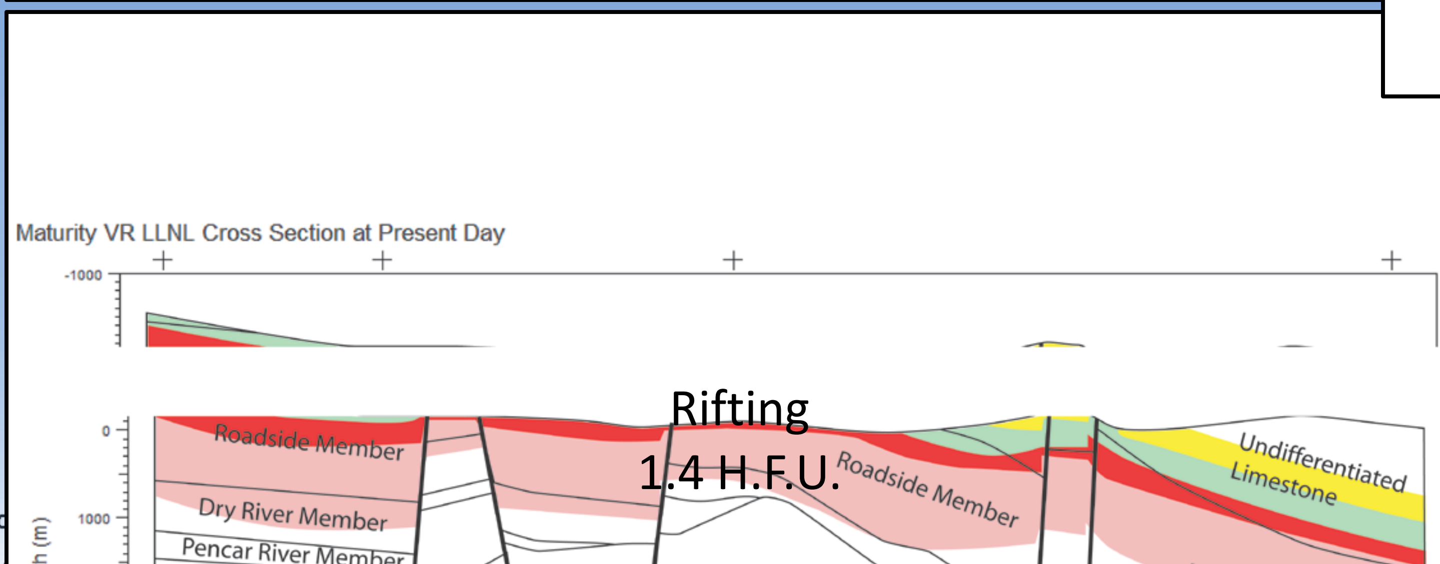
Maturity Analysis (E-W 2)





Rifting
0.96 H.F.U.



Rifting
1.4 H.F.U.

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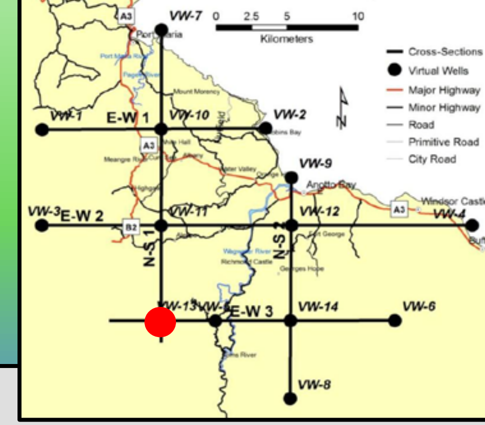
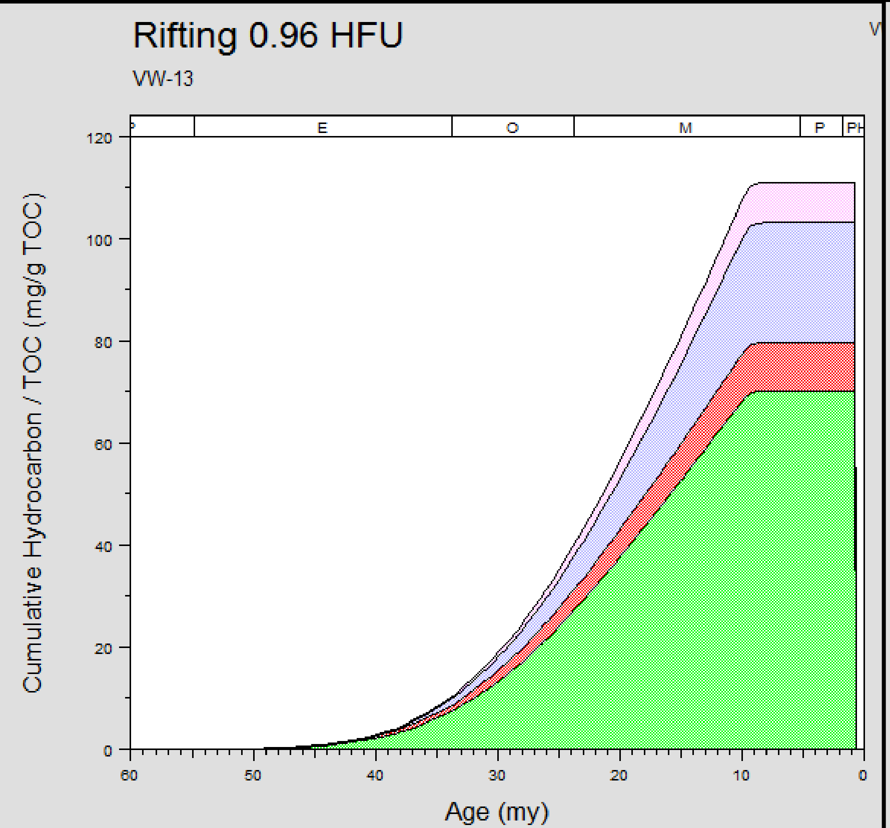
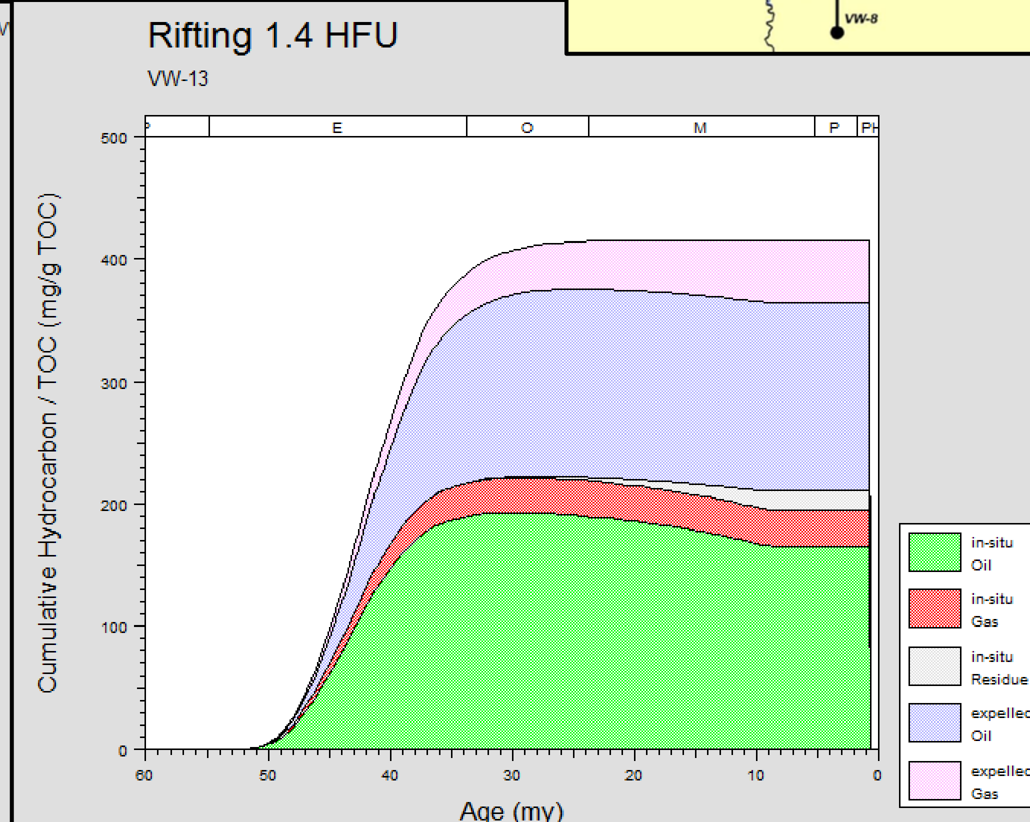
Migration: Hydrocarbon Expulsion







Hypothetical timing and quantity of in situ production and expulsion of hydrocarbons for Virtual Well #13.

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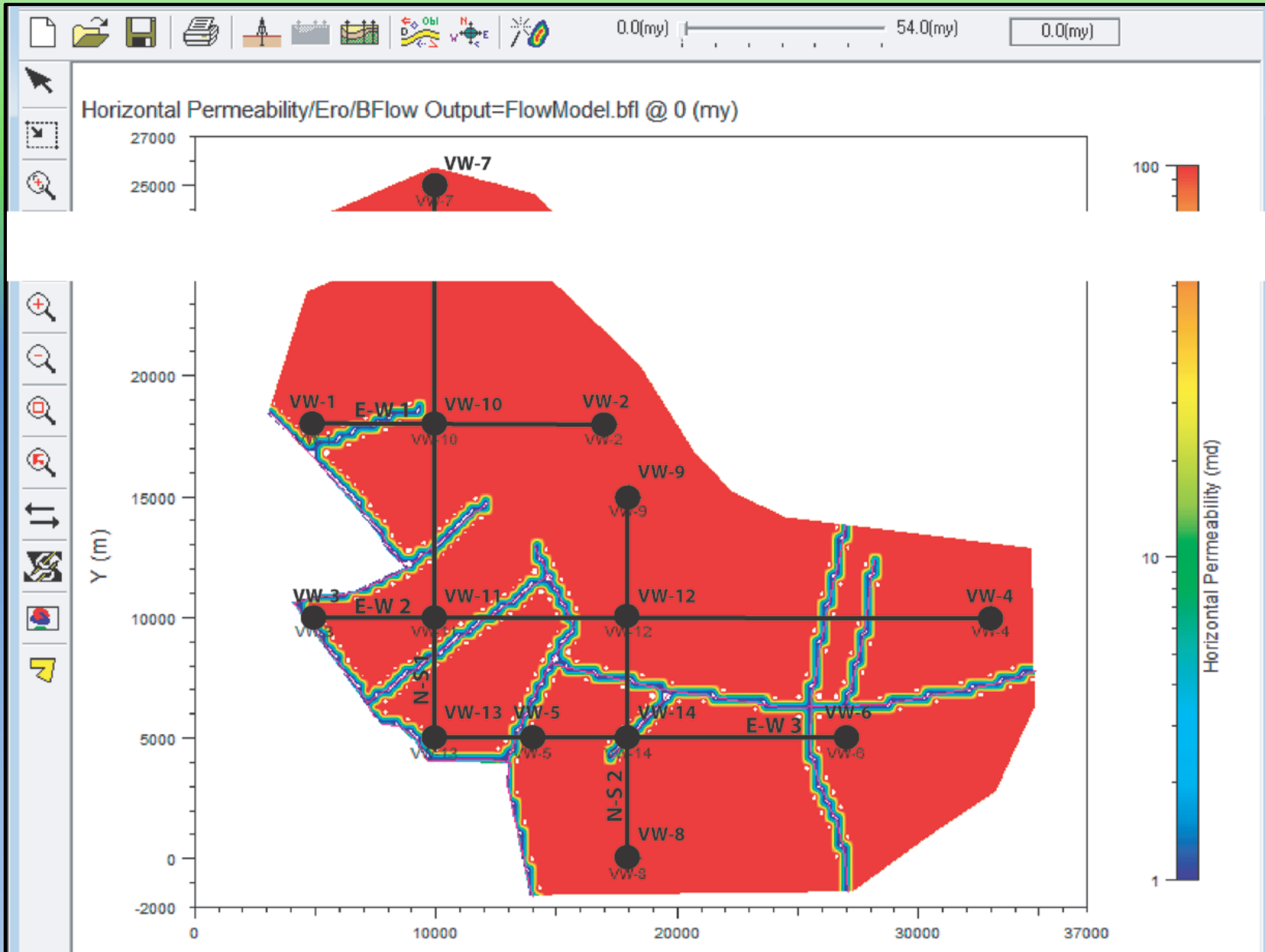
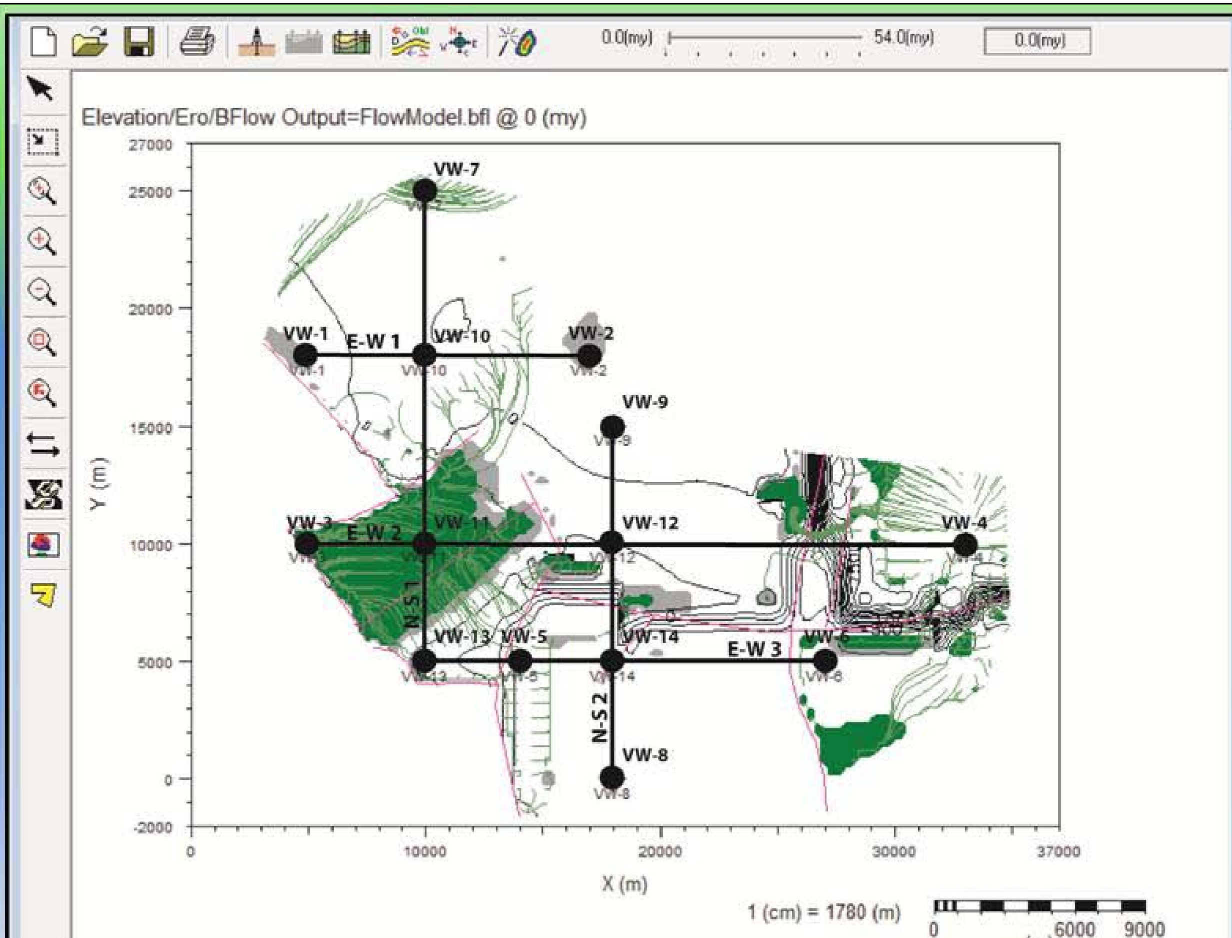
Primary Migration

- Because fault permeabilities are unknown, two end members of the model were created to model hydrocarbon flow in the basin:
  - Case I - Flow with impermeable fault barriers (1 md)
  - Case II - Flow with highly permeable fault barriers (1,000 md)



Primary Migration (Case I): Horizontal Permeability, Present-day



Primary Migration (Case I): Theoretical Hydrocarbon Flow and Accumulation Pathways , Present-day

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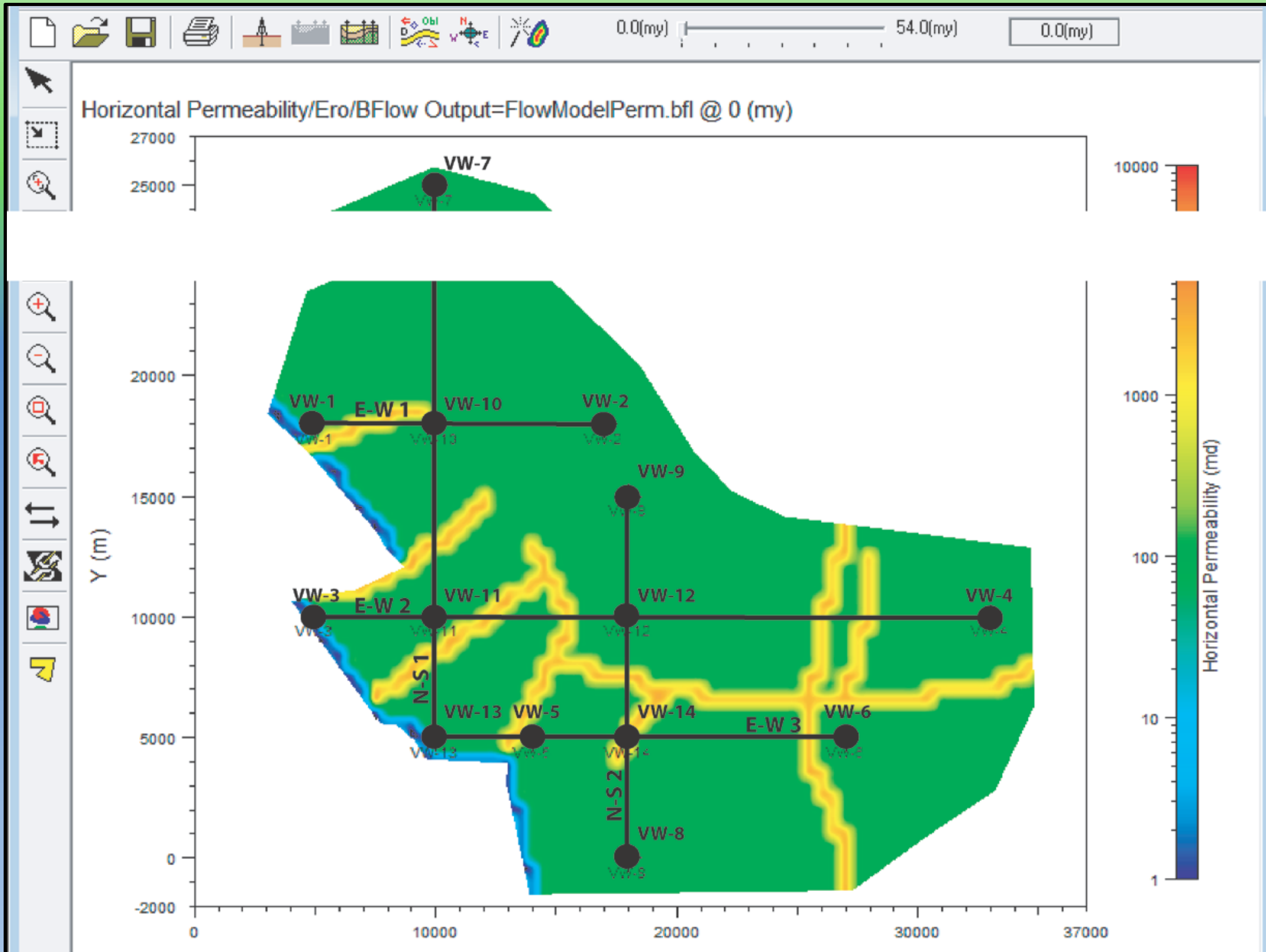
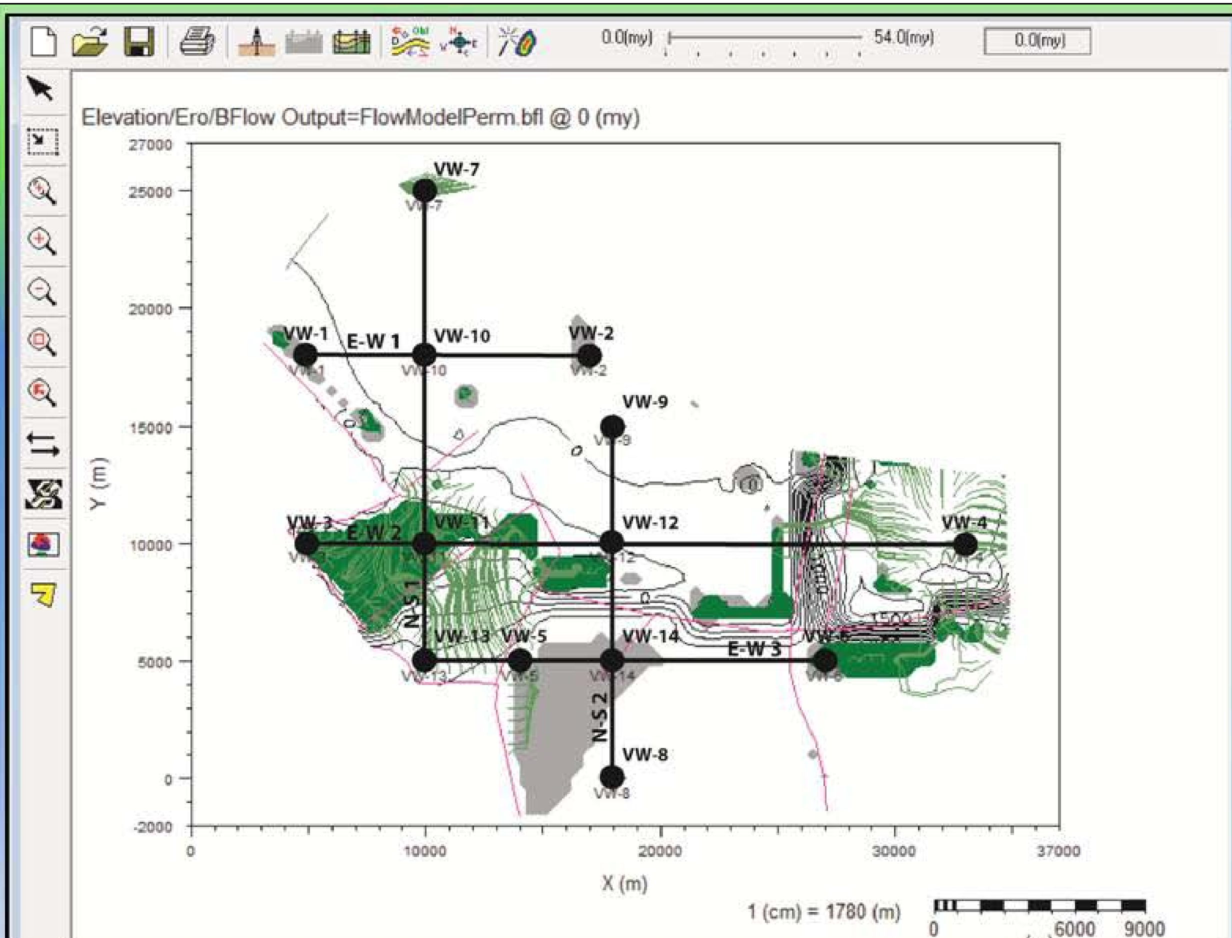
Notes by Presenter: Hydrocarbons would accumulate in traps along fault boundaries as well as on four-way closures on structural highs.



Primary Migration (Case II): Horizontal Permeability, Present-day



Primary Migration (Case II): Theoretical Hydrocarbon Flow and Accumulation Pathways , Present-day

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Notes by Presenter: Because hydrocarbons can freely move across faults, there are fewer traps and accumulations than the impermeable model (Case I).

Summary and Conclusions

Within the stipulated constraints and assumptions made, one may conclude the following

- Rifting initiated as a result of dextral shear during the Early Paleocene as the hanging wall of the Wagwater Fault went down toward the northeast.
- Movement on the fault continued through the Early Eocene. The Yallahs-Silver Hill Fault activated on the east side of the Wagwater Trough during the Eocene as its hanging wall went down to the west.
- The tectonic subsidence analyses reveal one fault mechanical episode (66-51 Ma / 1.66 β) and one uplift or shortening episode (10-0 Ma / 0.81 β)

Summary and Conclusions

- In summary, four cases (Rifting 1.4 H.F.U. vs. Rifting 0.96 H.F.U. Heat Flow Cases and Impermeable and Permeable Faults Cases) most likely bound the uncertainty of the basin study.
- Owing to the higher present-day heat flow, the 1.4 H.F.U. case has source rocks which are more mature than the 0.96 H.F.U. case.
- First theoretical in situ oil appeared at:
  - 52 Ma for the rifting 1.4 H.F.U. case
  - 49 Ma for the rifting 0.96 H.F.U. case
- First theoretical migration time was:
  - 50 Ma for rifting 1.4 H.F.U. case
  - 41 Ma for the rifting 0.96 H.F.U. case

Limitations of the models

- Virtual wells were constructed in lieu of seismic correlation, thus 3-D data between was extrapolated.
- Heat Flow values were only bracketed, thus precise temperature history is unknown.
- Organic carbon content is approximated and not measured.
- Organo-facies are approximated and not analyzed.
- Fault permeabilities are unknown and thus bracketed for migration assumptions.
- With the absence of vitrinite reflectance data, maturities were only modeled and not geovalidated.

Recommendations

This model should serve only as a preliminary basin study. In order to create a more accurate model the following are required

- Borehole temperature measurements
- Source rock geochemical measurements
- Fault permeability measurements
- For a perfect world 3-D seismic

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