A Systematic Approach To Geothermal Power Classification

Proposed Geothermal Power Classification System

Geologic Environment		Geologic Feature	Crustal Heat Source	Resource Category	Rock Type
Plate Margin Environment	**Convergent (Compressional)**	Back Arc Basins	Magmatic	Steam Hydromagmatic	Igneous Sedimentary
		Volcanic Arc Complex			
		Continental Volcanism			
		Intrusive Complex			
	Divergent (Extensional)	Volcanic Spreading Center	Magmatic	Steam Hydromagmatic	Igneous Sedimentary
		Rift Systems			
	Transform (Strike-Slip)	Pull-Apart Basins	Magmatic	Steam Hydromagmatic	Igneous Sedimentary
		Transtensional Faults			
		Volcanic / Magmatic Centers			
Intraplate Environment		Mantle Plumes (Hot Spots)	Magmatic	Steam Hydromagmatic	Igneous Sedimentary
		Extensional Terrain			
		Cratonic Basins	Thermal Gradient	Stranded	Sedimentary
				Geopressured	
		Passive Margin Basins		Hydrostatic	
				Co-Produced	
		Basement Complex	Radiogenic	Hot Dry Rock	Igneous

Richard J. Erdlac, Jr.
Peter Gross
Edward McDonald

Energy America Geothermal, LLC

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Energy America Inc.

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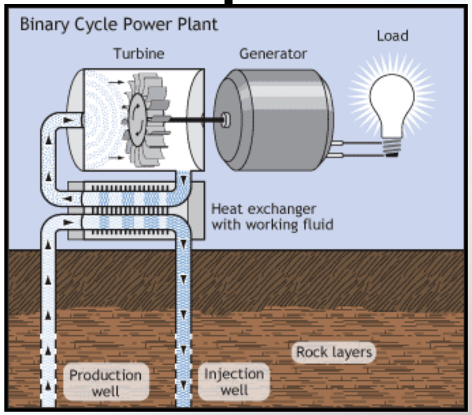
Trading & Supply

POWER



GEOEXCHANGE

Presentation Overview

- **Multiple Classifications – Geology Example**
- **Historic Geothermal Classifications**
- **New Classification Rationale**
- **Proposed Power Classification**
  - Five Categories
- **Geologic Environment / Feature**
  - Plate Margin Environment – 9 Features
  - Intraplate Environment – 5 Features
- **Conclusions**

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Geology Classification Examples

Classification = systematic arrangement in groups or categories according to established criteria.

Multiple classification systems can be developed to describe the same object or process.

FOLK CLASSIFICATION SYSTEM				
	Allochemical Rocks		Orthochemical Rocks	Reef Rock
Allochemical Clast Type	Class 1 - Sparry Calcite Cement	Class 2 - Micrite Matrix	Class 3	Class 4
Intraclasts	Intrasparite	Intramicrite	Micrite	Biolithite
Oolites	Oosparite	Oomicrite		
Fossils	Biosparite	Biomicrite		
Pellets	Pelsparite	Pelmicrite		
		Sparry Calcite Cement		Lime Mud Matrix

Particles
Micrite
Cement

Microscope thin section description.

Limestone Classifications

Hand specimen and in outcrop.

DUNHAM DEPOSITIONAL TEXTURE CLASSIFICATION				
Original components not bound together during deposition.				Original components bound together during deposition, as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.
Contains Mud (particles of clay and fine silt size)			Lacks Mud	
Mud-Supported		Grain-Supported		
Less than 10% grains.	More than 10% grains.			
Mudstone	**Wackestone**	**Packstone**	**Grainstone**	**Boundstone**

Texture & Grain Size

Geology Classification Examples

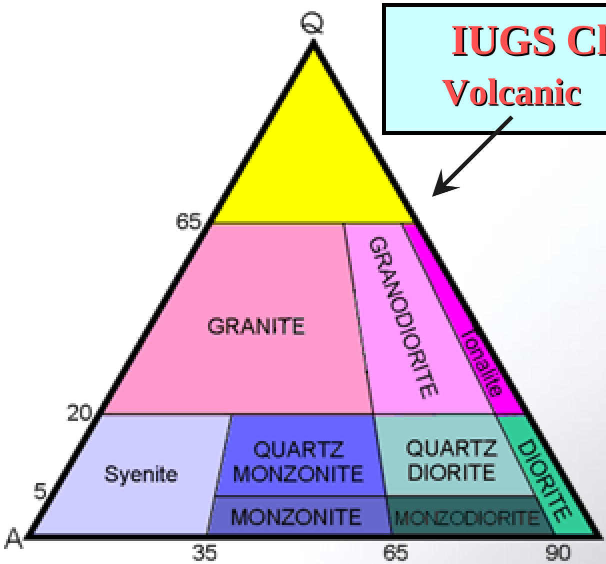
Color / **Texture**

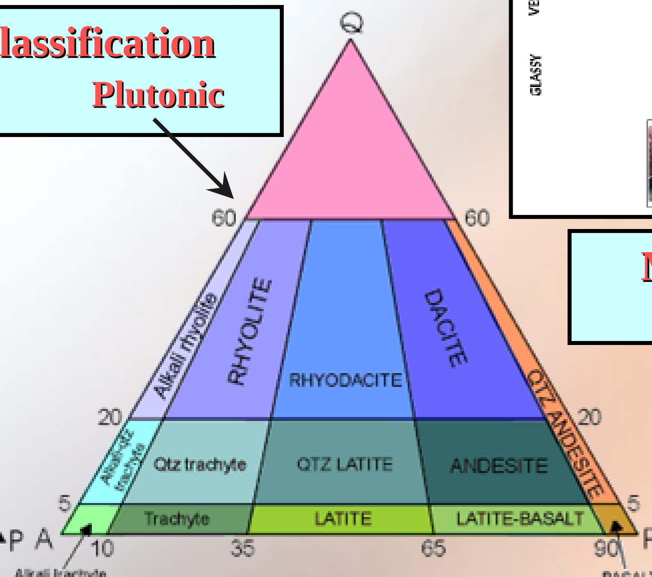
	Felsic (light color)	Intermediate	Mafic (dark color)	Ultramafic
Coarse	Granite	Diorite	Gabbro	Peridotite
Fine	Rhyolite	Andesite	Basalt	
Vesi-cular	Pumice		Scoria	
Glassy	Obsidian			
	Minerals Present			
	QUARTZ K-FELDSPAR NA-PLAG	NA-CA PLAG AMPHIBOLE	CA PLAG PYROXENE	PYROXENE OLIVINE

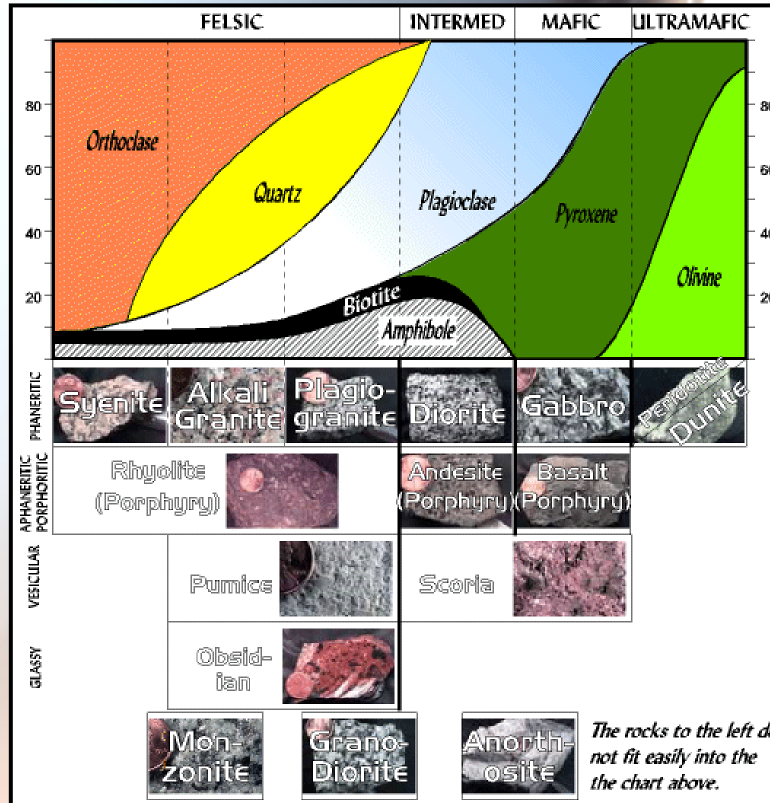
Igneous Rock Field Classification

IUGS Classification

Volcanic **Plutonic**







Modal Igneous Classification

(Mineral Abundance)

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Historic Geothermal Classifications

Comparison of USGS Geothermal Resource Types			
Circular 726 - 1975		Circular 790 - 1979	
Conductive transport of heat		Conduction-dominated thermal regime	
		Geopressured-geothermal resources (thermal & chemical)	
Igneous-related systems		Igneous-related systems	
	Energy directly from molten systems		
	Hot but cooling systems		Hot but cooling systems
Hydrothermal convection system		Hydrothermal convection system (T ≥ 90ºC)	
		Low-temperature systems (T ≤ 90ºC)	

Comparison of NREL & MIT Geothermal Resource Categories		
NREL - 2006	MIT - 2007	
Deep geothermal	Conduction-dominated EGS	
		Sedimentary rock formations
		Crystalline basement rock formations
		Supercritical volcanic EGS (USGS 790)
Shallow hydrothermal (identified) > 90ºC	Hydrothermal (USGS 726, 790)	
Shallow hydrothermal (unidentified) > 150ºC		
Co-produced & Geopressured	Coproduced fluids (McKenna, et al., 2005)	
	Geopressured systems	

CLASSIFICATION:
- Low temp. (< 90ºC or 194º F)
- Moderate temp (90º-150º C or 194º- 302º F)
- High temp. (> 150ºC or 302º F)

Geo-Heat Center
Oregon Institute of Technology

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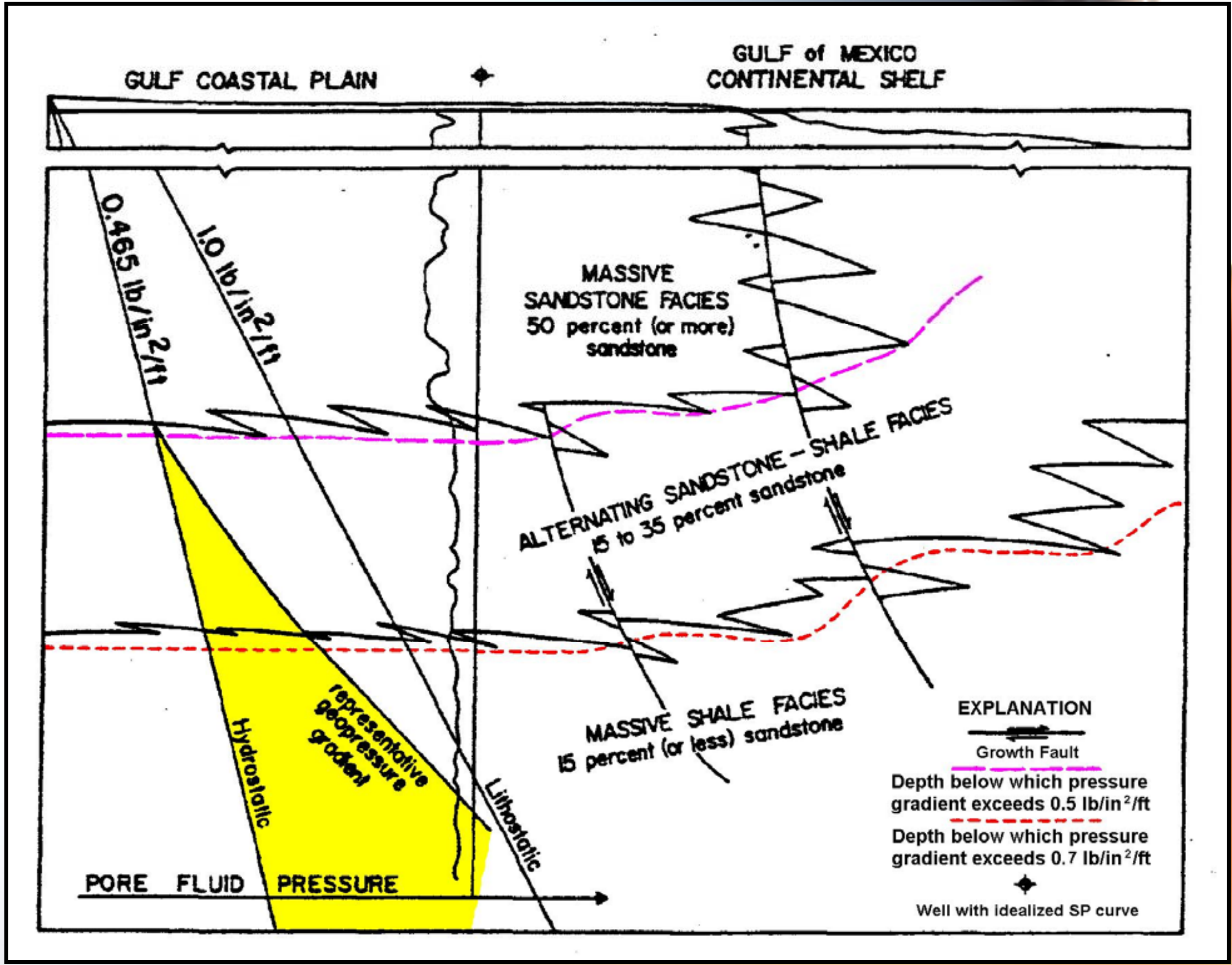
Rationale For New Classification - One

Company Discussion

Geothermal from sedimentary basins:

1 – Stranded = water behind pipe
- **A) lithostatic = geopressured**
- **B) hydrostatic**

2 – Co-Produced = natural flow or pumped along with oil / gas



Rationale For New Classification – Two

Comparison of USGS Geothermal Resource Types		
Circular 726 - 1975		**Circular 790 - 1979**
Conductive transport of heat (Heat Transfer)		Conduction-dominated thermal regime (← Heat Transfer)
		Geopressured-geothermal resources (thermal & chemical) (← Resource Category)
Igneous-related systems (Geologic Environment)		Igneous-related systems (Geologic Environment)
	Energy directly from molten systems	
	Hot but cooling systems	Hot but cooling systems
Hydrothermal convection system		Hydrothermal convection system (T ≥ 90°C) (← Heat Transfer & Resource Category)
		Low-temperature systems (T ≤ 90°C) (← Heat Transfer & Resource Category)

Heat Transfer & Resource Category (→ Hydrothermal convection system)

Terminology Mixing

Comparison of NREL & MIT Geothermal Resource Categories		
NREL - 2006	**MIT - 2007**	
Deep geothermal (← Geologic Environment)	Conduction-dominated EGS (Heat Transfer)	
		Sedimentary rock formations (← Geologic Environment)
		Crystalline basement rock formations (← Geologic Environment)
		Supercritical volcanic EGS (USGS 790) (← Geologic Environment)
Shallow hydrothermal (identified) > 90°C (← Resource Category)	Hydrothermal (USGS 726, 790) (Resource Category)	
Shallow hydrothermal (unidentified) > 150°C (← Resource Category)		
Co-produced & Geopressured (← Resource Category)	Coproduced fluids (McKenna, et al., 2005) (← Resource Category)	
	Geopressured systems (← Resource Category)	

Proposed Power Classification

Five Distinct Categories

1 – Geologic Environment
  A) Plate Margin
  B) Intraplate
2 – Geologic Feature
3 – Crustal Heat Source
4 – Resource Category
5 – Rock Type

Proposed Geothermal Power Classification System

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		Passive Margin Basins		Hydrostatic	
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		Basement Complex	Radiogenic	Hot Dry Rock	Igneous

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Power Classification – Plate Margin

Proposed Geothermal Power Classification System

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Plate Margin Environment	Convergent (Compressional)	Back Arc Basins	Magmatic	Steam Hydromagmatic	Igneous Sedimentary
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		Volcanic / Magmatic Centers			

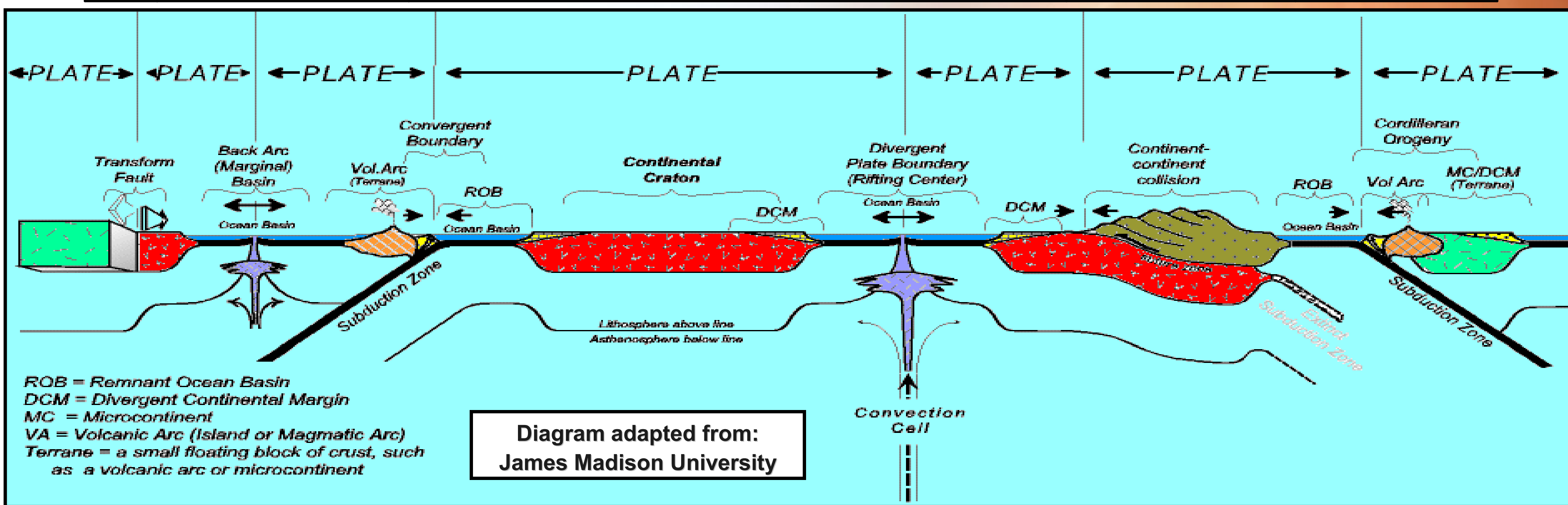
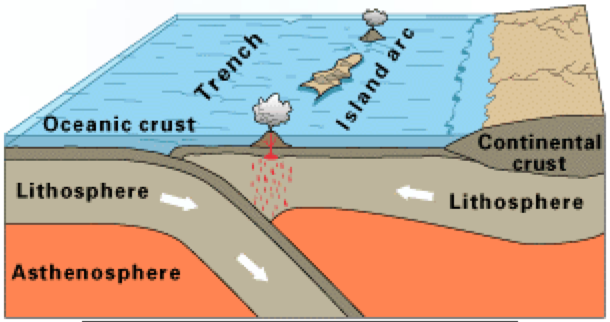


Plate Margin – Convergent (Compression)

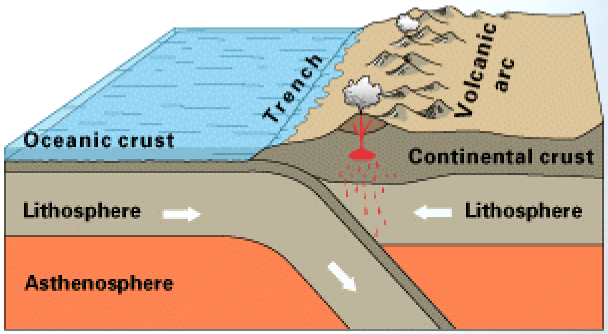
Images from: University of Michigan



Oceanic - Oceanic

Marianas; Japan

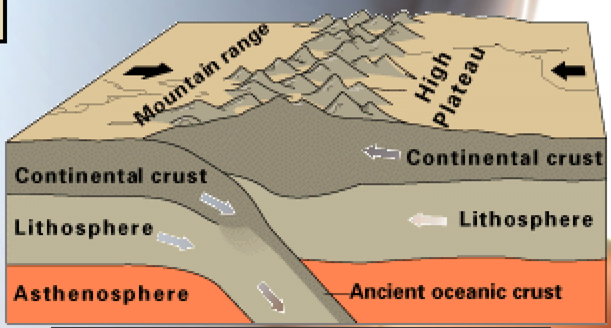
Basaltic
Andesitic



Oceanic - Continental

Andes; Cascades

Andesitic
Dacite
Rhyolite



Continent - Continent

Himalayas

Andesitic
Dacite
Rhyolite

Rock type data from:
San Diego State University
&
"Volcanology and Geothermal Energy"

Summary Table

Magma Type	Solidified Rock	Chemical Composition	Temperature	Viscosity	Gas Content
Basaltic	Basalt	45-55 SiO_2 %, high in Fe, Mg, Ca, low in K, Na	1000 - 1200 °C	Low	Low
Andesitic	Andesite	55-65 SiO_2 %, intermediate in Fe, Mg, Ca, Na, K	800 - 1000 °C	Intermediate	Intermediate
Rhyolitic	Rhyolite	65-75 SiO_2 %, low in Fe, Mg, Ca, high in K, Na	650 - 800 °C	High	High

Table from: Tulane University

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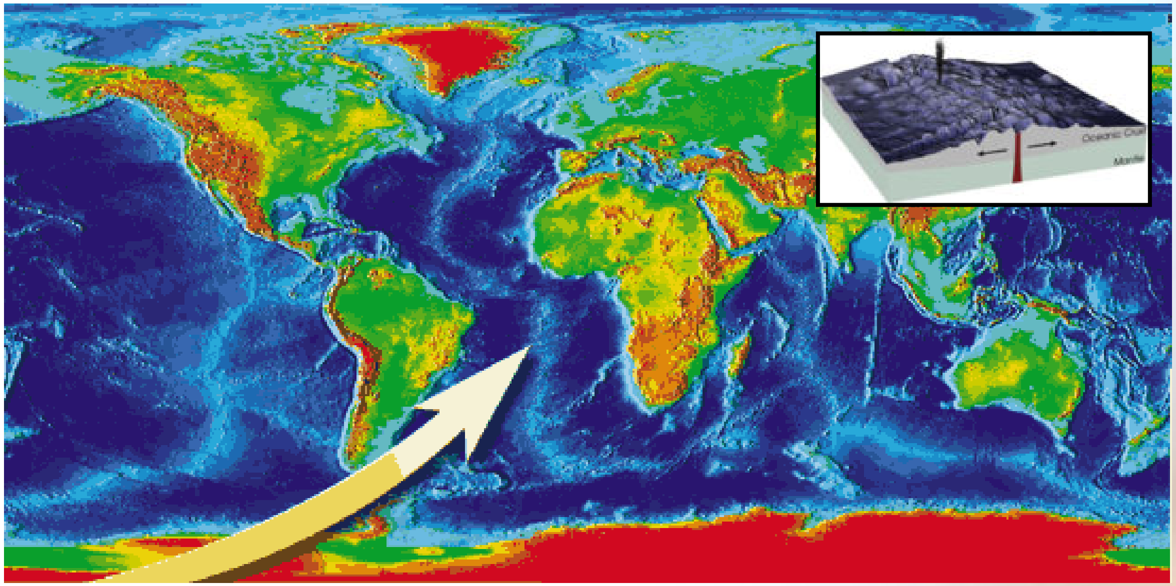
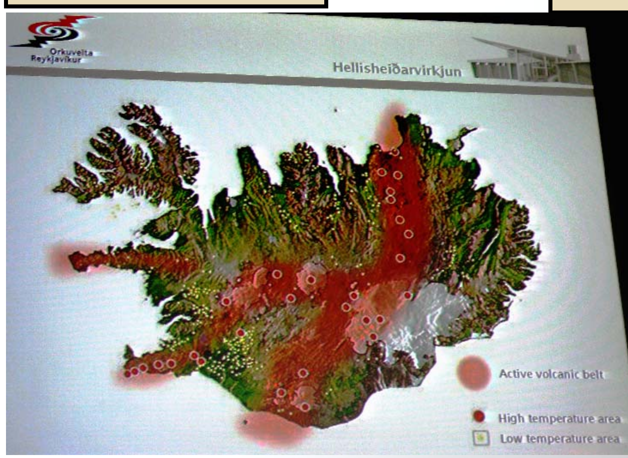
Plate Margin – Divergent (Extension)

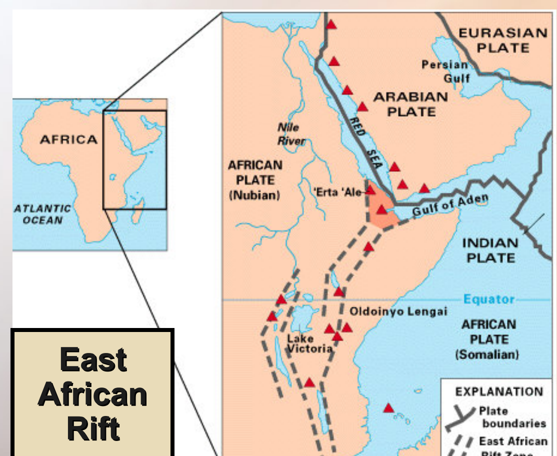
Volcanic Spreading Center



Mid-Ocean Ridge

Image from: University of Delaware





East African Rift

Rift Systems

New Mexico? Texas?

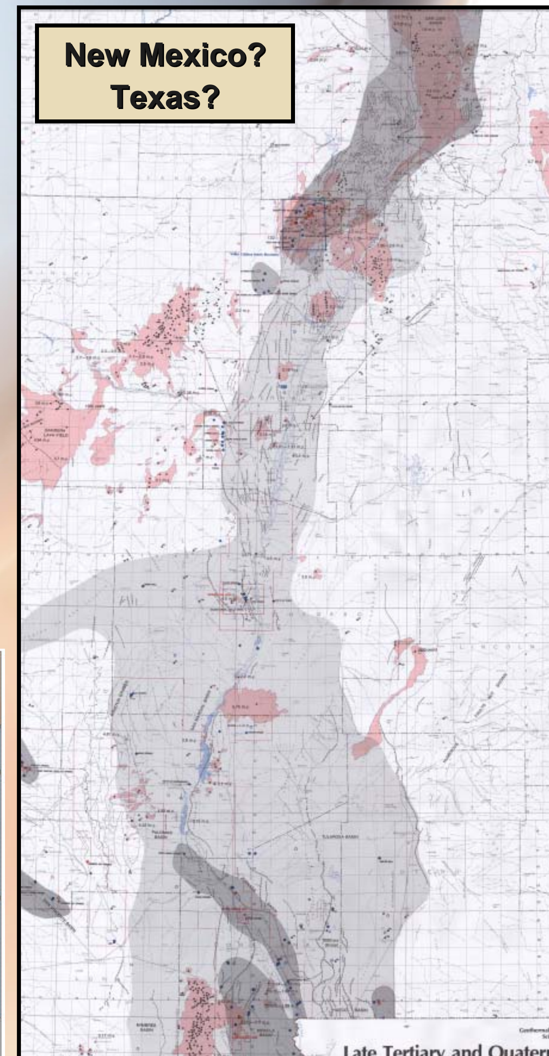


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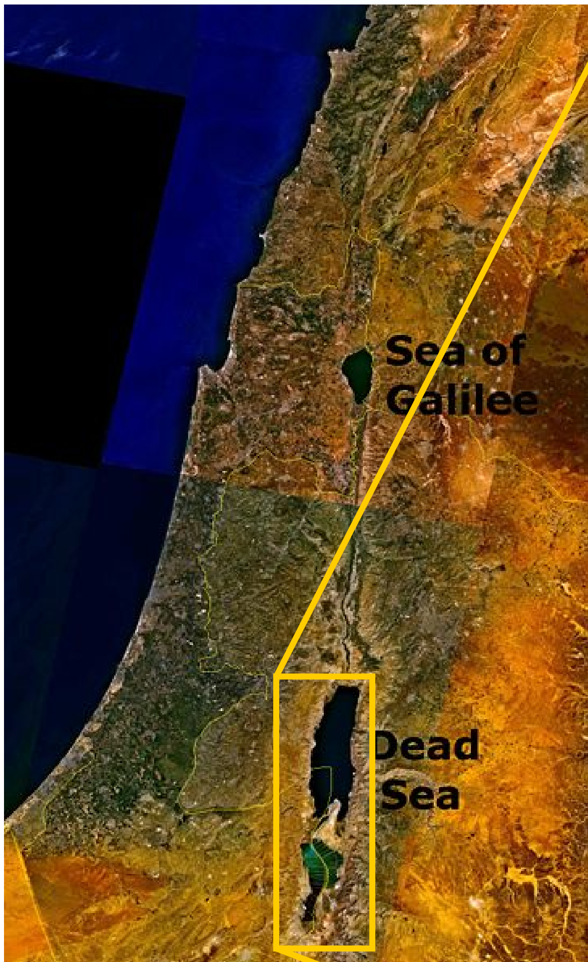
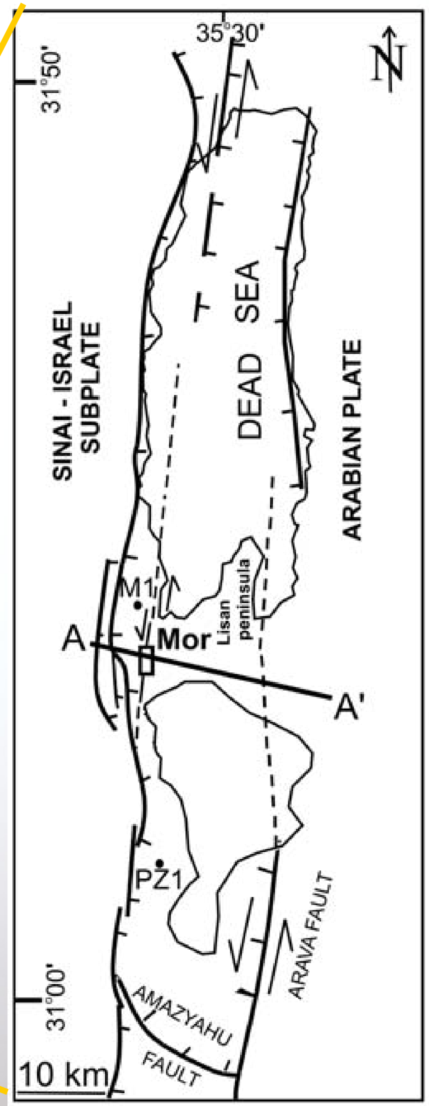
Plate Margin – Transform (Strike-Slip)

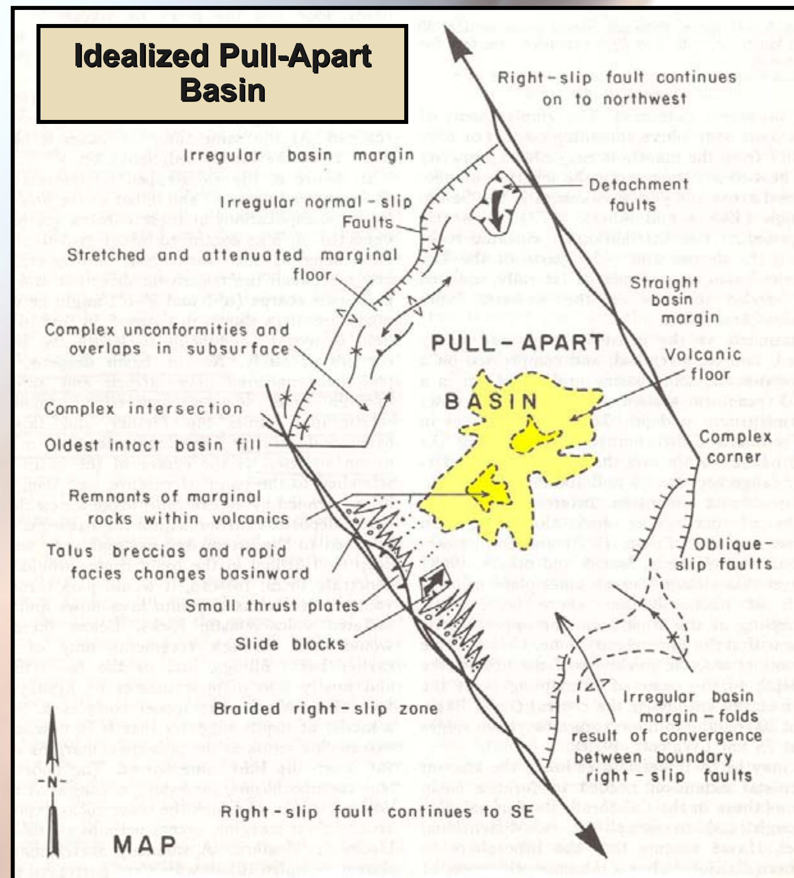
Pull – Apart Basin

Bartov & Sagy, 2004, Geol. Mag.
Hebrew University of Jerusalem



Transform



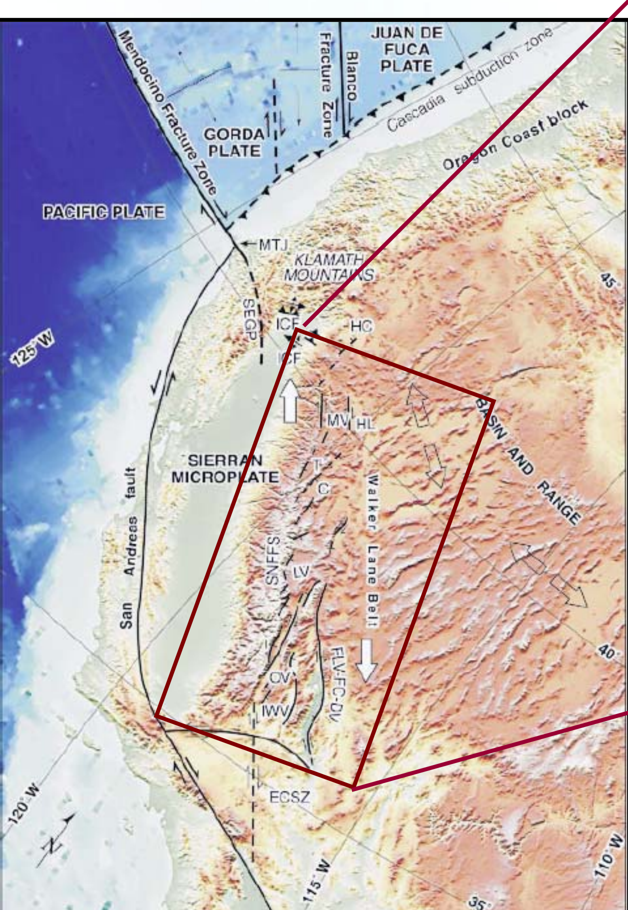


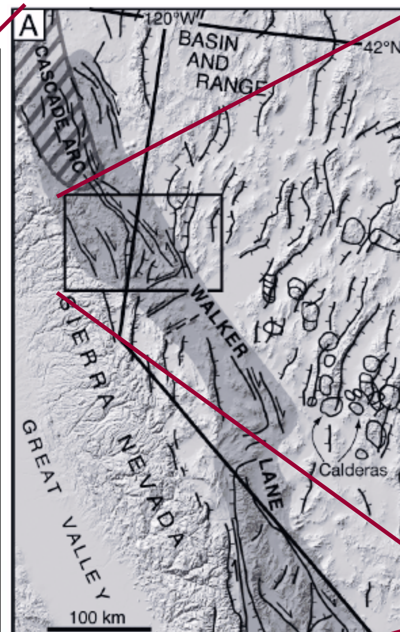
Crowell, 1984, AAPG Reprint Series No. 28

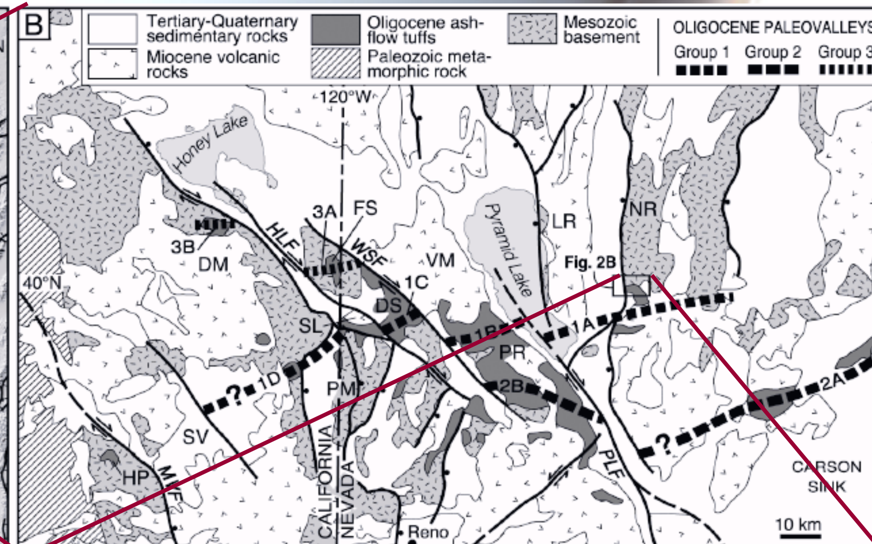
Plate Margin – Transform (Strike-Slip)

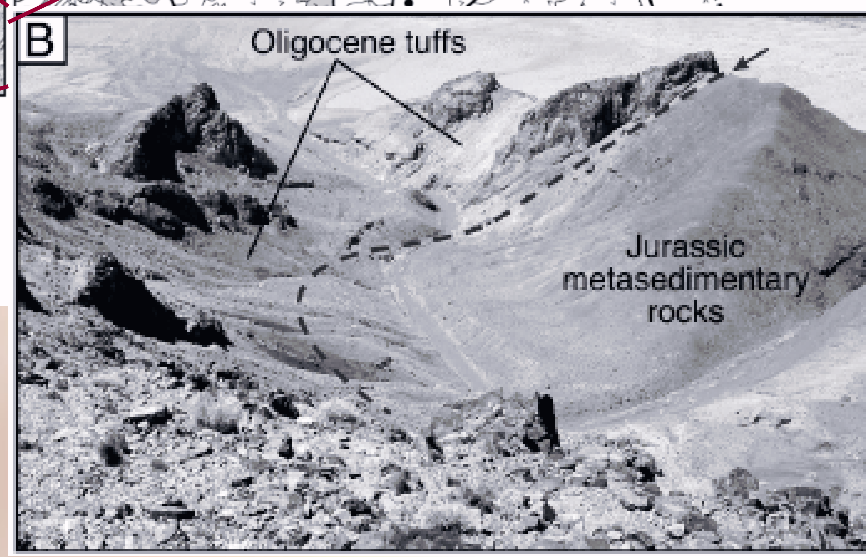
Transtension / Volcanic

Faulds, Henry, & Hinz, 2005, GSA









Unruh, Humphrey, & Barron, 2003, GSA

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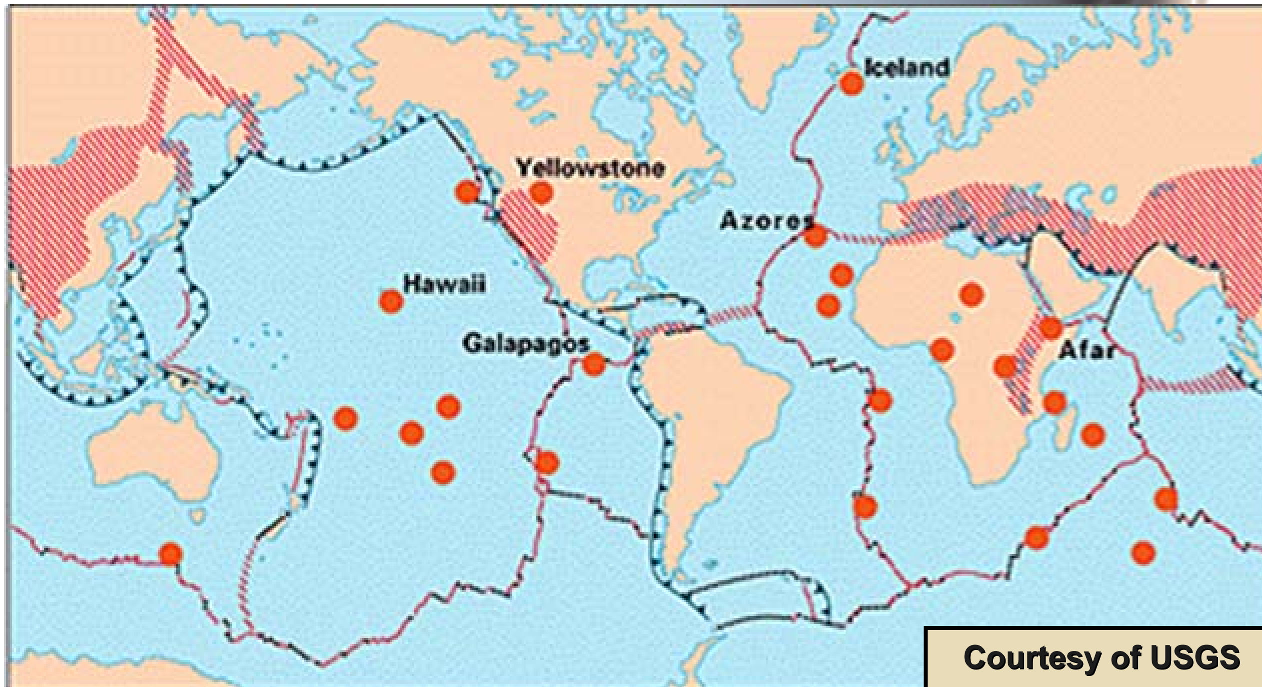
Power Classification – Intraplate Environment

Proposed Geothermal Power Classification System				
Geologic Environment	**Geologic Feature**	**Crustal Heat Source**	**Resource Category**	**Rock Type**
Intraplate Environment	Mantle Plumes (Hot Spots)	Magmatic	Steam Hydromagmatic	Igneous Sedimentary
	Extensional Terrain			
	Cratonic Basins	Thermal Gradient	Stranded	Sedimentary
			Geopressured	
	Passive Margin Basins		Hydrostqatic	
			Co-Produced	
	Basement Complex	Radiogenic	Hot Dry Rock	Igneous

Intraplate – Mantle Plumes (Hot Spots)

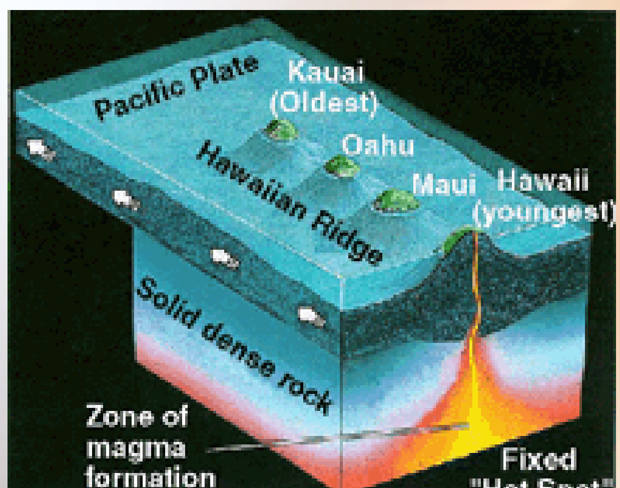
EXPLANATION

- Divergent plate boundaries— Where new crust is generated as the plates pull away from each other.
- Convergent plate boundaries— Where crust is consumed in the Earth's interior as one plate dives under another.
- Transform plate boundaries— Where crust is neither produced nor destroyed as plates slide horizontally past each other.
- Plate boundary zones—Broad belts in which deformation is diffuse and boundaries are not well defined.
- Selected prominent hotspots



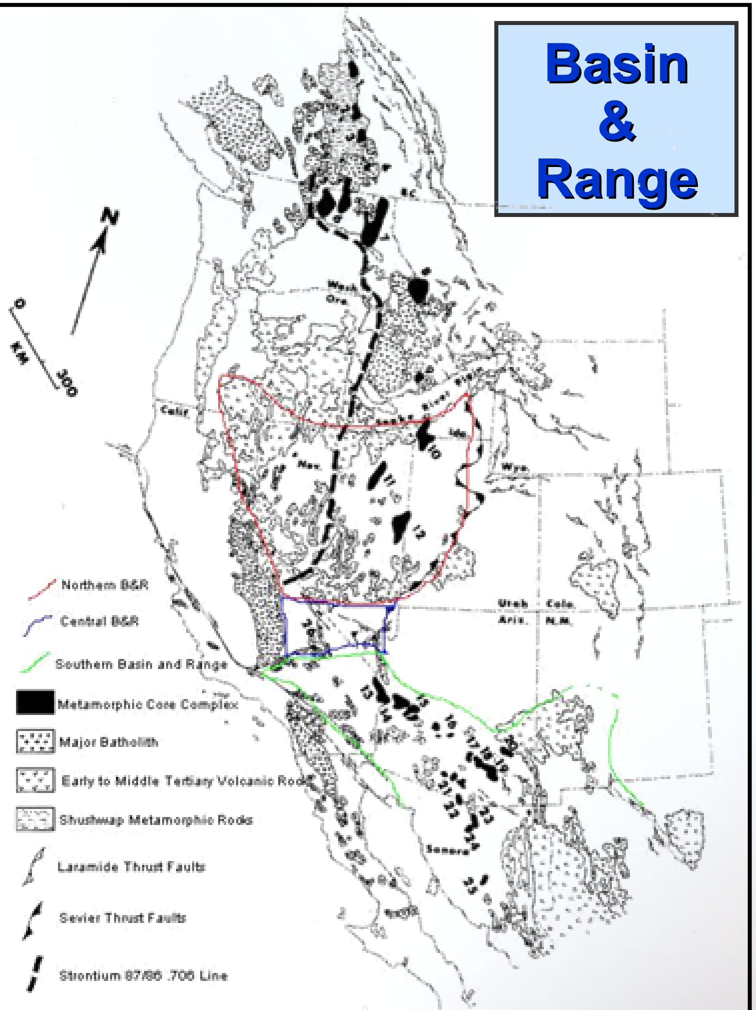
Courtesy of USGS

Basaltic

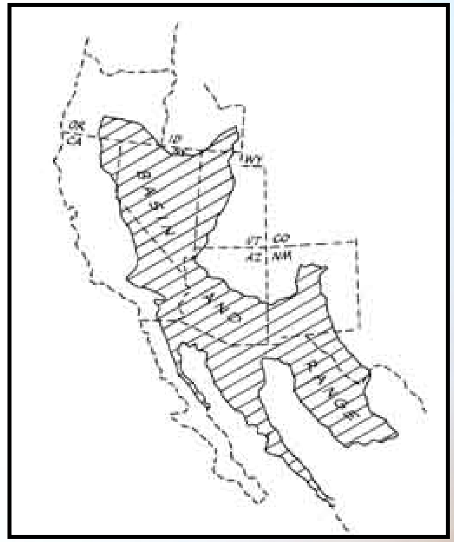


Images from:
San Diego State University
and
Minnesota supercomputing lab.

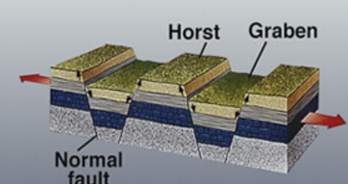
Intraplate – Extensional Terrain



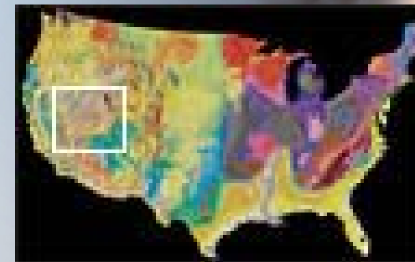
http://www.colorado.edu/GeolSci/Resources/WUSTectonics/CoreComplex/5700.html



Basaltic To Rhyolitic



Courtesy of USGS

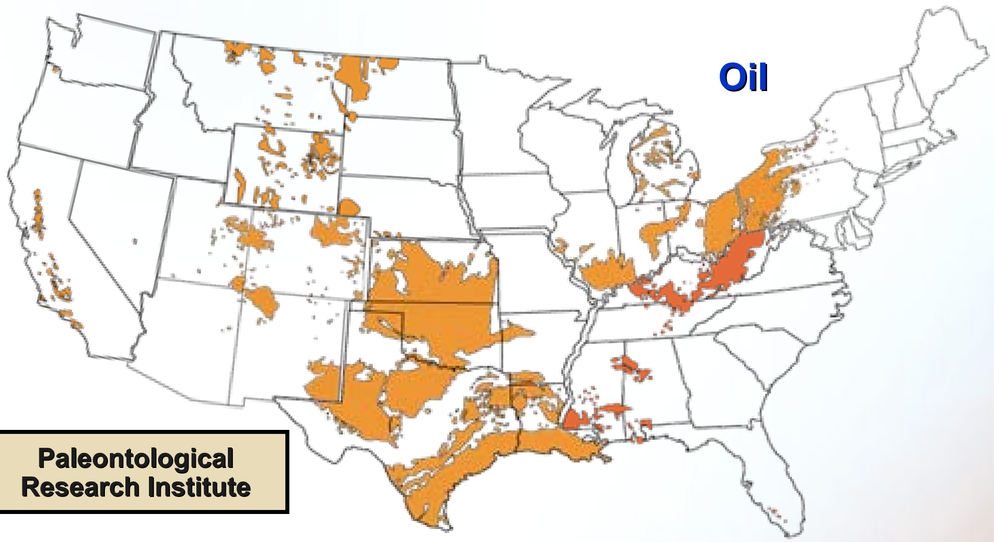


Basin and Range

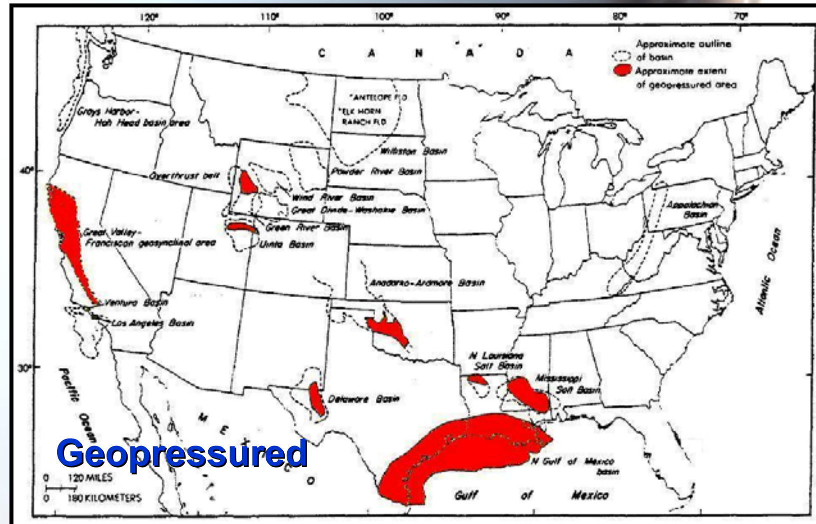
Intraplate – Cratonic Basins

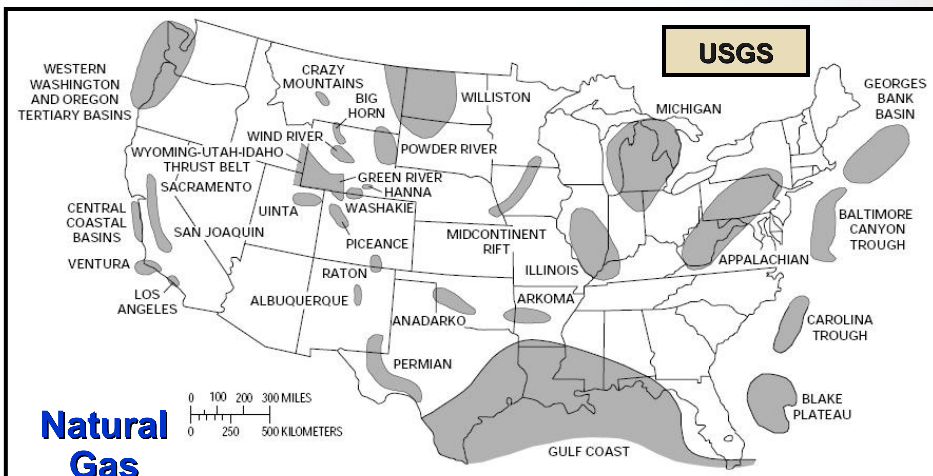
Cratonic Basins

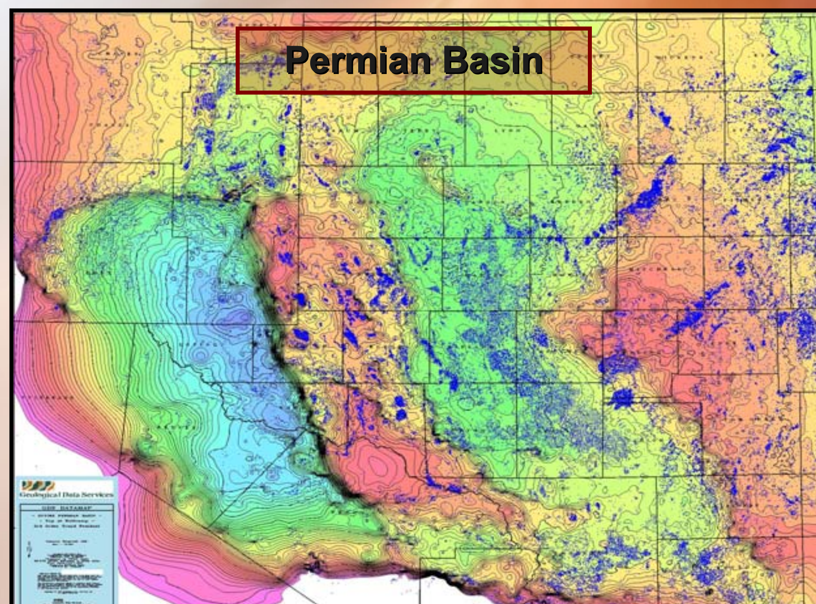
Wallace, 1982



Paleontological Research Institute







Geological Data Services 2004
Wolfcamp Structure Map

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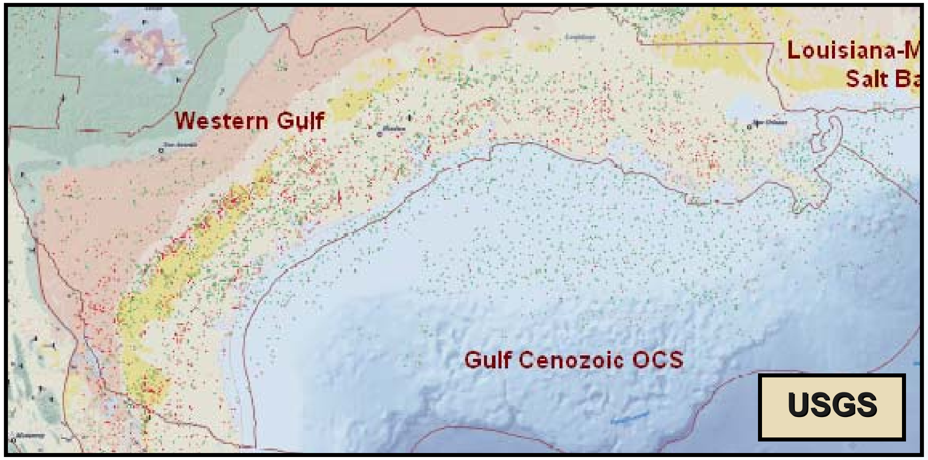
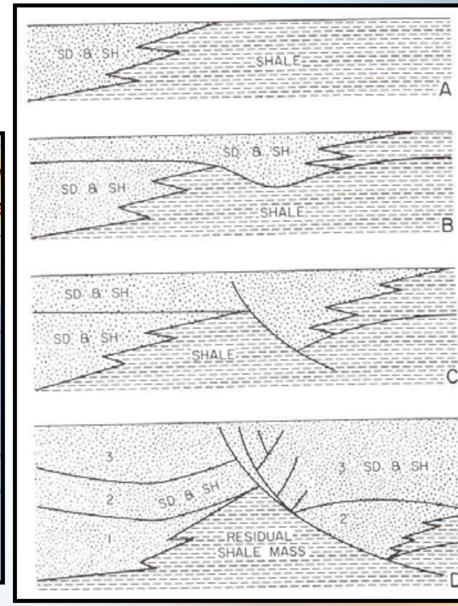
Intraplate – Passive Margin Basins

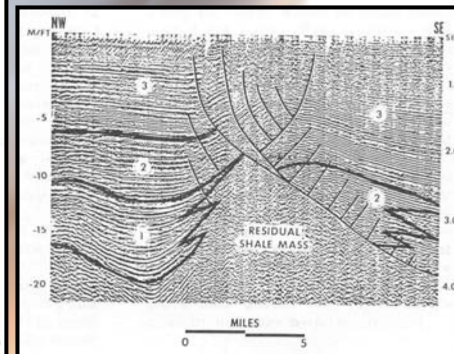
Passive Margin Basins

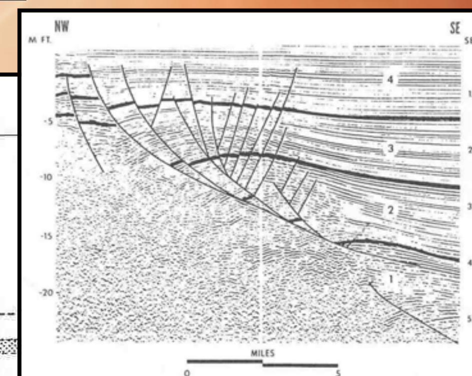


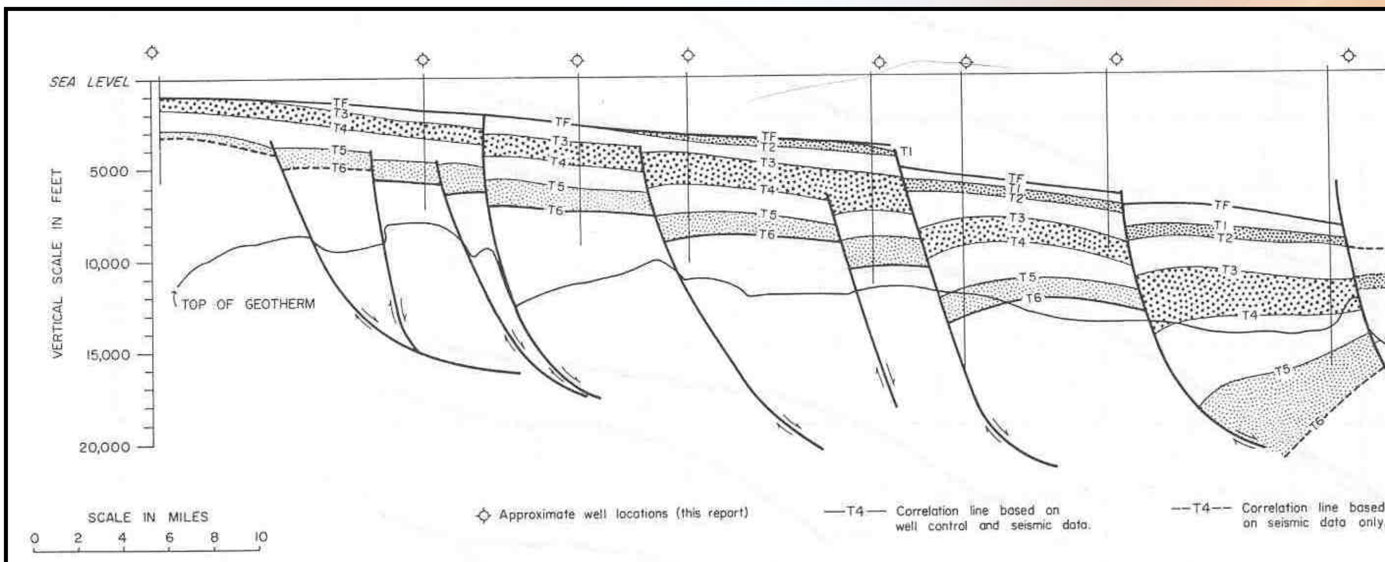


Transgressive – Regressive Sequence

BEG Publications

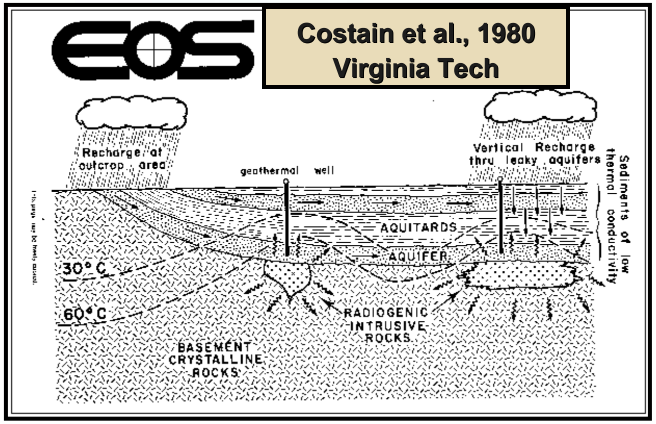




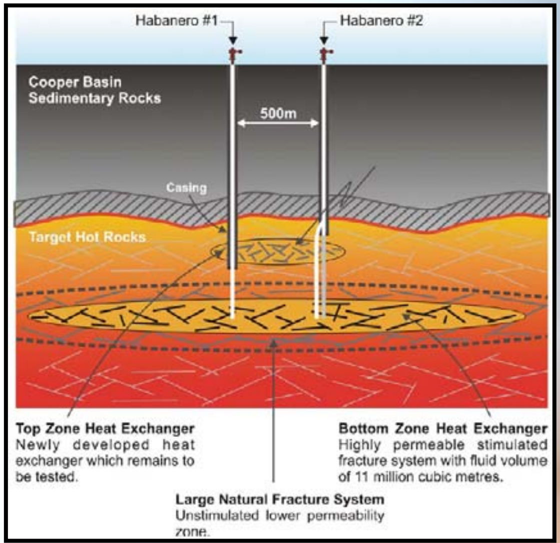


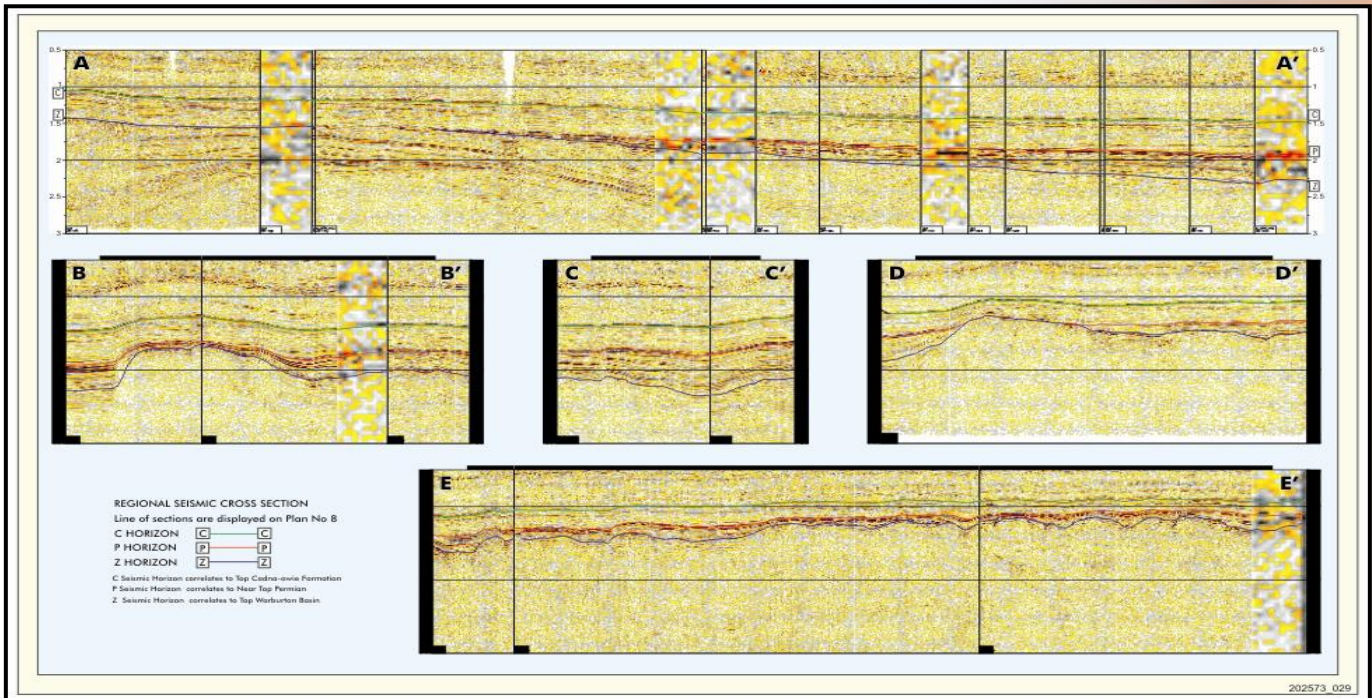
Intraplate – Basement Complex

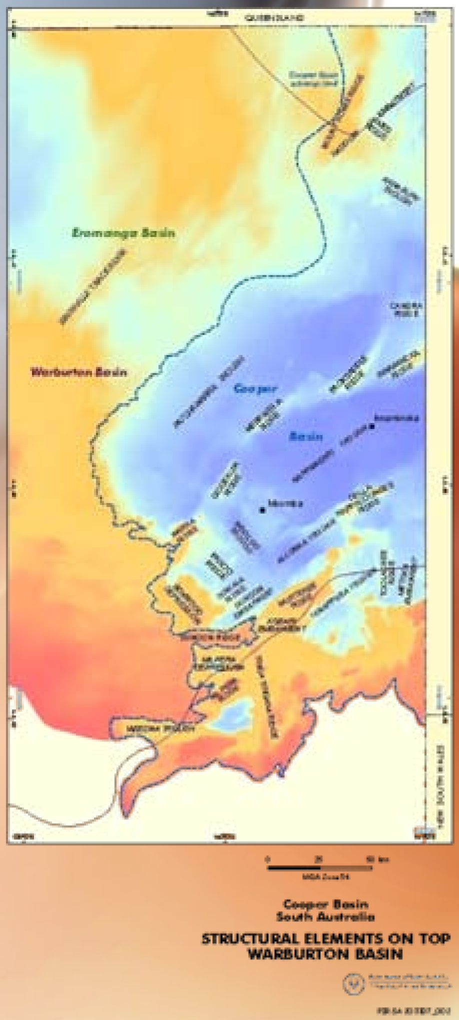
Basement Complex



Costain et al., 1980
Virginia Tech







Cooper Basin
Australia

Conclusions

Previous geothermal classifications have at times attempted to be all encompassing regarding geothermal energy application.

Previous geothermal classifications have often mixed geologic, engineering, & heat transfer terminology.

The proposed geothermal power classification systematically organizes characteristics or criteria into five specific categories.

The proposed classification allows target sites to be categorized by geology and should help in exploration and economic planning of projects.