Constructing, Editing, and Visualizing Integrated Models of Earth Structure

(A view to the future)

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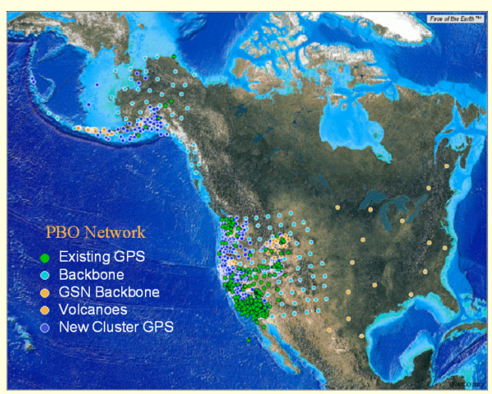
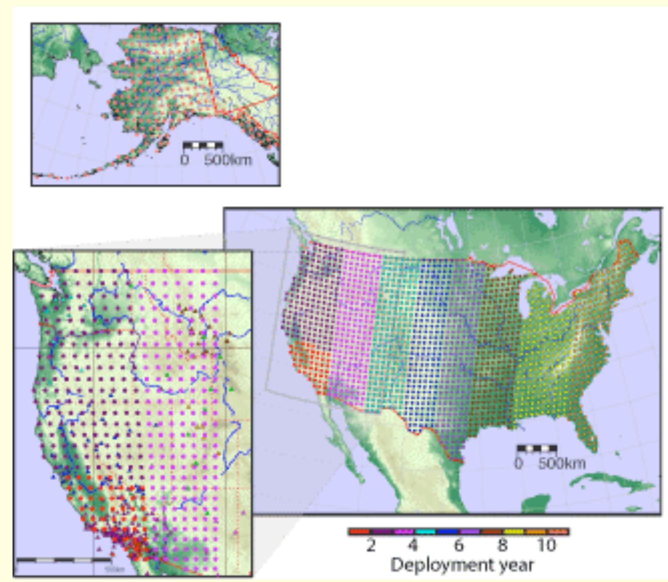
EarthScope - A facility that includes transportable and fixed seismic instrumentation, a network GPS units and strainmeters, and magnetotelluric instrumentation

Integrated analysis to derive 4-D models of the lithosphere is a major science driver in EarthScope



USArray will cover the entire USA

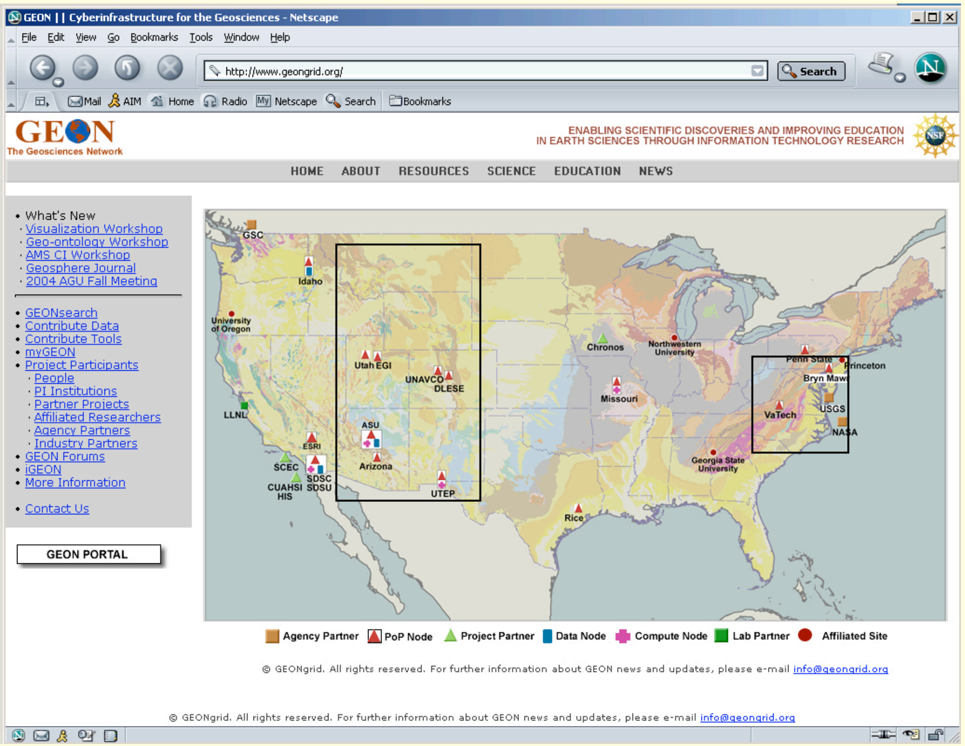


GEON "GEOsciences Network"
NSF Large Scale Information Technology Research (ITR)

Some major goals

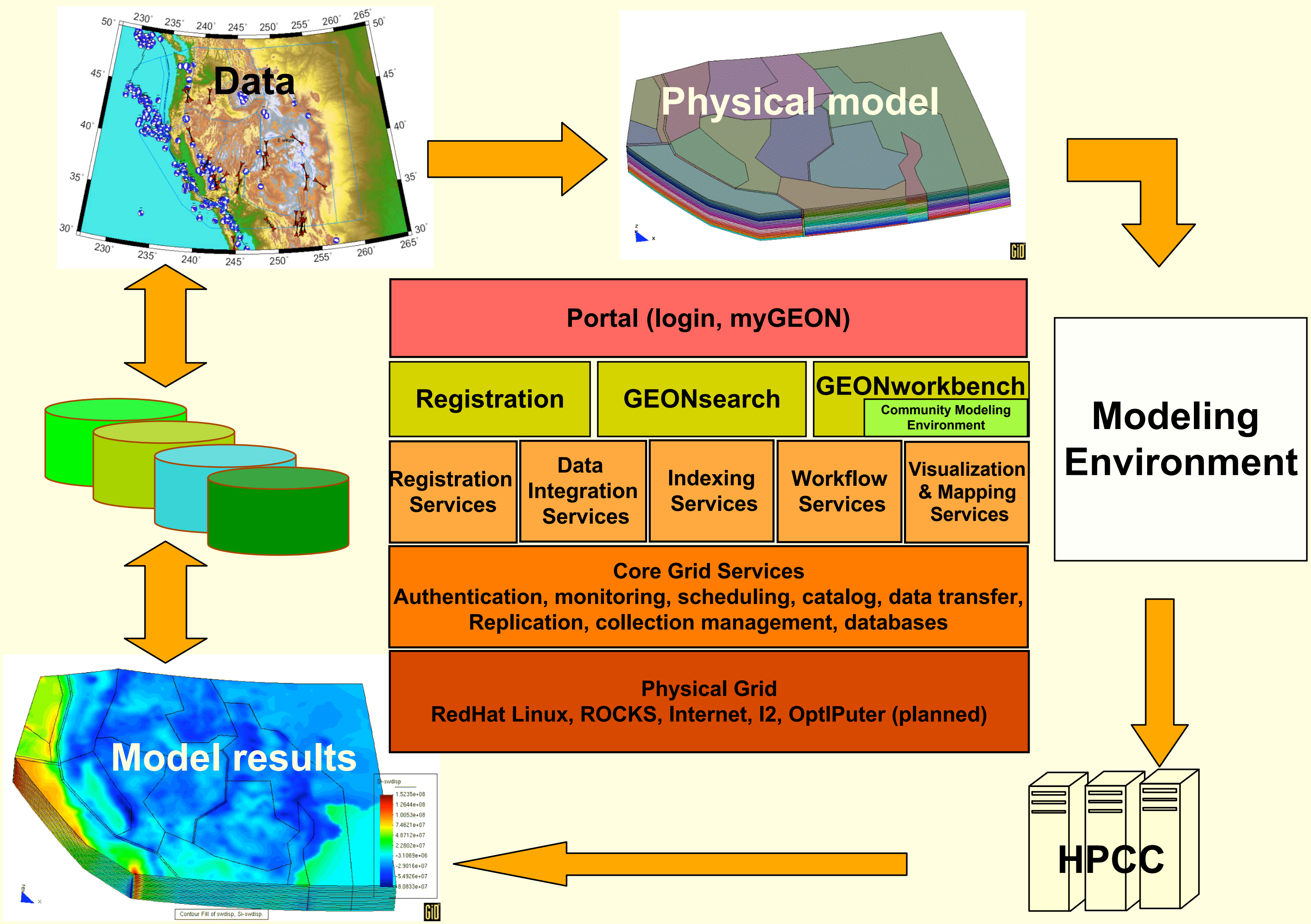
Develop a distributed, services-based system that enables geoscientists to publish, share, improve, <u>integrate</u>, analyze, and visualize their data, <u>ontologies</u>, tools, workflows, applications, and <u>models</u>

Conduct and facilitate <u>highly integrated scientific studies</u> on targets of opportunity in two test beds in concert with the geosciences community



GEON
The Geosciences Network

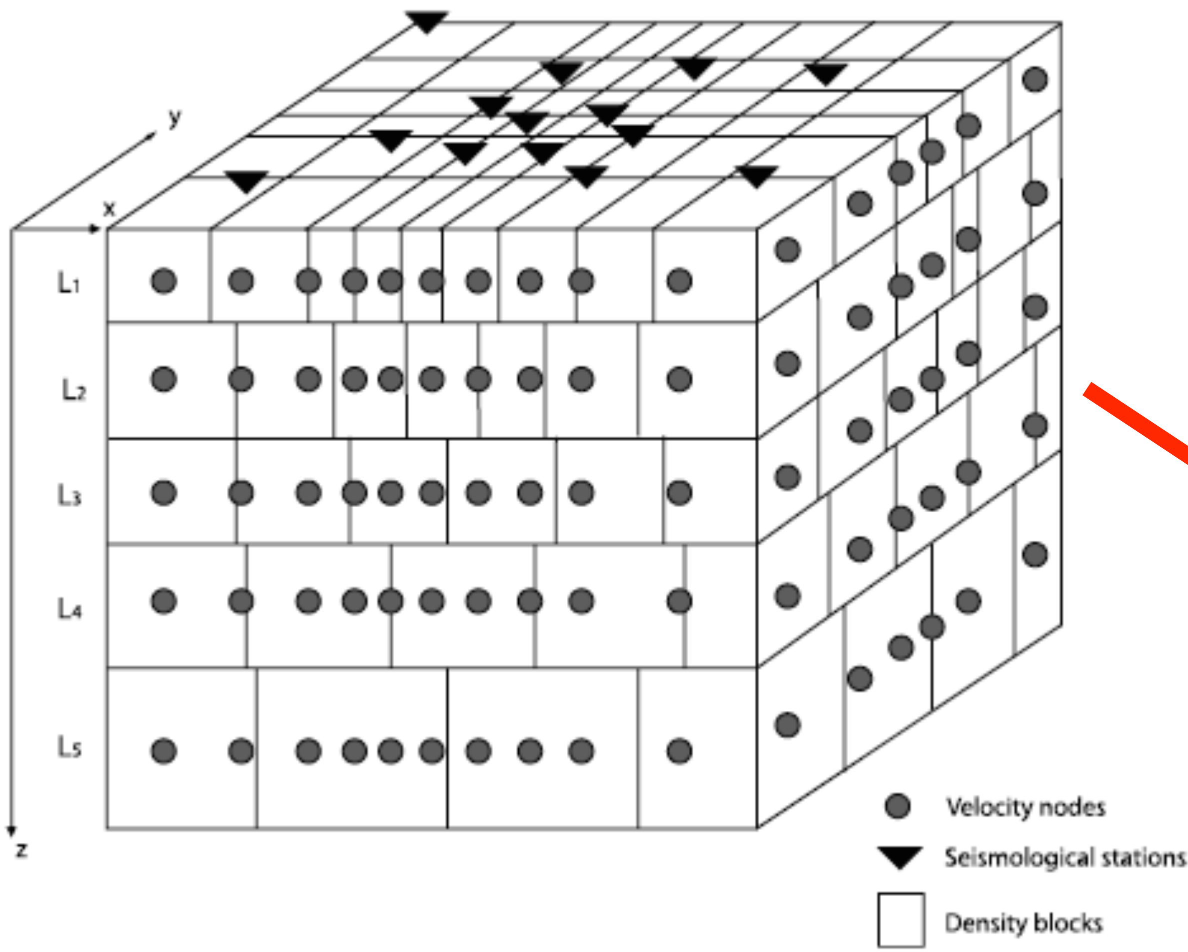
GEON Overall Architecture

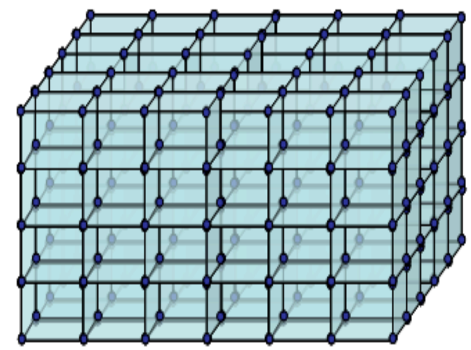


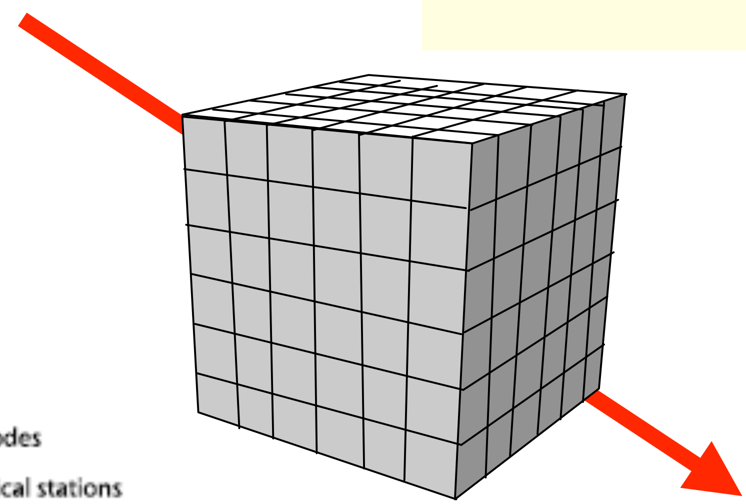
GEON
The Geosciences Network

The ultimate goal in geophysics is..

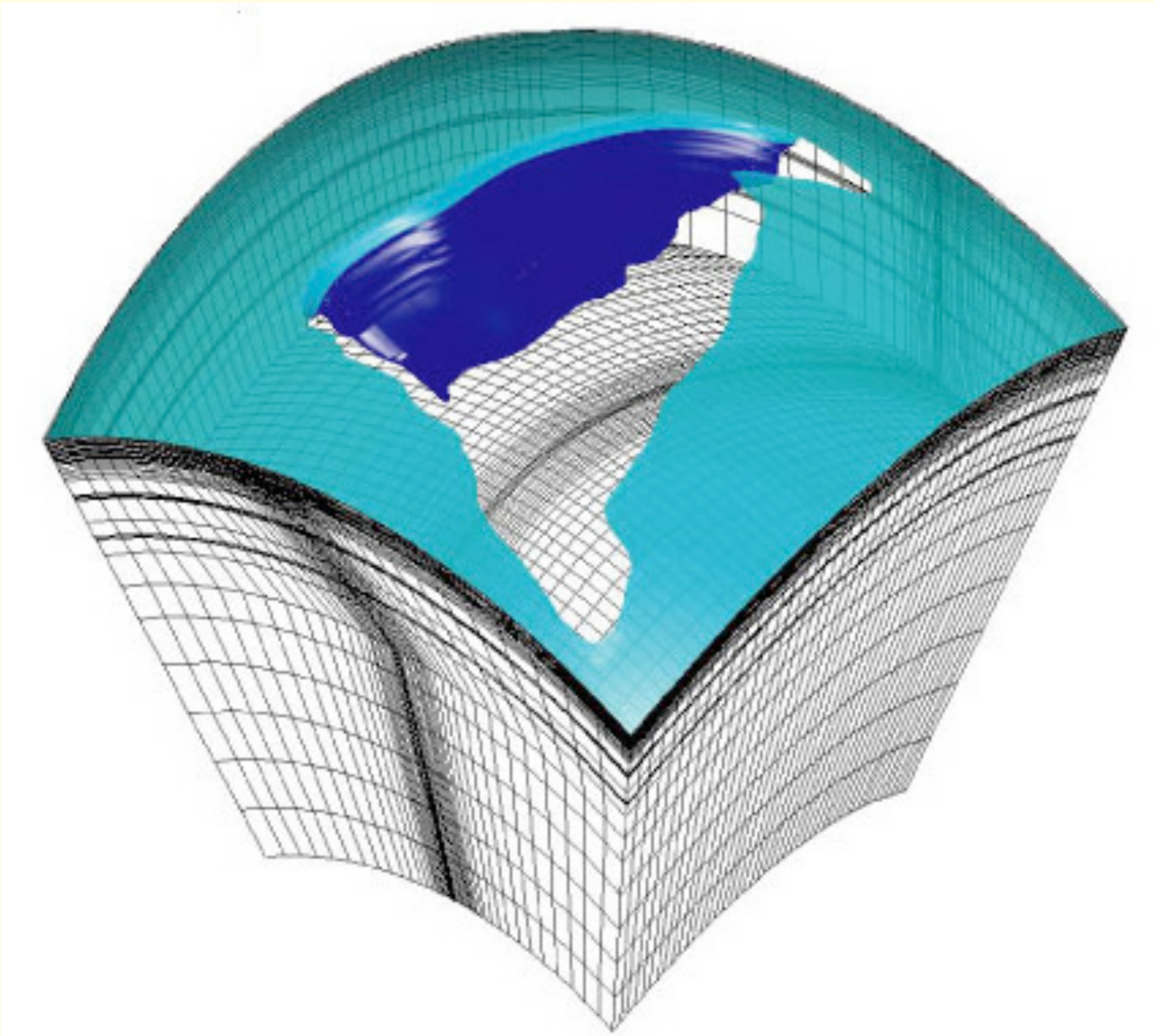
Construction of 3-D volumes with as many physical properties as possible assigned to each volume element

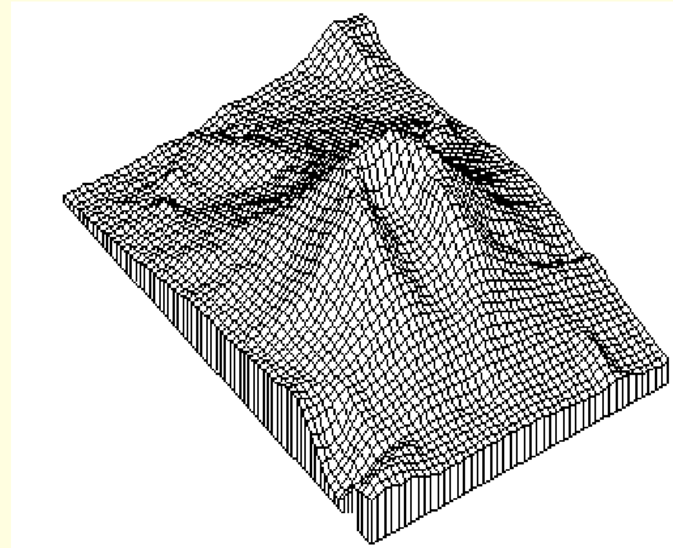






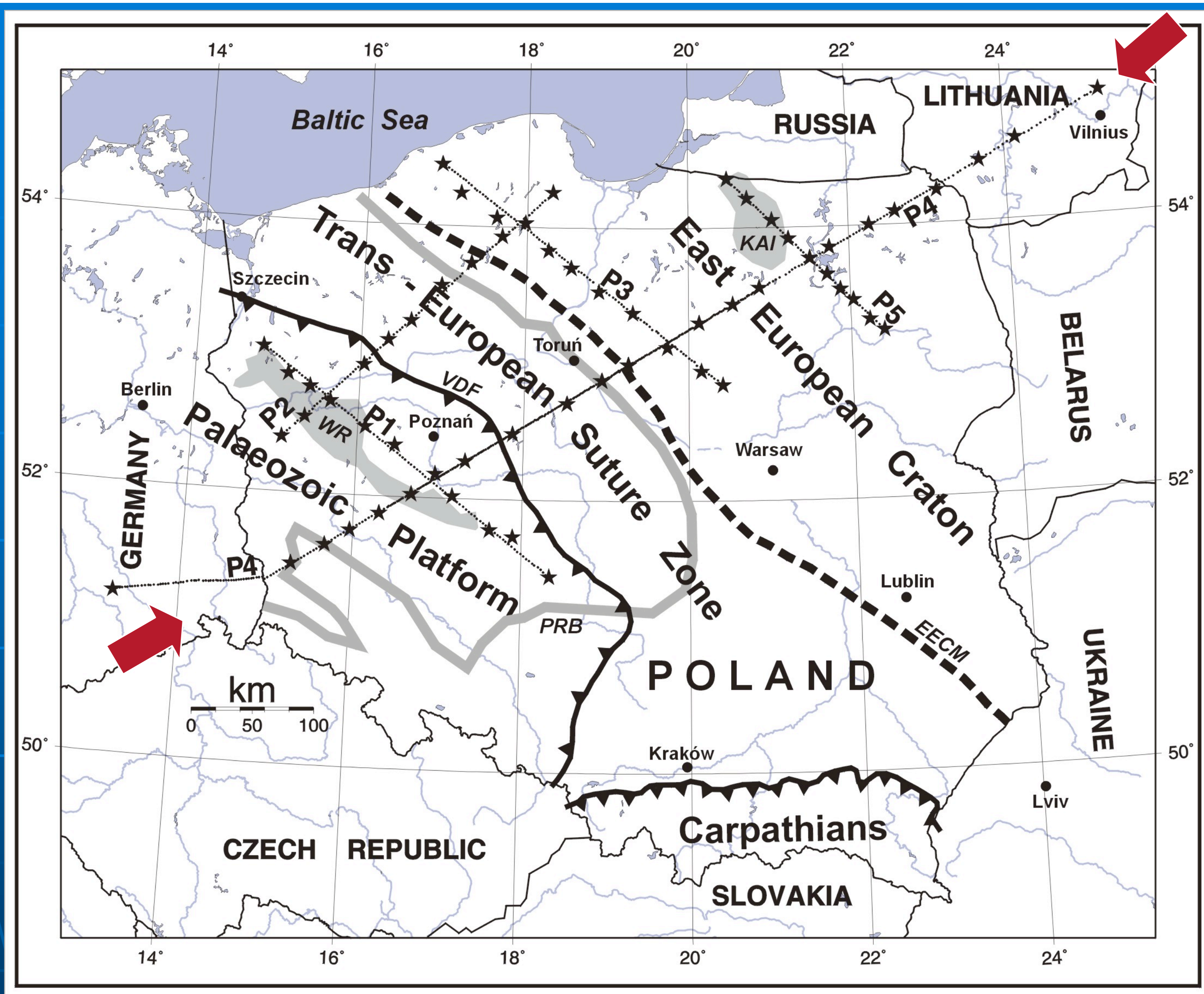
Discontinuities are also important, and we need to be able to insert them and manipulate them





We also want the results to be compatible with various modeling programs (e.g. groundwater, geodynamics)

A 2-D example from seismology

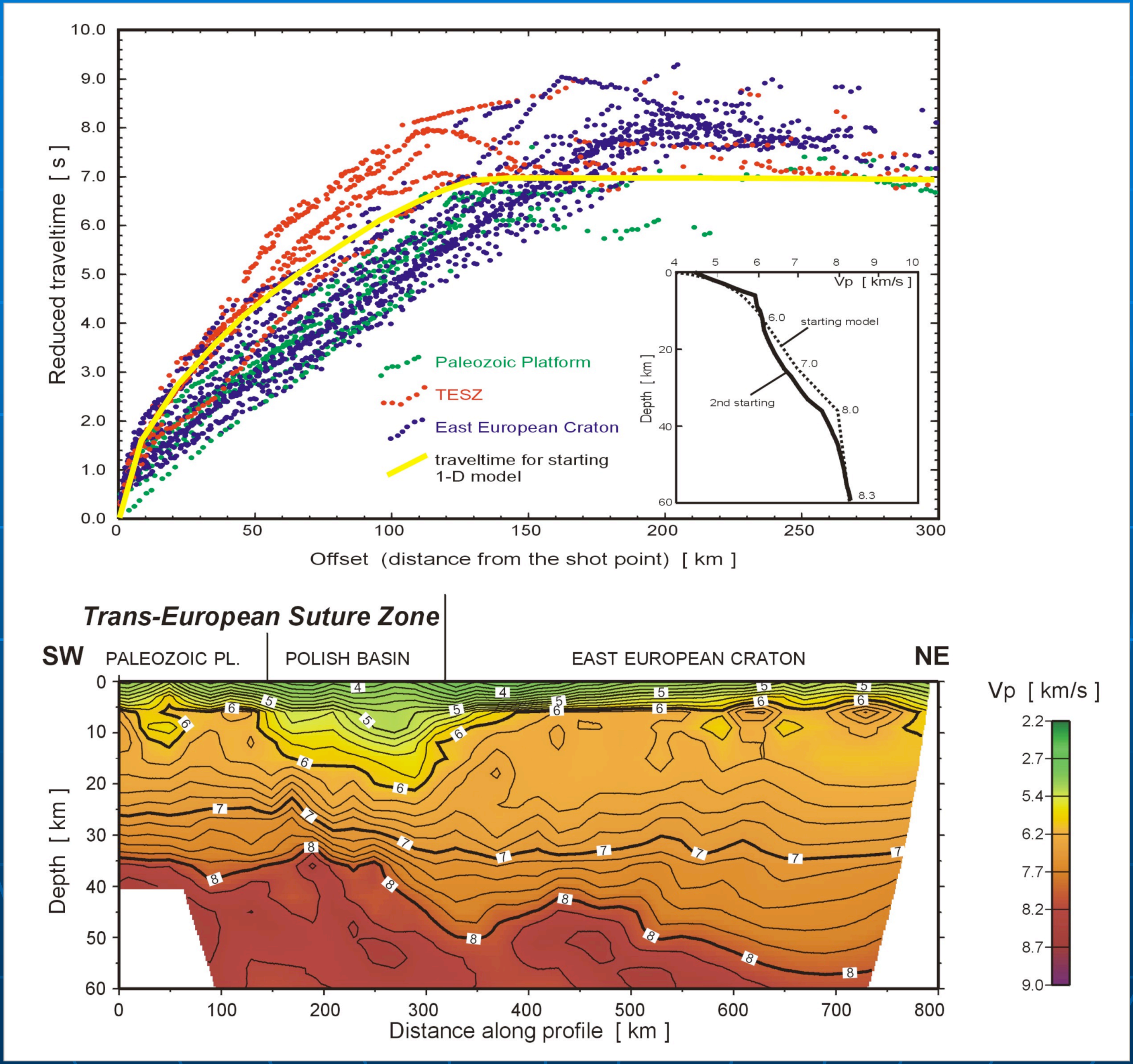


POLONAISE'97

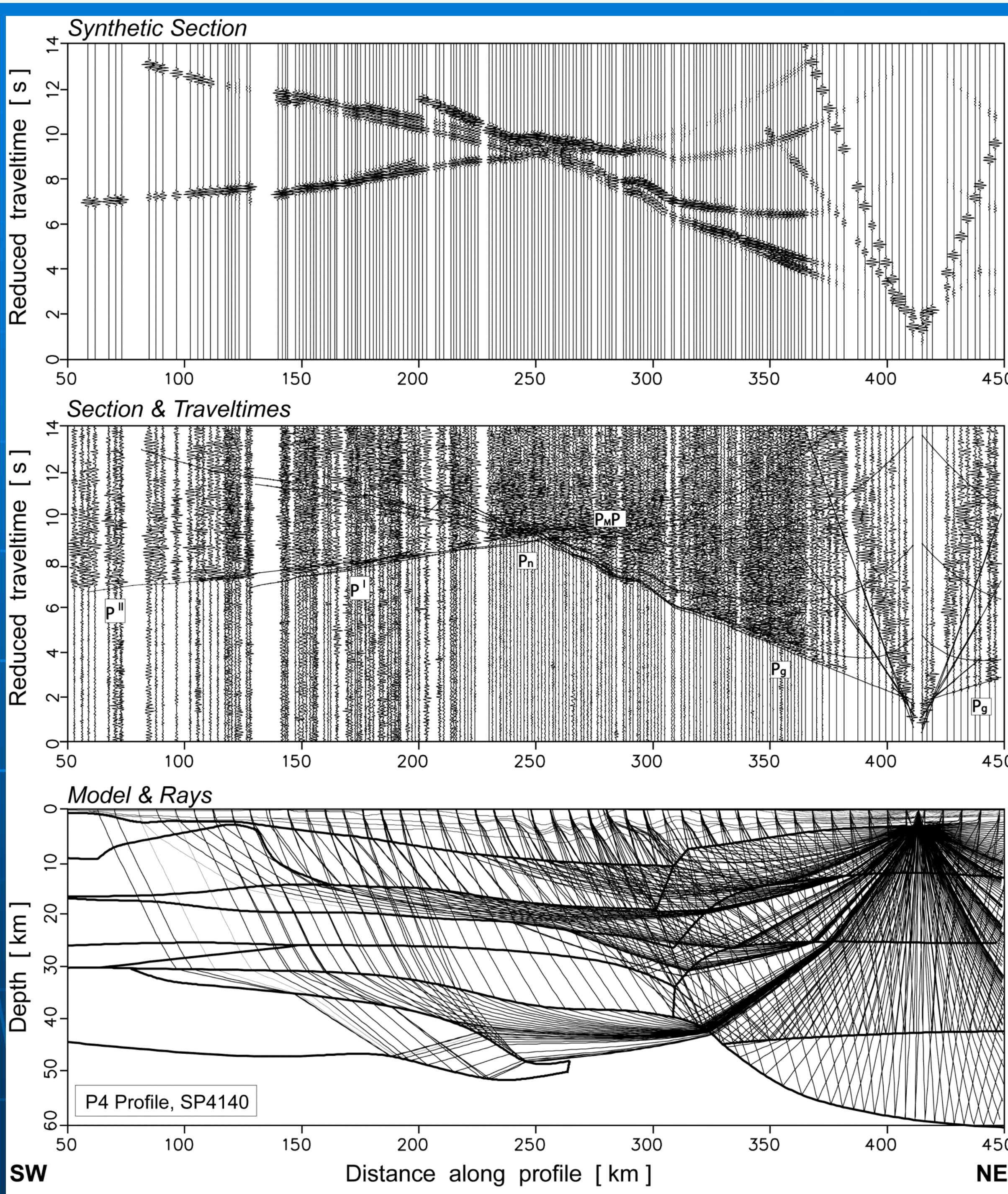
- 64 shots
- 613 stations
- 5 profiles
- 3-D records

(Guterch et al., 1999)

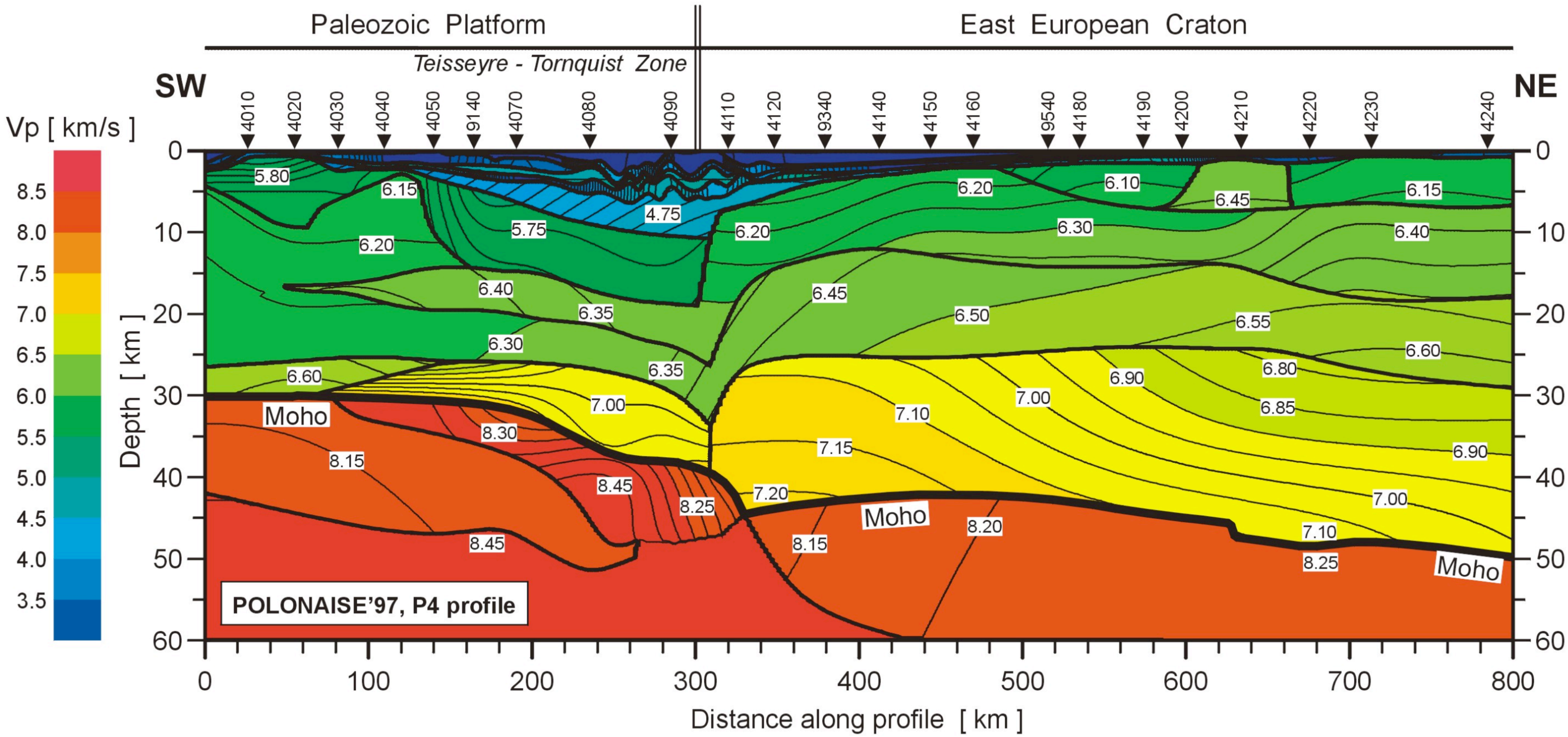
Tomographic inversion (CAT scan) of first arrivals is the first step in the analysis and produces a smooth voxel-based model of the variations in velocity.



Ray tracing and analysis of synthetic seismograms can be employed to model the velocity discontinuities (interfaces) and the velocity variations.

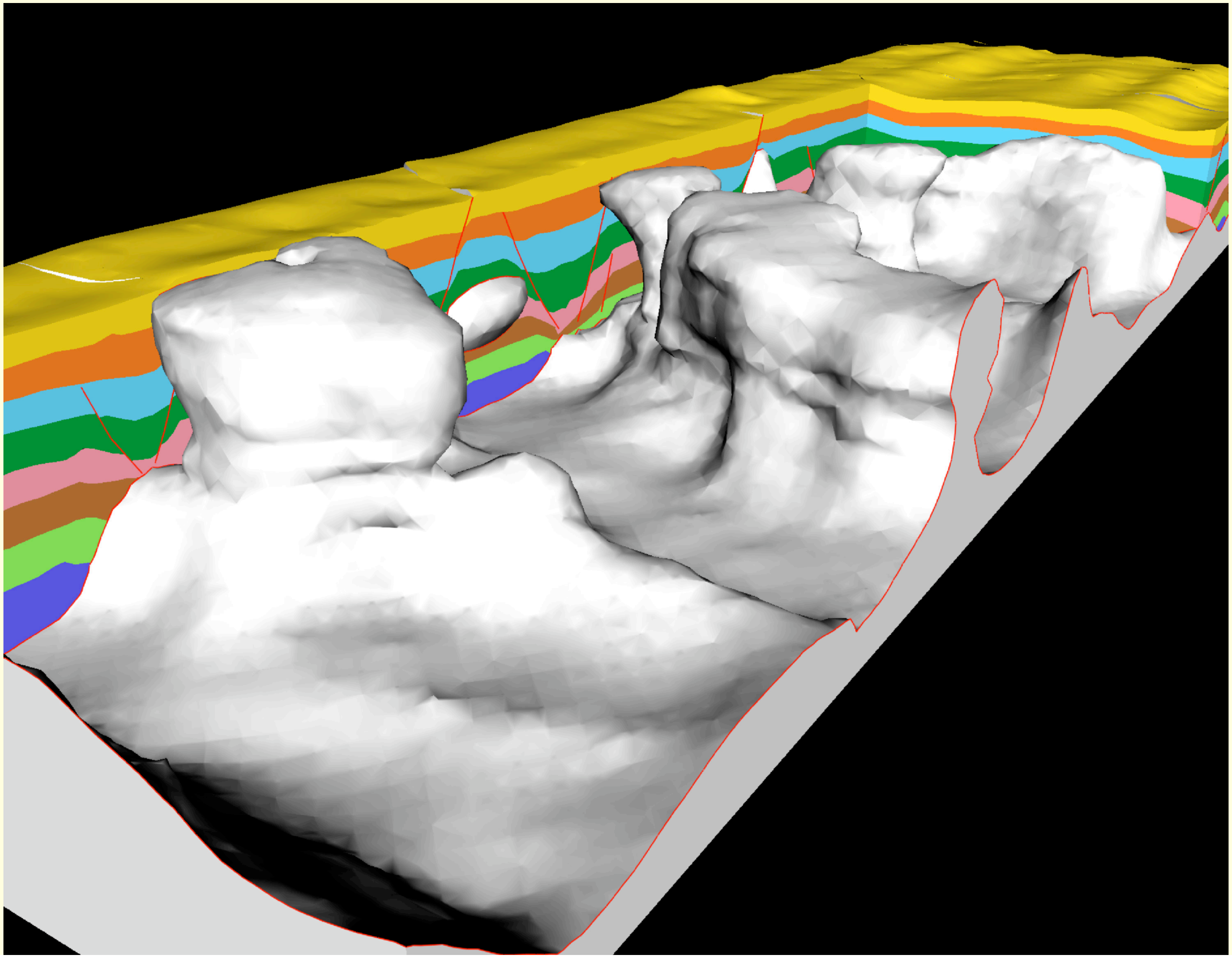


The final integrated velocity model with velocity variations, interfaces, and geologic constraints



POLONAISE'97, Profile P4 ***(Grad et al., Jour. of Geophysical Res, 2003)***

A number of geophysical techniques can produce 3-D voxel models (e.g., tomography), and others produce interfaces. The big challenges are to include interfaces in voxel-based models and to be able edit and visualize the models as one proceeds.



Dimensionality in the Geosciences

2-D (x, y) Mapping or cross-sections
Components: objects (points, lines polygons), raster grids

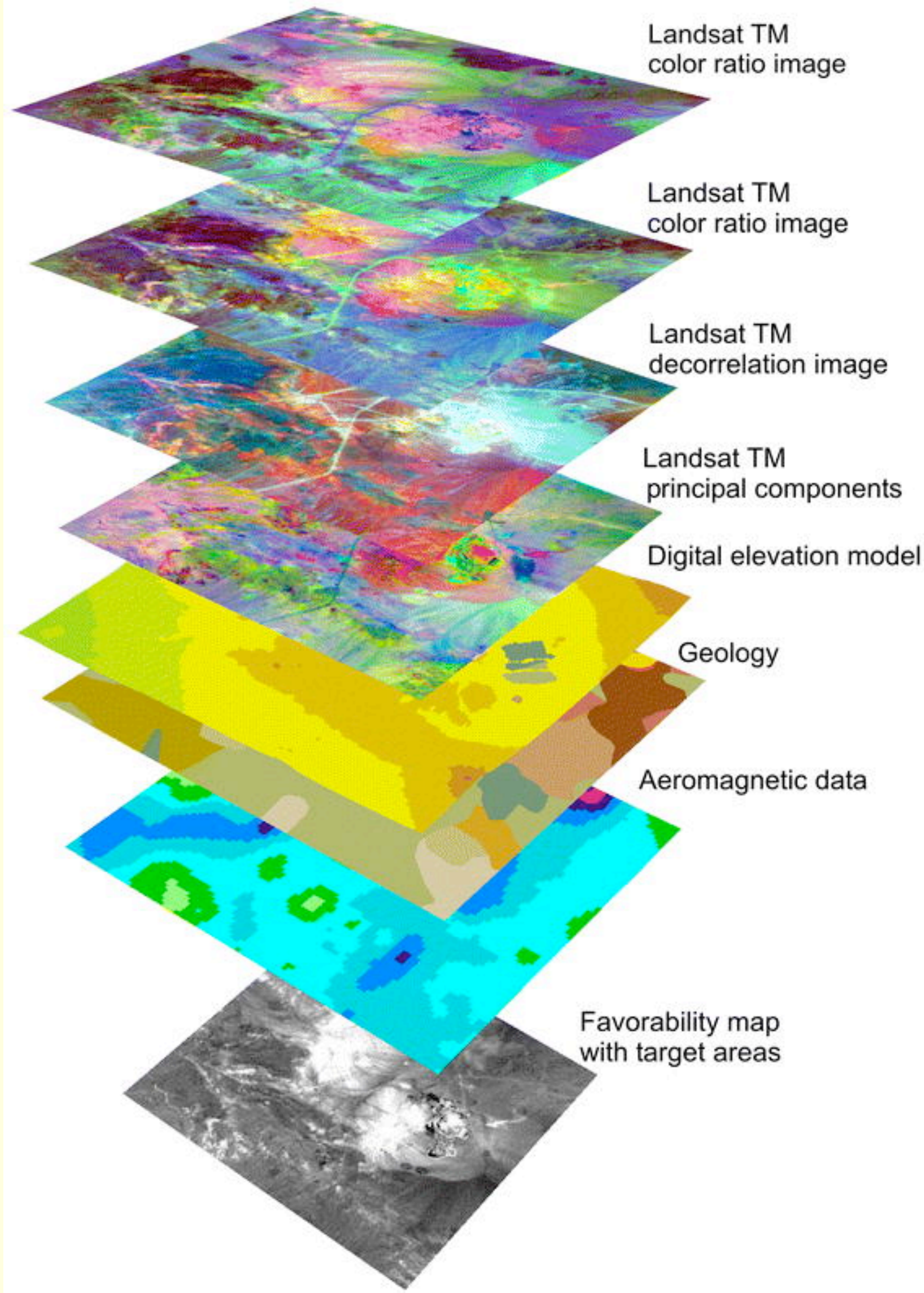
2.5-D (x, y, Height) Adds height (e.g. surface or relief)
Sometimes erroneously called 3-D mapping
Components: Raster grids of elevation (DEM)
A fly-through gives the appearance of time varying but is just a visualization tool. Draping another data layer on the DEM is another visualization scheme.

3-D (x, y, z) Volume mapping and rendering
Components: 3-D Raster grids, 3-D grid cells (Voxel, volumetric elements), iso-volumes. Add cross-sections, horizontal slices, cut-outs, rotation, etc.

4-D (x, y, z, Time) Adds time variation and possibly animation

Multi-dimensional (x, y, z, a_1, a_2, …a_n) Adds multiple attributes (physical measurements) to 3-D or 4-D

In recent years, government, industry, and academic database efforts have developed a vast array of 2-D data layers. These data represent a powerful scientific tool, but they are 2-D in nature.



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Visualizations such as this are really useful but we are still looking only at the Earth's surface.

Raster representations of other types of data can be draped on a DEM

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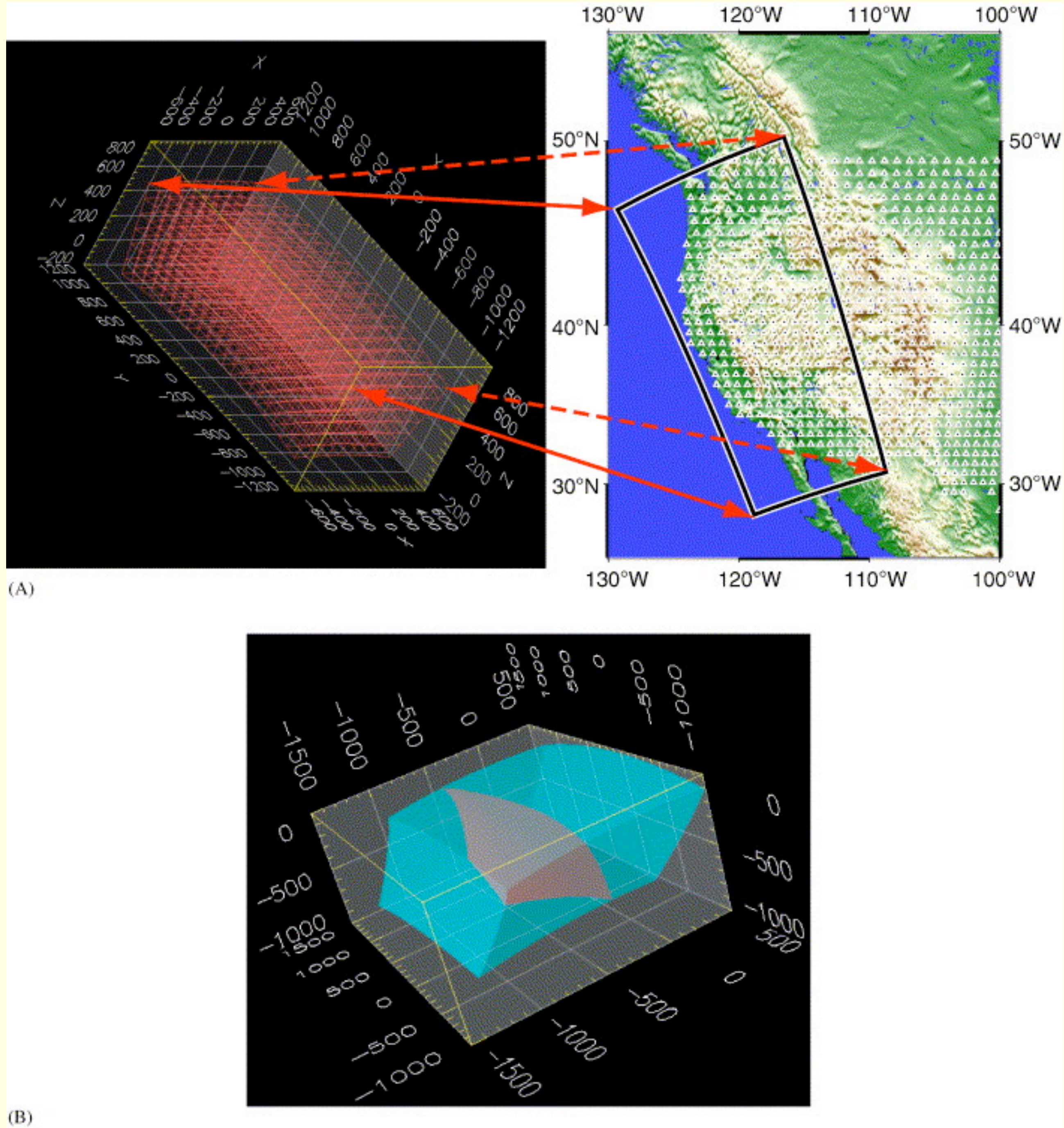
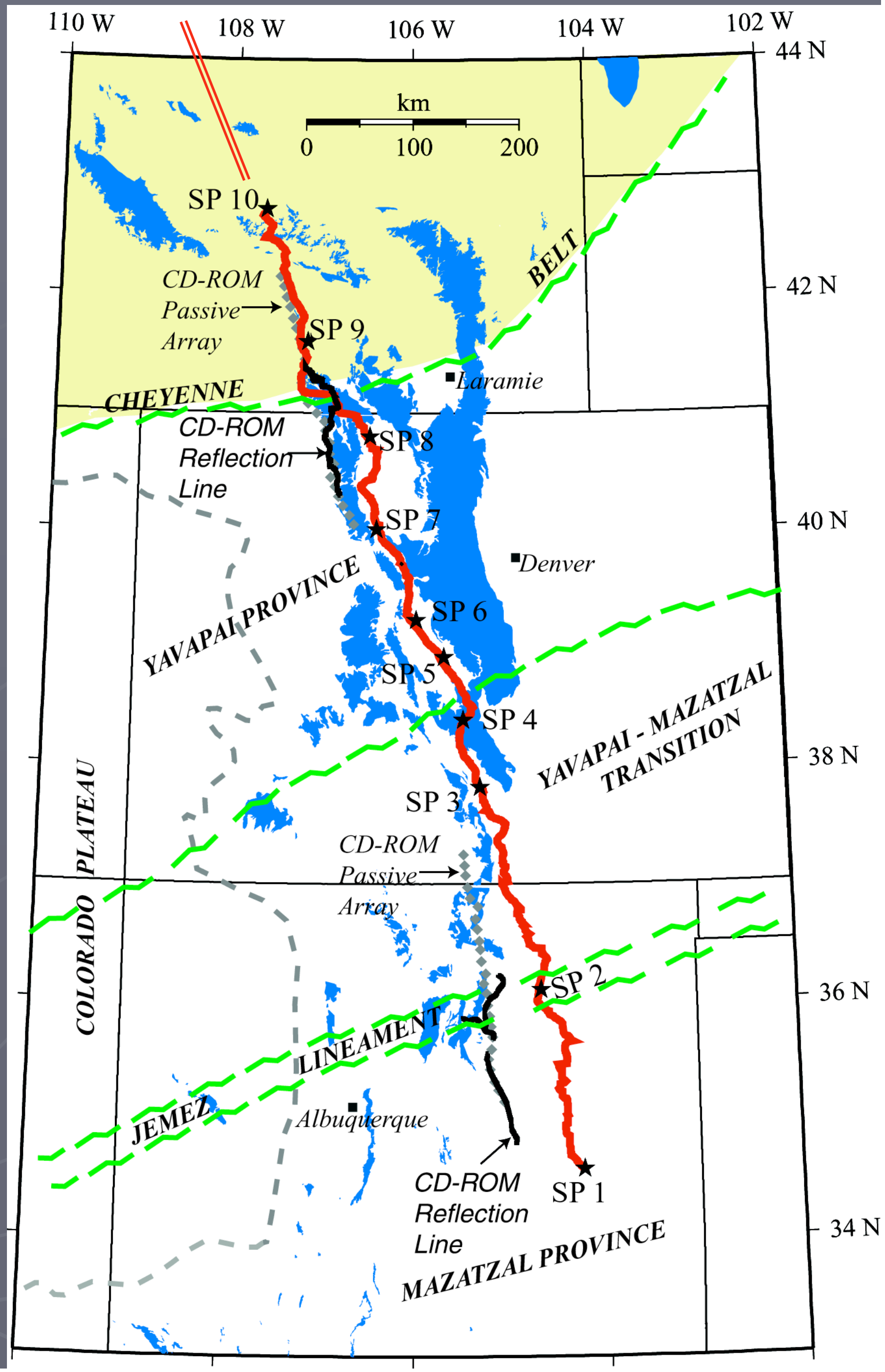
The USArray component of EarthScope is designed to produce 3-D models of the distribution of seismic velocity in the crust and upper mantle.



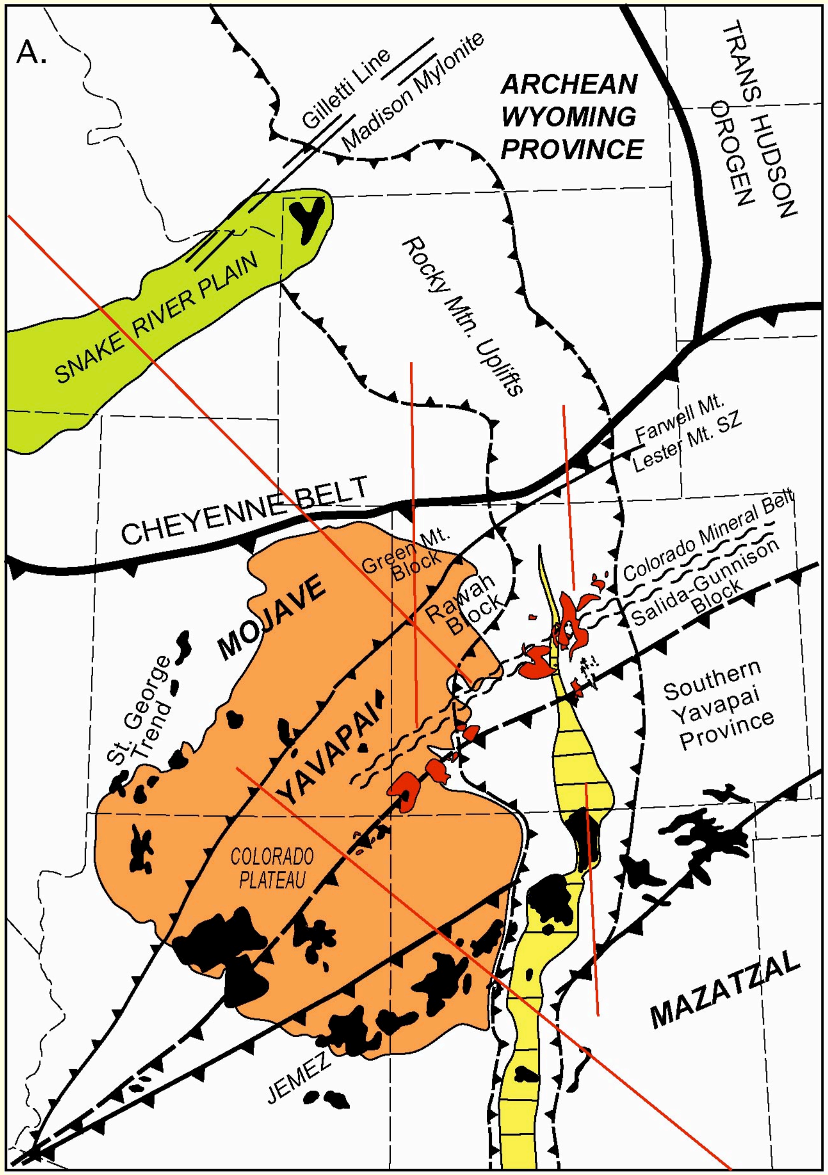
Continental Dynamics of the Rocky Mountains Project (CD-ROM)

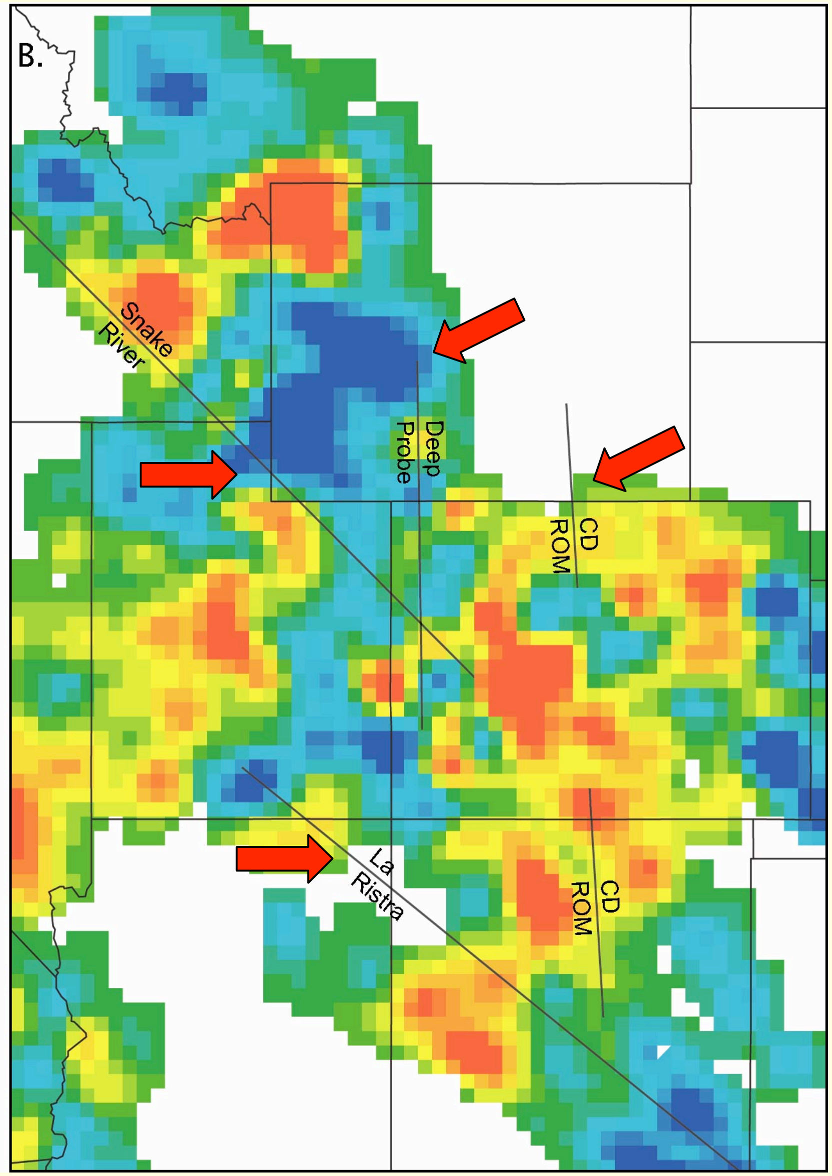
CD-ROM involved a broad range of geoscience investigations that focus around a transect extending from southern Wyoming to Northern New Mexico. The goal of this project is to understand the assembly, evolution, and disassembly of the lithosphere of southwestern North America.

CD-ROM featured coordinated teleseismic, seismic refraction, and deep reflection experiments whose results have been integrated with a wide variety of geologic data.



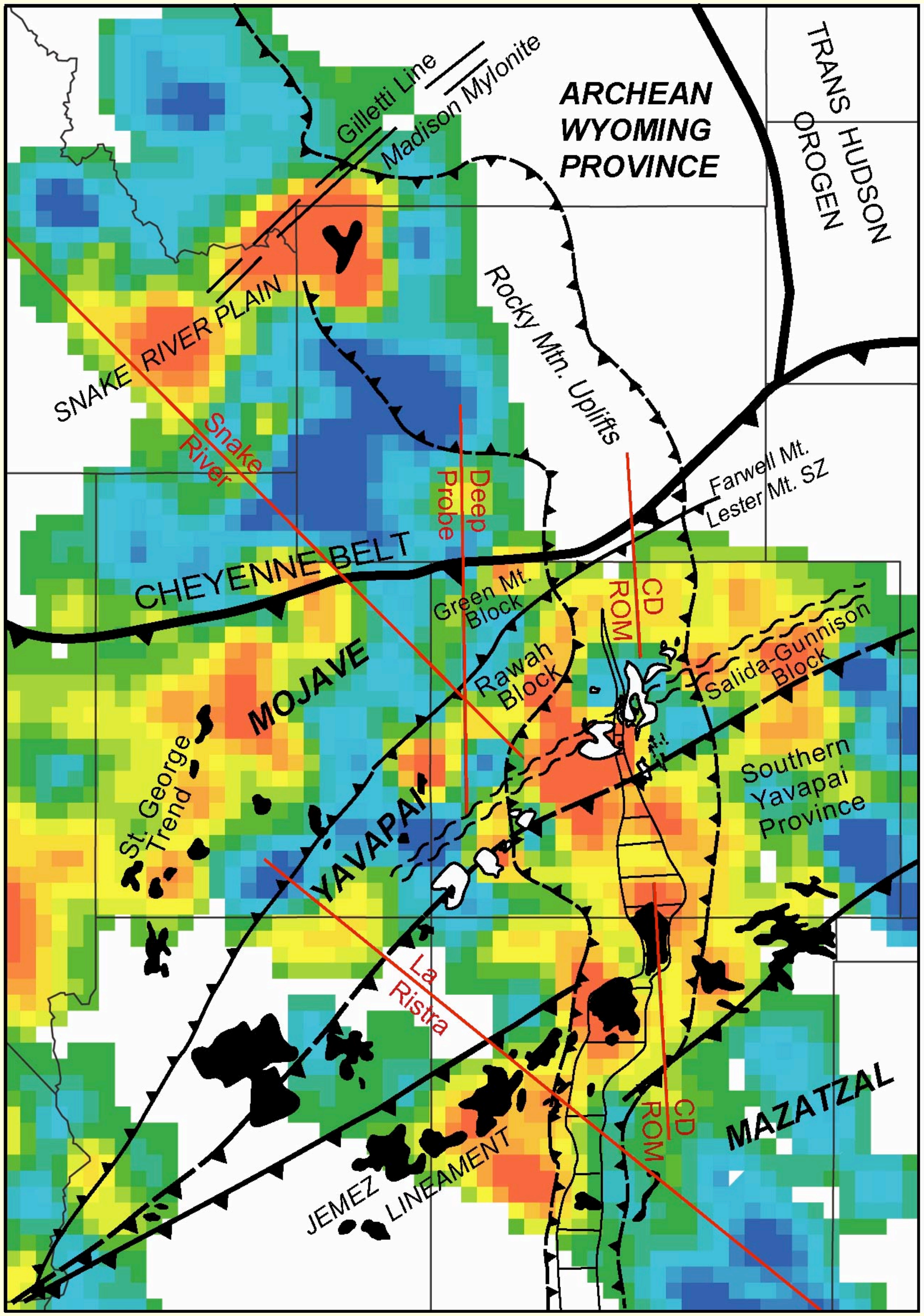
Seismic tomography result from the CD-ROM project



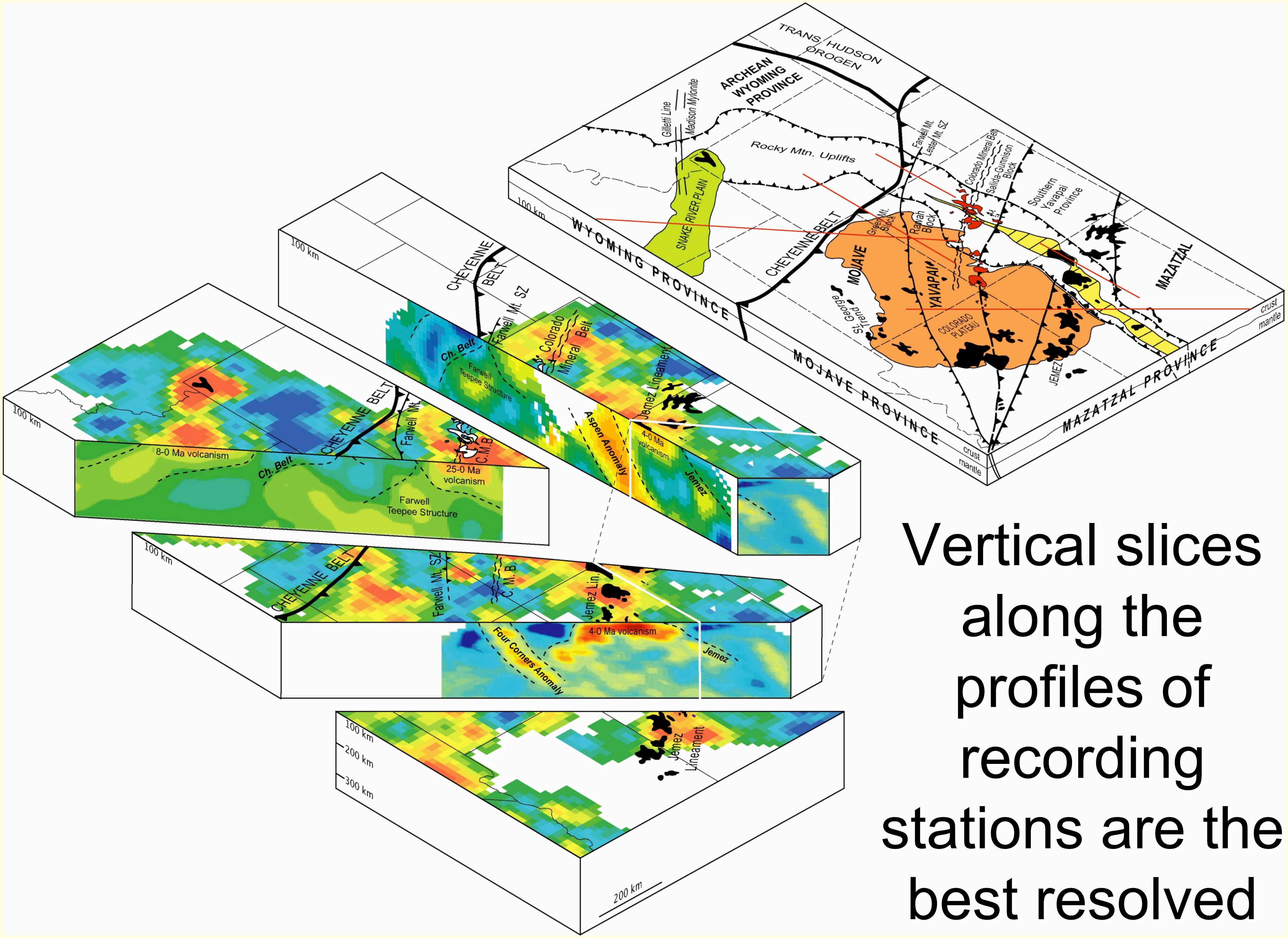


A slice through the best resolved portion of the tomographic volume (z=100 km)

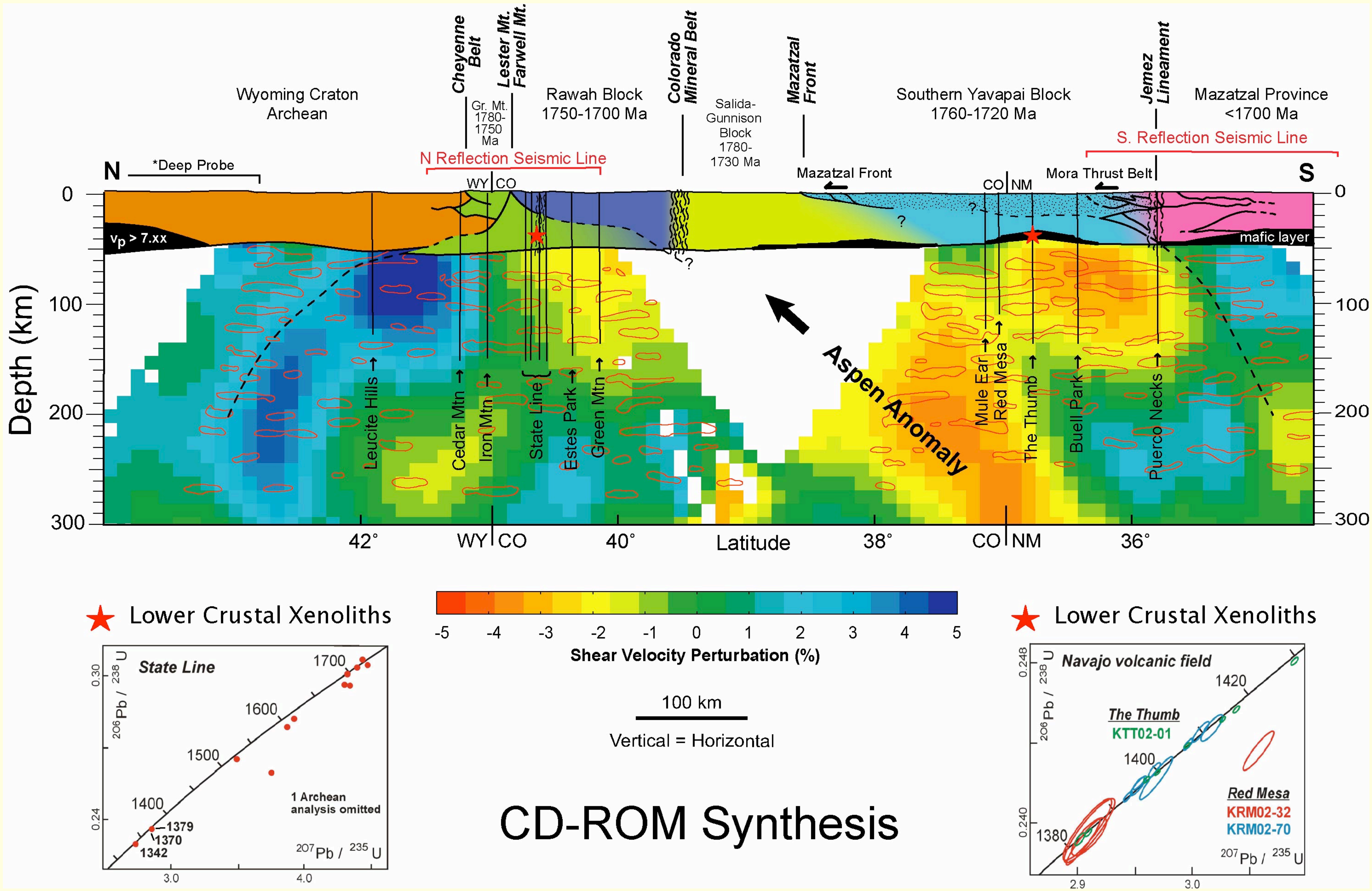
Ken Dueker, University of Wyoming



The slice at 100 km displays some interesting correlations with known geologic features



Vertical slices along the profiles of recording stations are the best resolved



Data overlays are a useful qualitative type of integration

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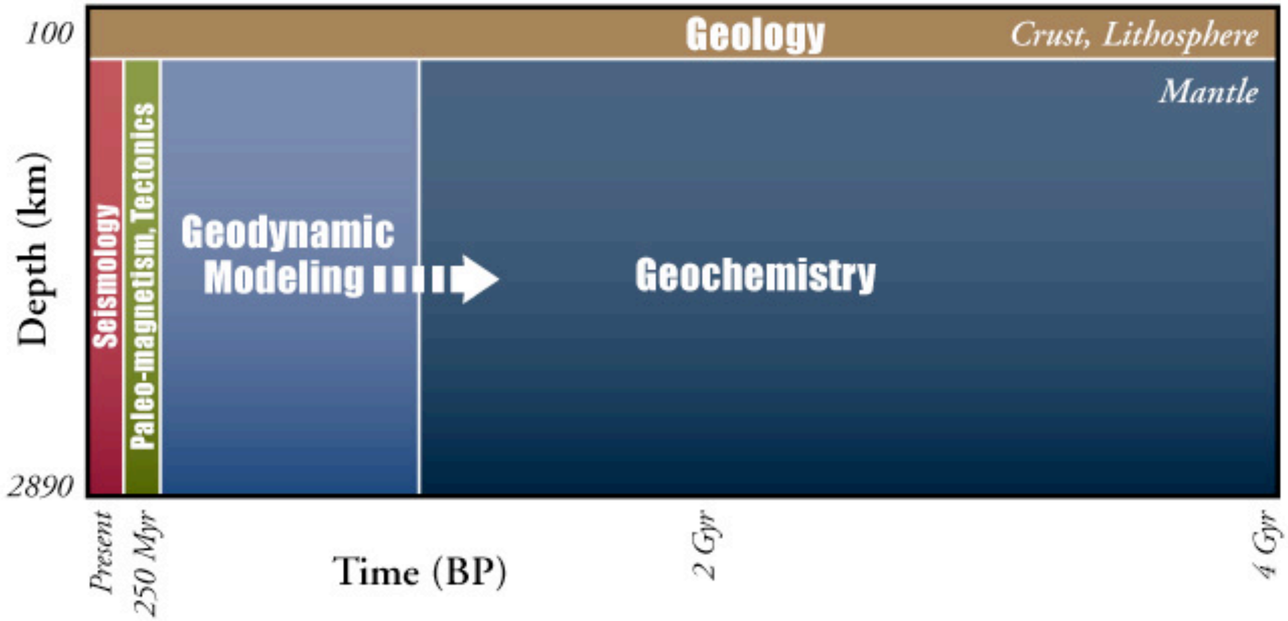
Innovative integration of geological and geophysical data is needed to produce a 4-D analysis back through geologic time

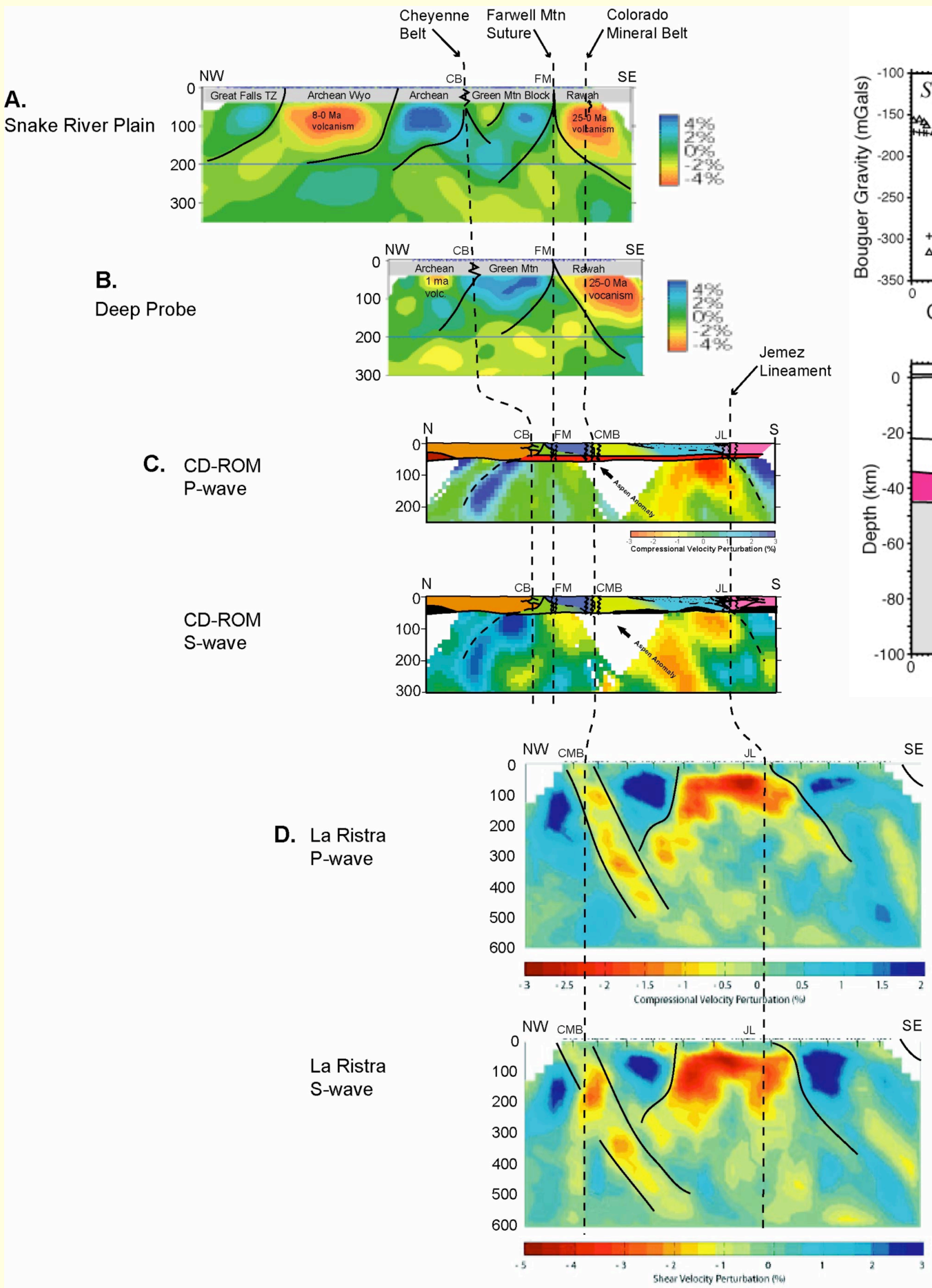
Geophysical, Geological & Geochemical Observations

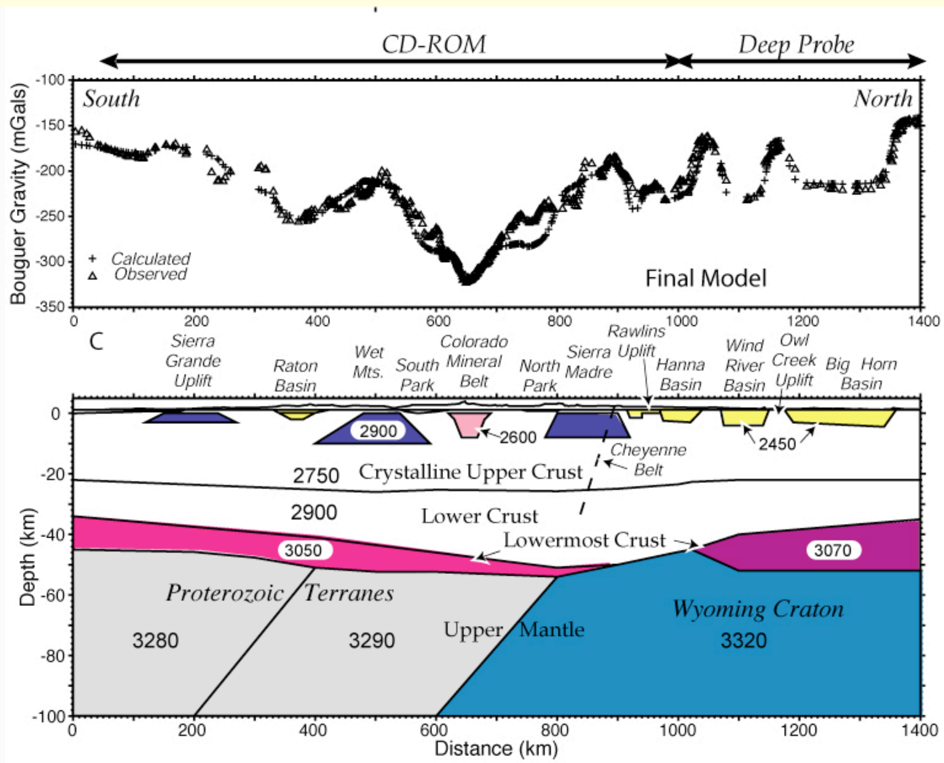
- **Geophysical:** limited to recent times
- **Geological:** limited to shallow depths
- **Geochemical/Petrological:** shallow and deep mantle, early history

Depth-Time Diagram for the Earth



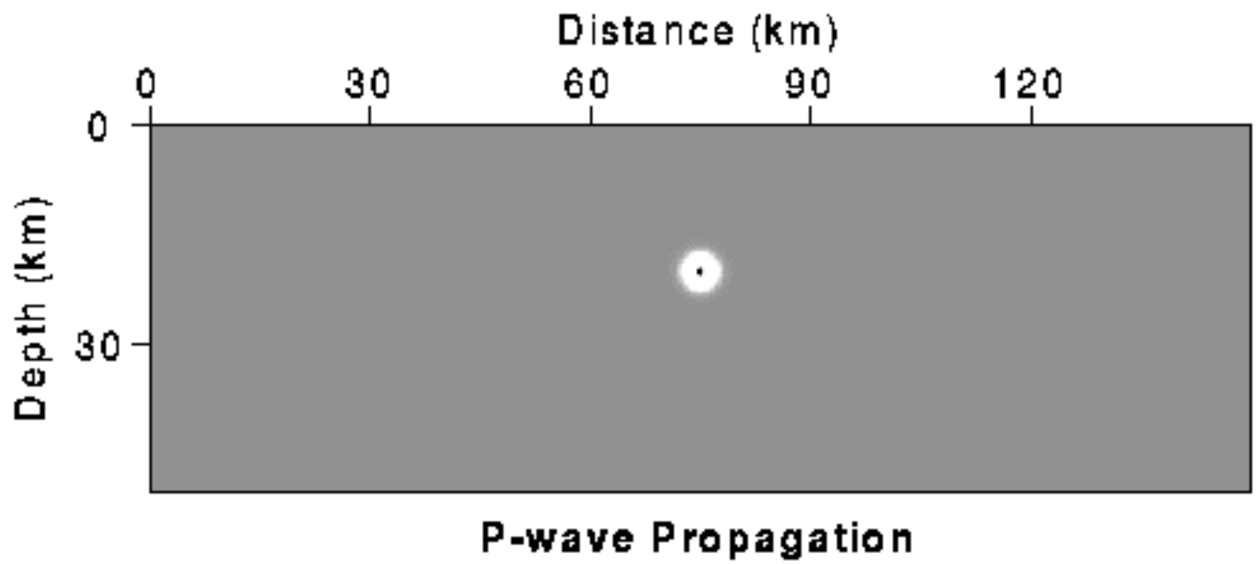
- **Geodynamic Modeling:**
  - Explores related physical and chemical processes.
  - Facilitates hypothesis testing of complex systems.
  - Provides context for interpreting a large range of observations.

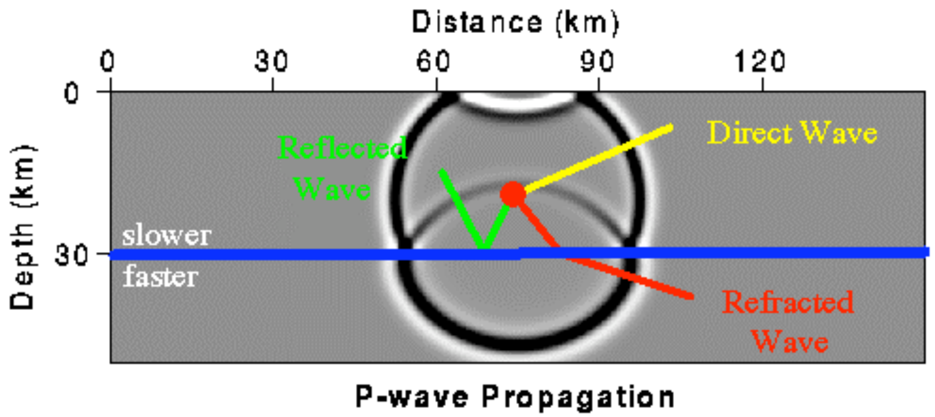




Interpreting the age of these velocity and density anomalies is an attempt to produce a 4-D result.

Another way to achieve 4-D is through mathematical modeling of geological and geophysical phenomena and processes.





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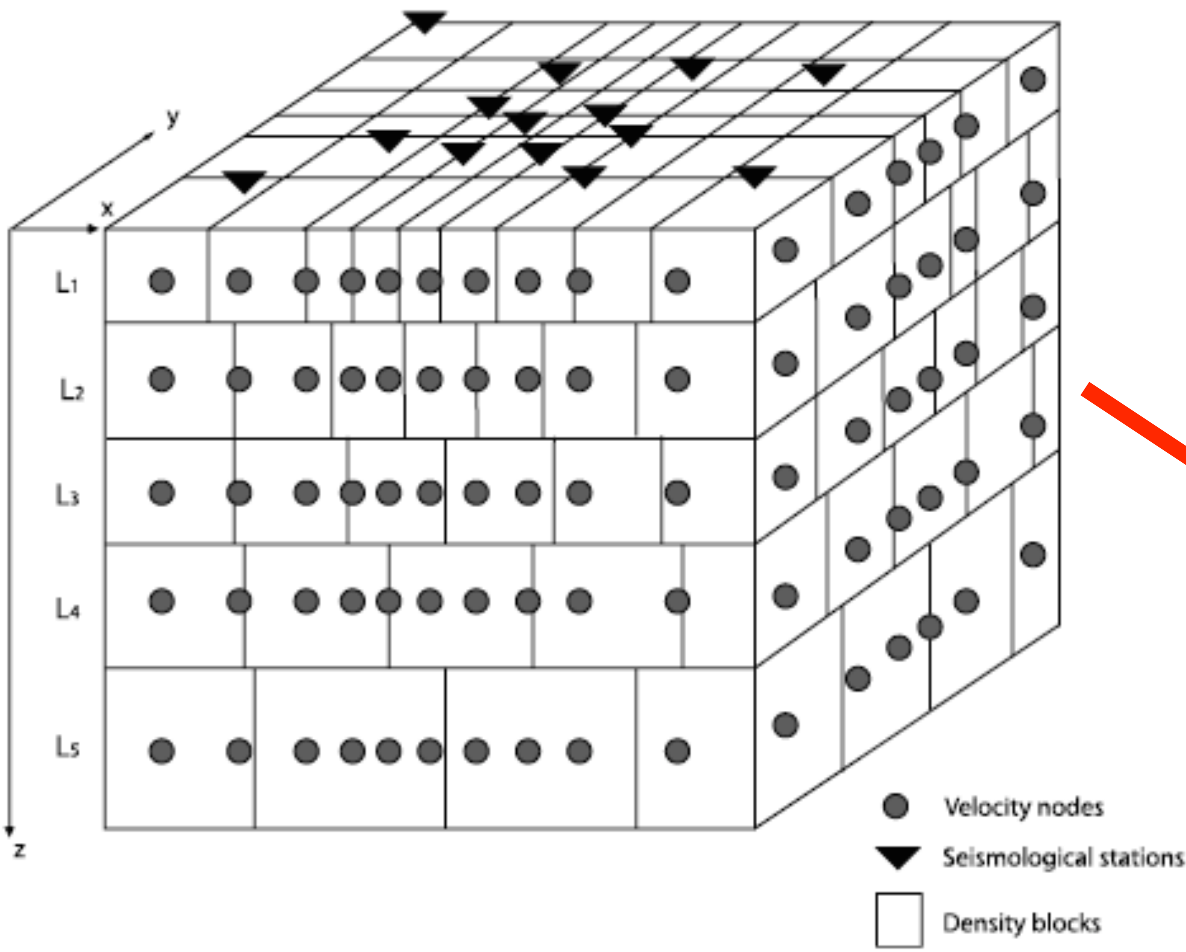
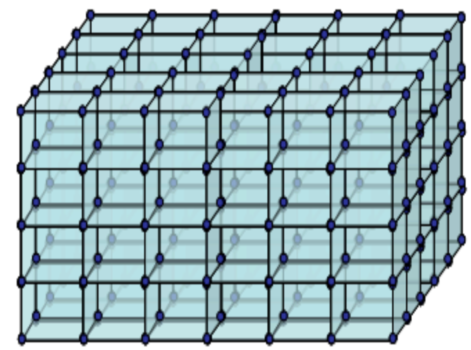
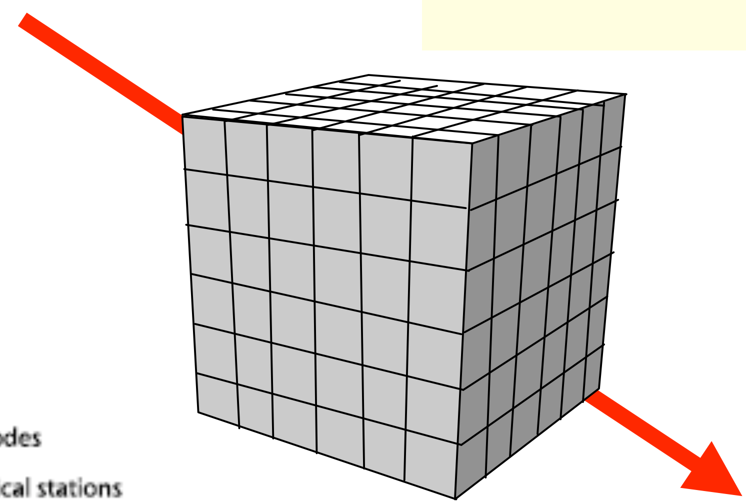
The ultimate goal in geosciences is a multi-dimensional model that includes geological interfaces





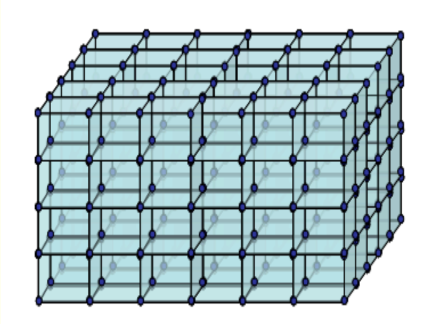


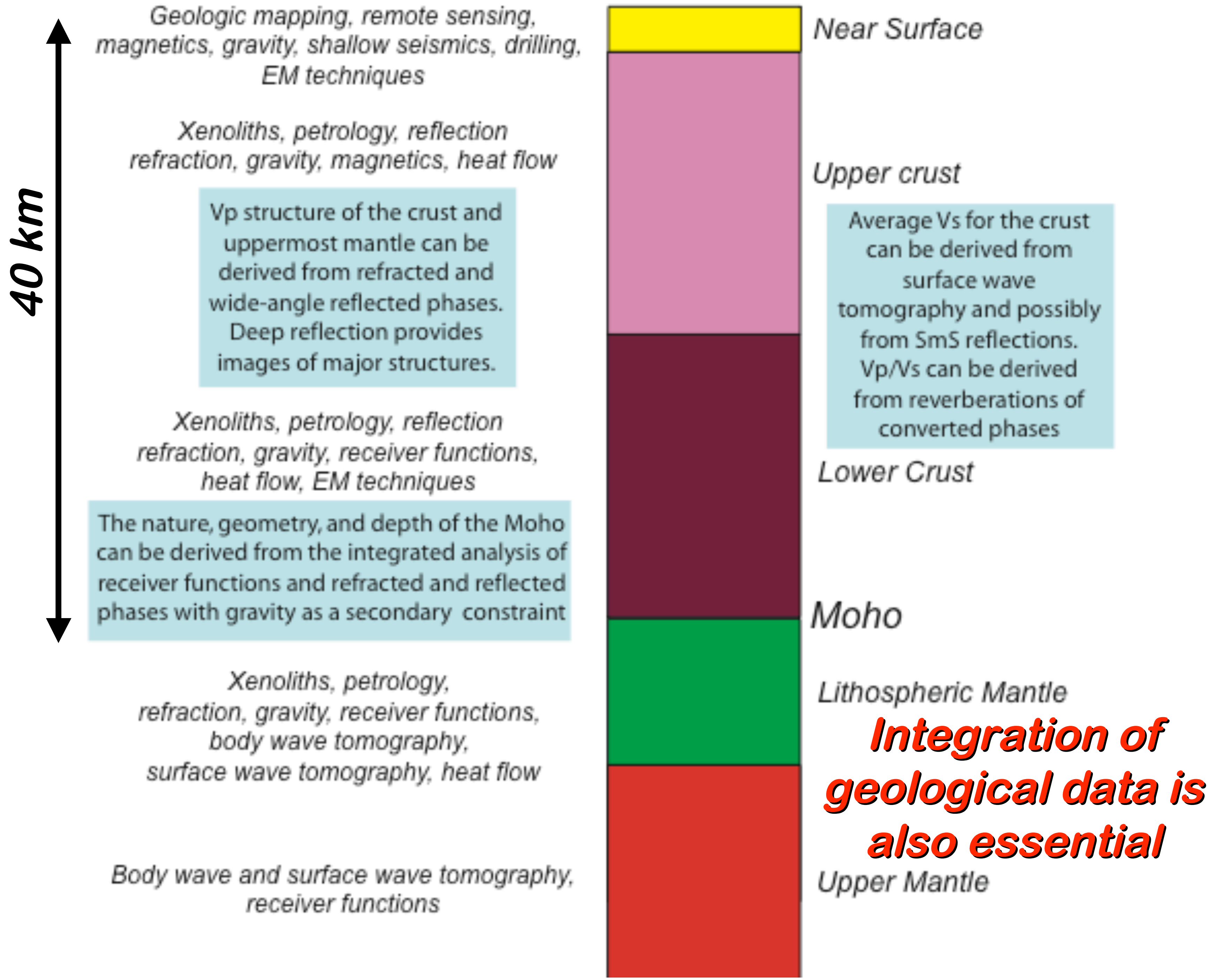
How might we go about constructing the desired 3-D model and then make it multi-dimensional?

Obviously if we are to determine Vp, Vs, density, magnetic properties, electrical properties, anisotropy, attenuation (Q), temperature, etc., we must use a highly integrated approach that takes advantage of all the geological and geophysical constraints available.

In most cases, seismology has the potential of providing the greatest resolution, but it is the mostly costly approach and many diverse techniques are available. Thus, an integration scheme for seismic results is an important first step in any study.

Such a scheme logically begins with seismic tomography and there are many possible way to proceed from there seismically.



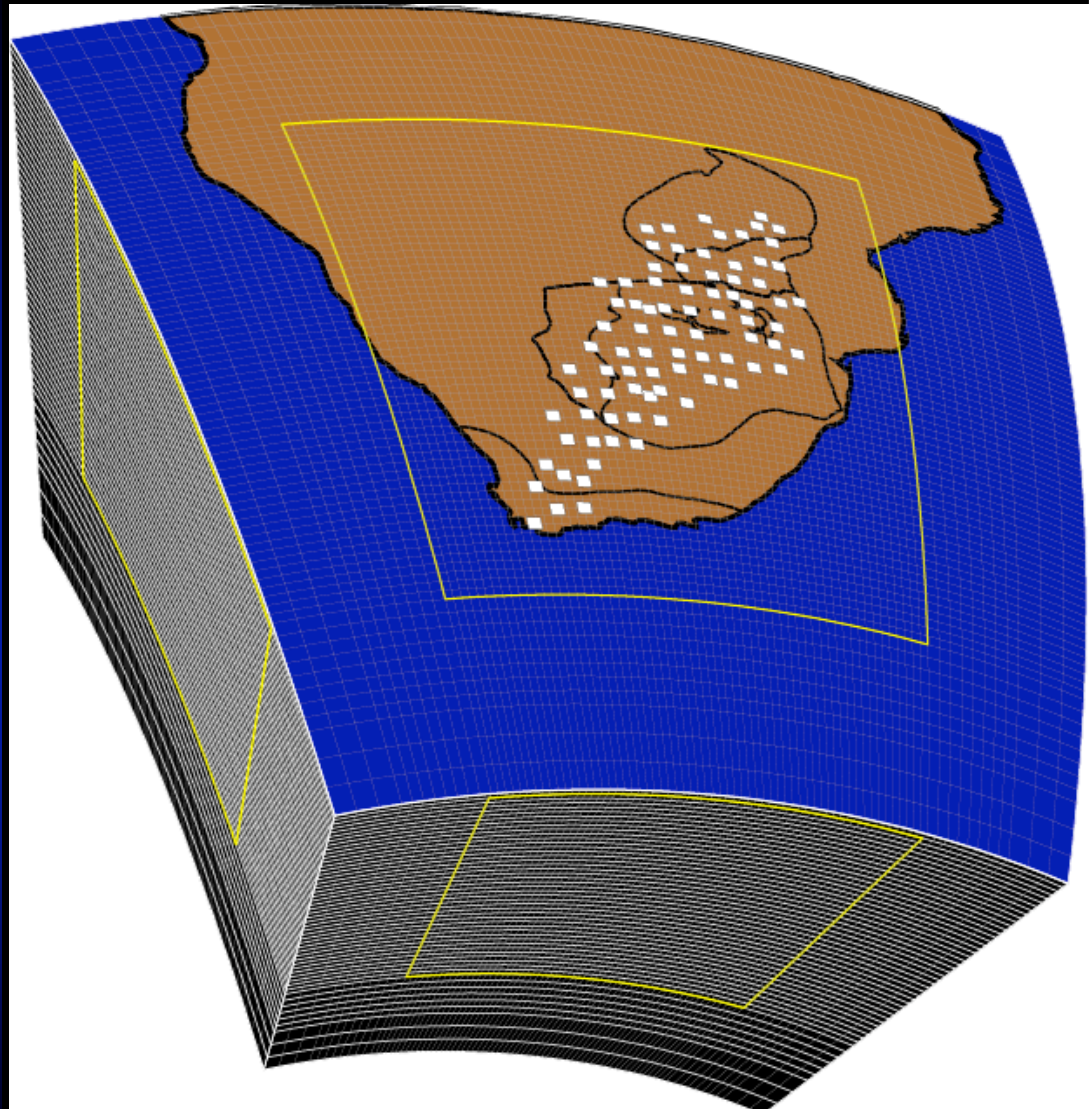


40 km
Geologic mapping, remote sensing, magnetics, gravity, shallow seismics, drilling, EM techniques
Xenoliths, petrology, reflection refraction, gravity, magnetics, heat flow
Vp structure of the crust and uppermost mantle can be derived from refracted and wide-angle reflected phases. Deep reflection provides images of major structures.
Xenoliths, petrology, reflection refraction, gravity, receiver functions, heat flow, EM techniques
The nature, geometry, and depth of the Moho can be derived from the integrated analysis of receiver functions and refracted and reflected phases with gravity as a secondary constraint
Xenoliths, petrology, refraction, gravity, receiver functions, body wave tomography, surface wave tomography, heat flow
Body wave and surface wave tomography, receiver functions
Near Surface
Upper crust
Average Vs for the crust can be derived from surface wave tomography and possibly from SmS reflections. Vp/Vs can be derived from reverberations of converted phases
Lower Crust
Moho
Lithospheric Mantle
Integration of geological data is also essential
Upper Mantle

The best starting point would usually be derived from 3-D tomography

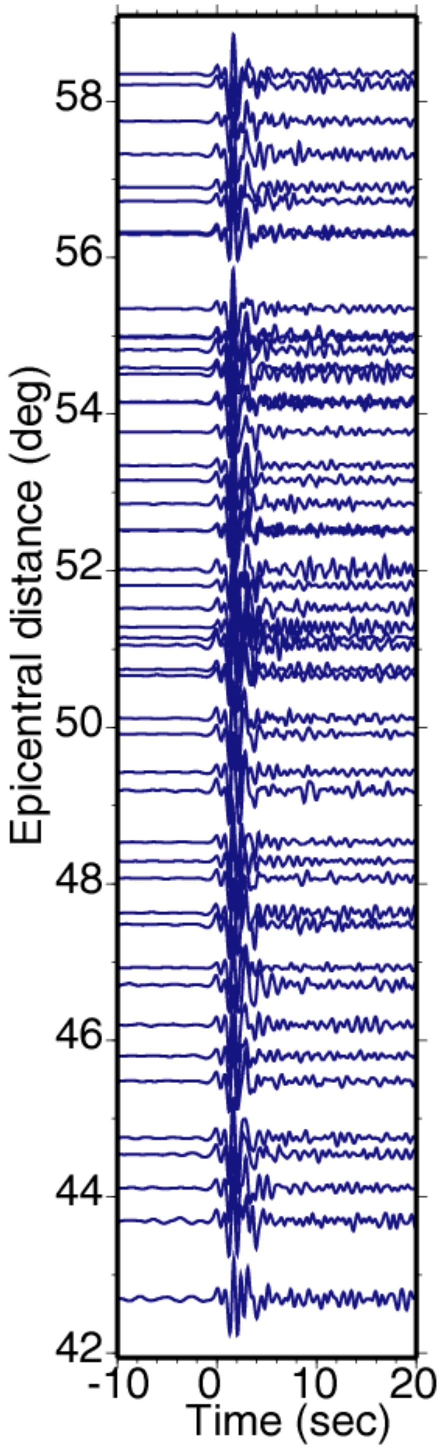
Example from Southern Africa provided by Matt Fouch

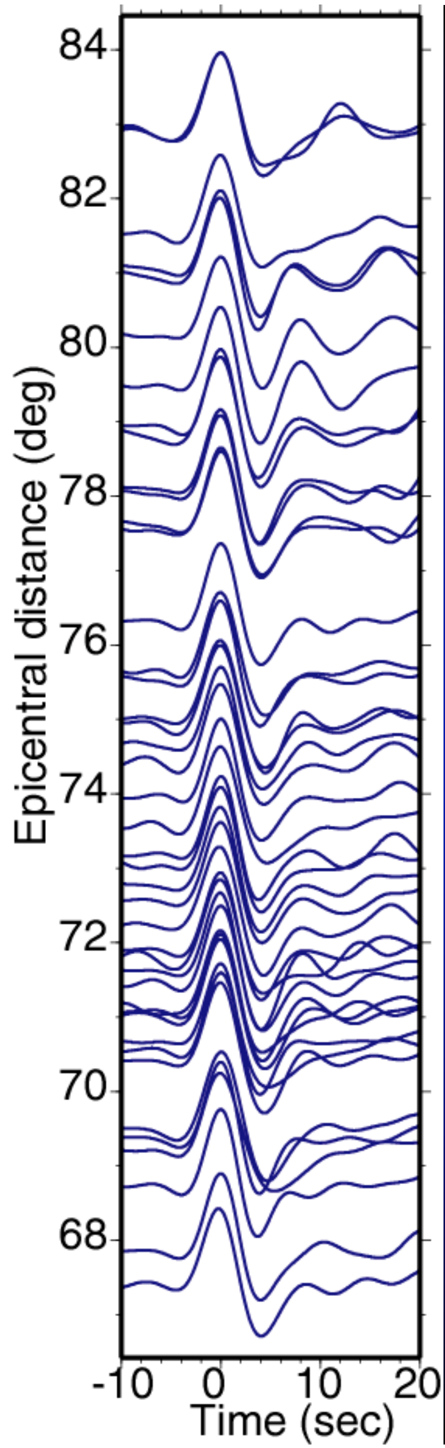
- 1/3 ° X 1/3° lateral grid
- 33 km vertical grid
- 371,176 grid points in this model



Fouch et al. [2004]

Seismic Data Record Section

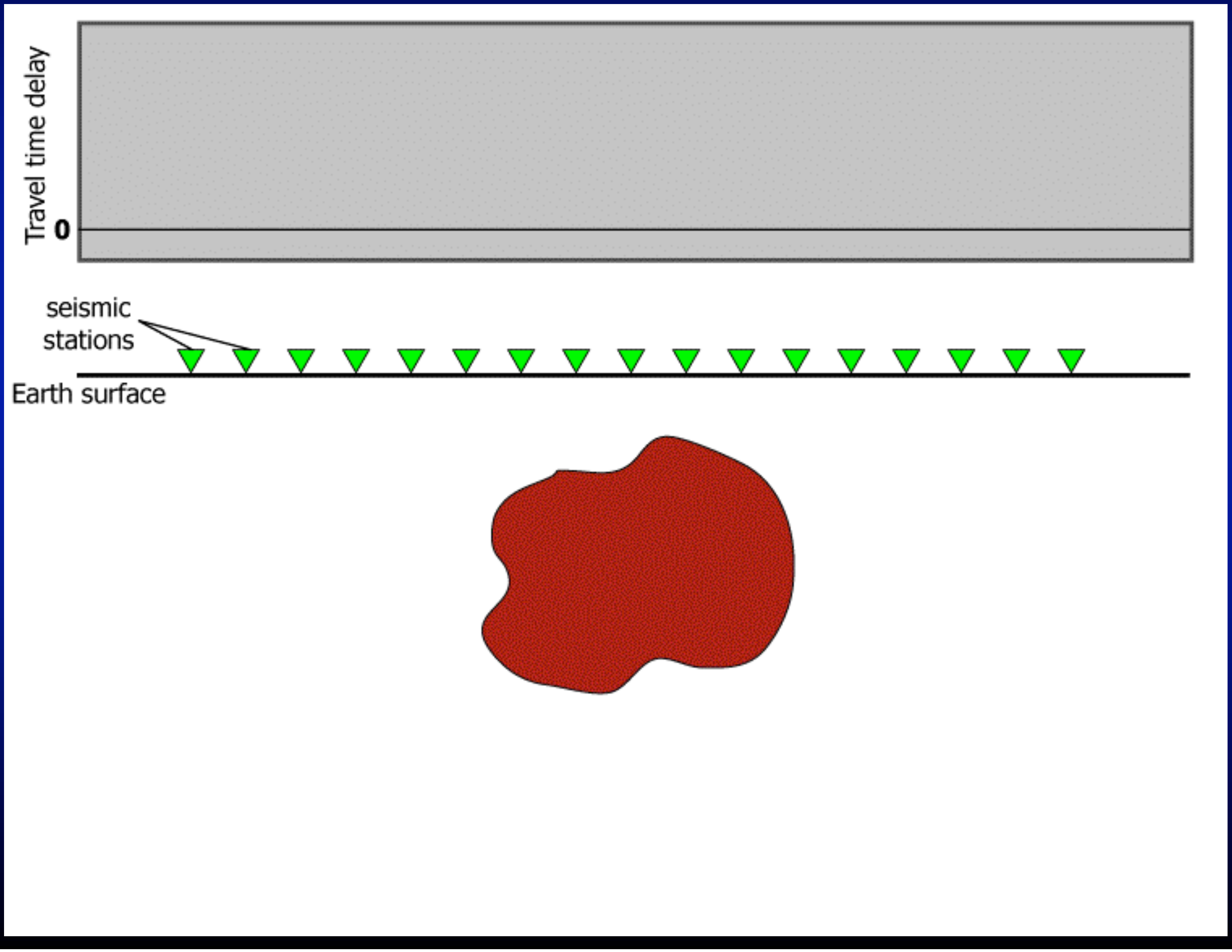




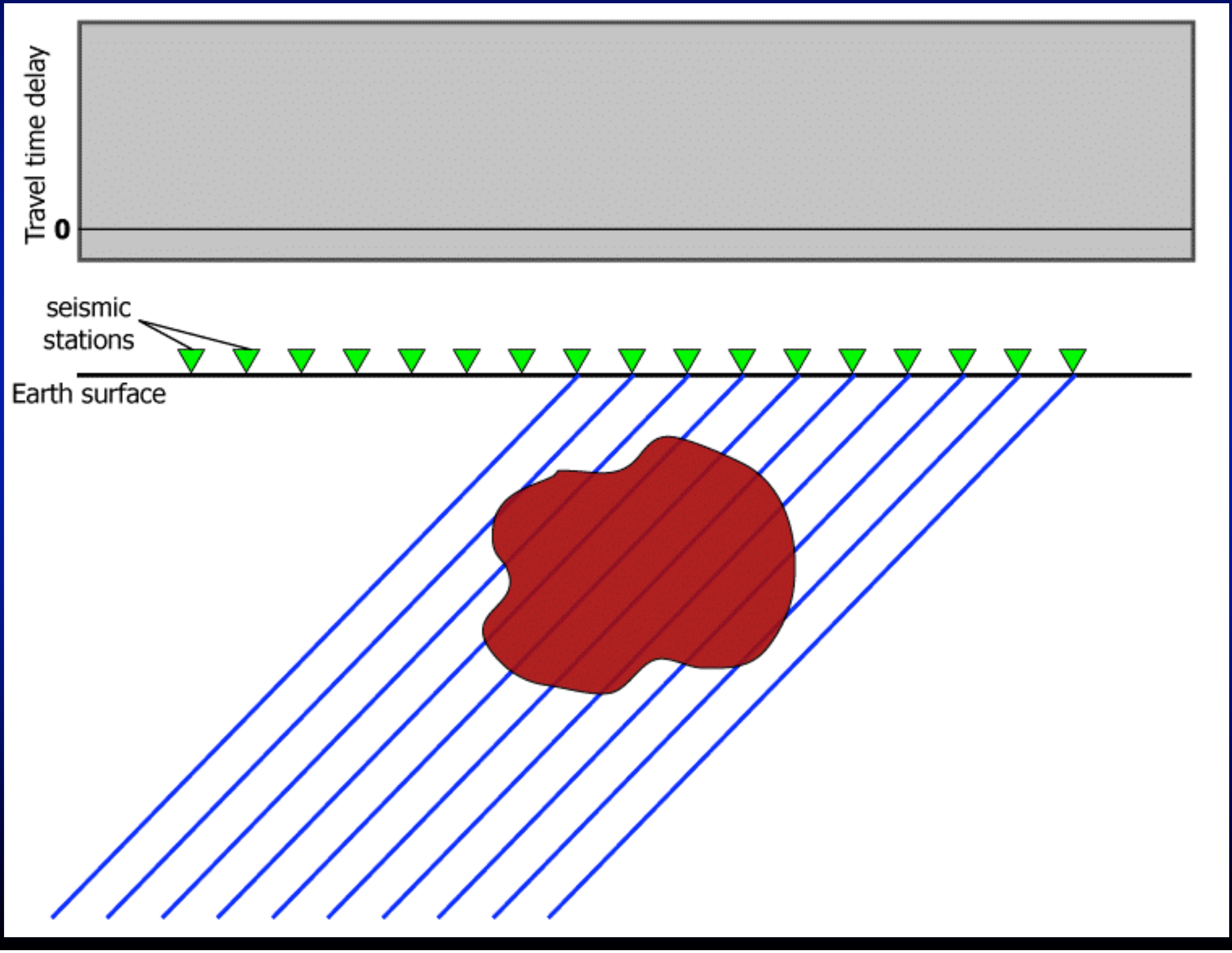
- P waves (left)
- S waves (right)
- Aligned on first peaks of arrivals
- Relative arrival variations measured

Fouch et al. [2004]

Relative Delay Time Example



Relative Delay Time Example



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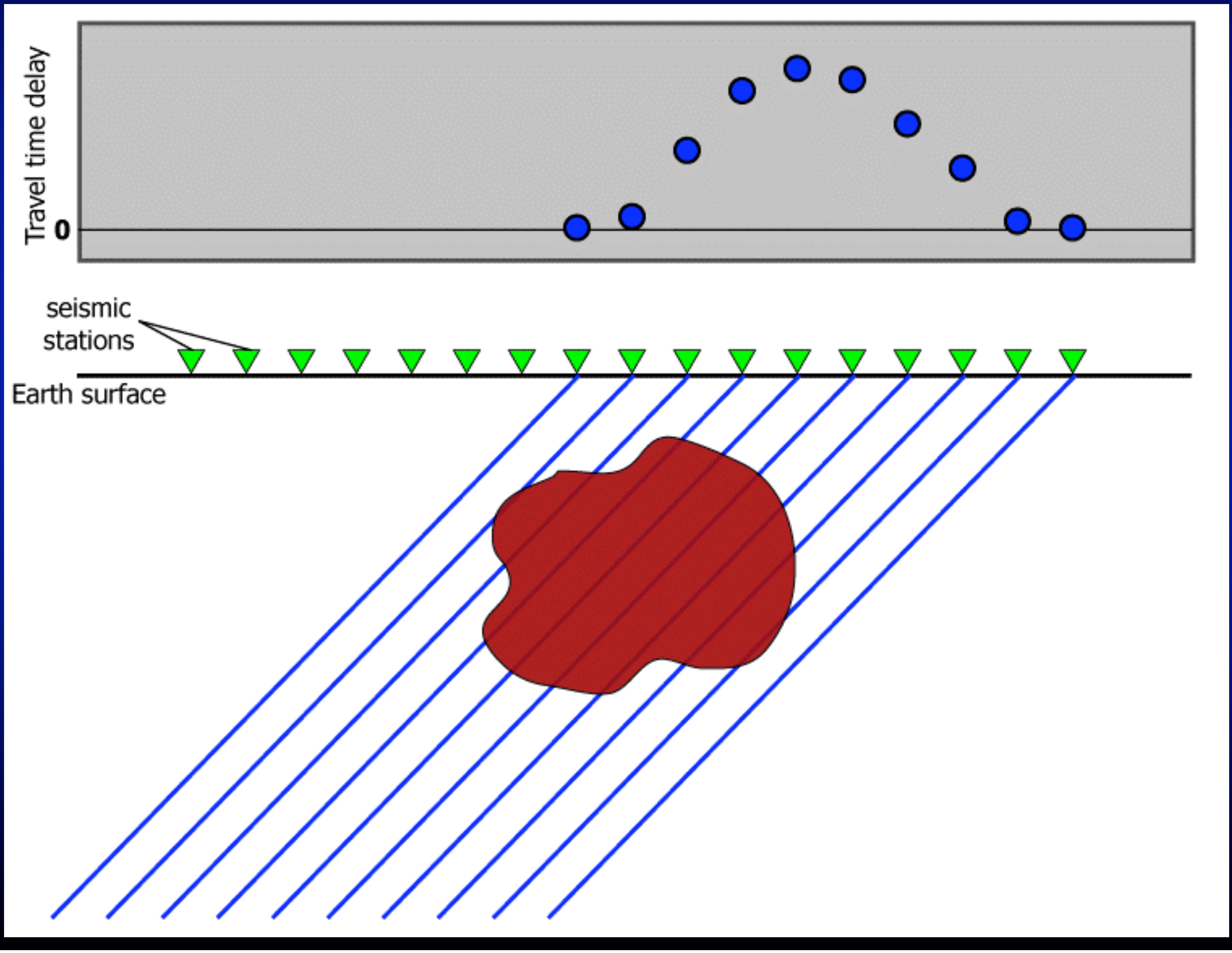

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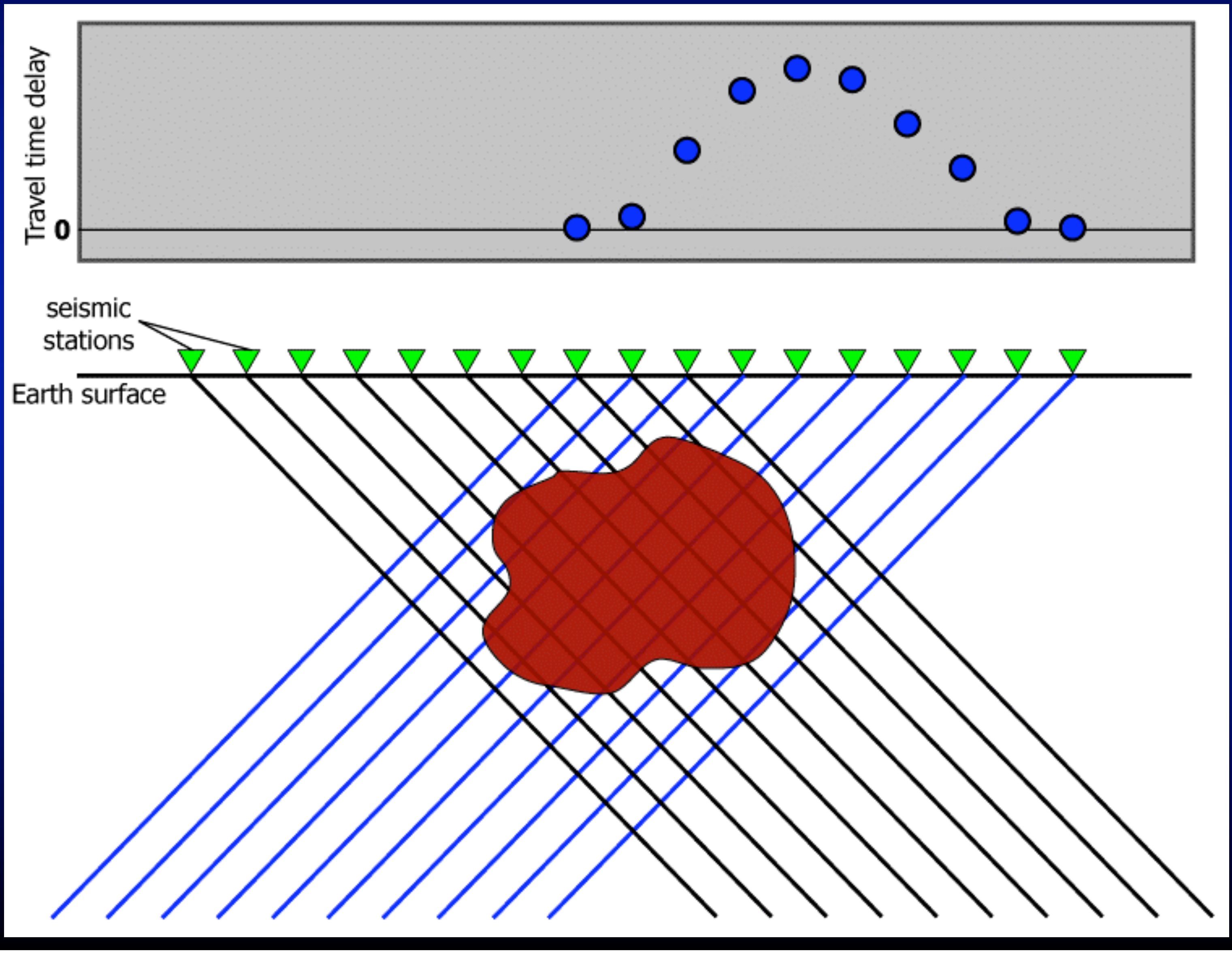

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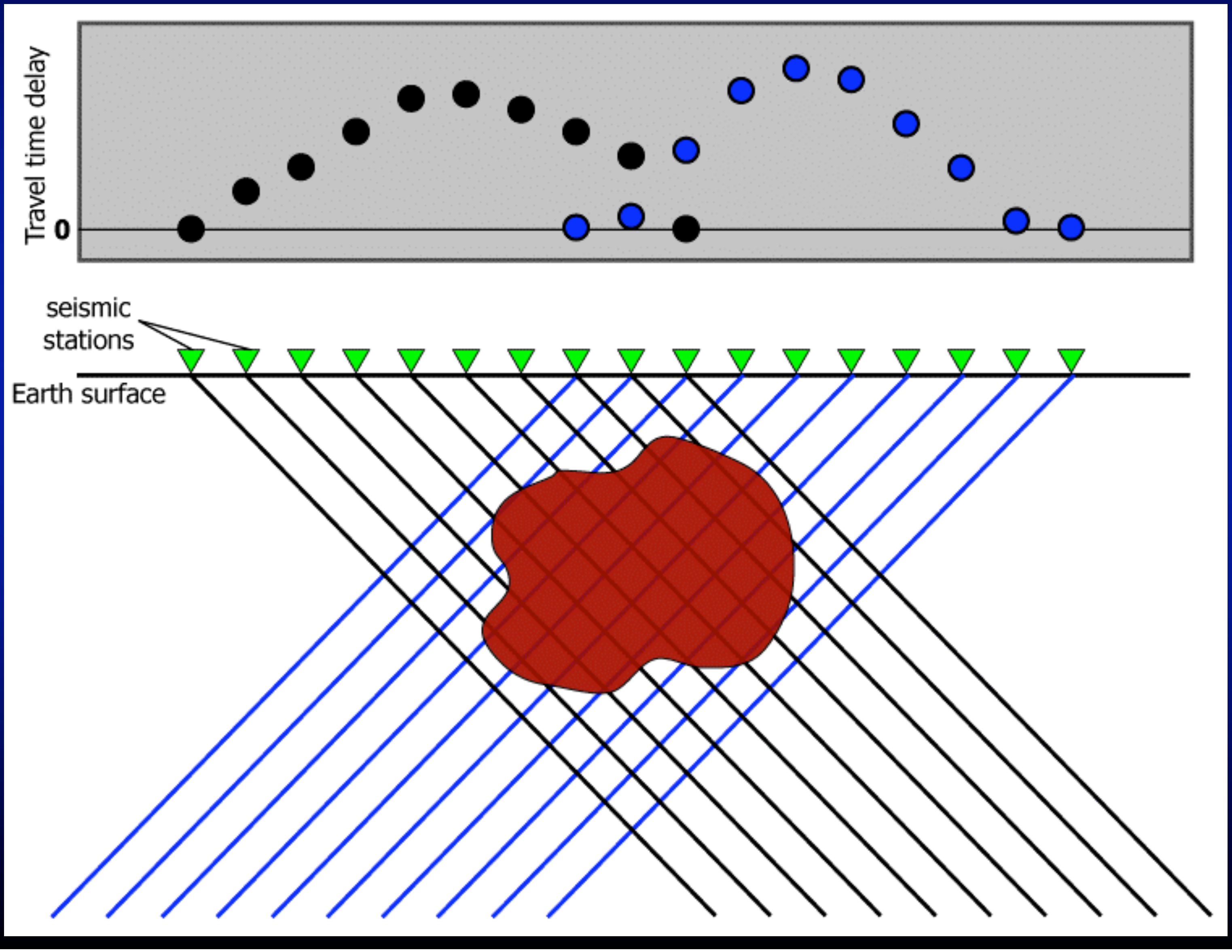
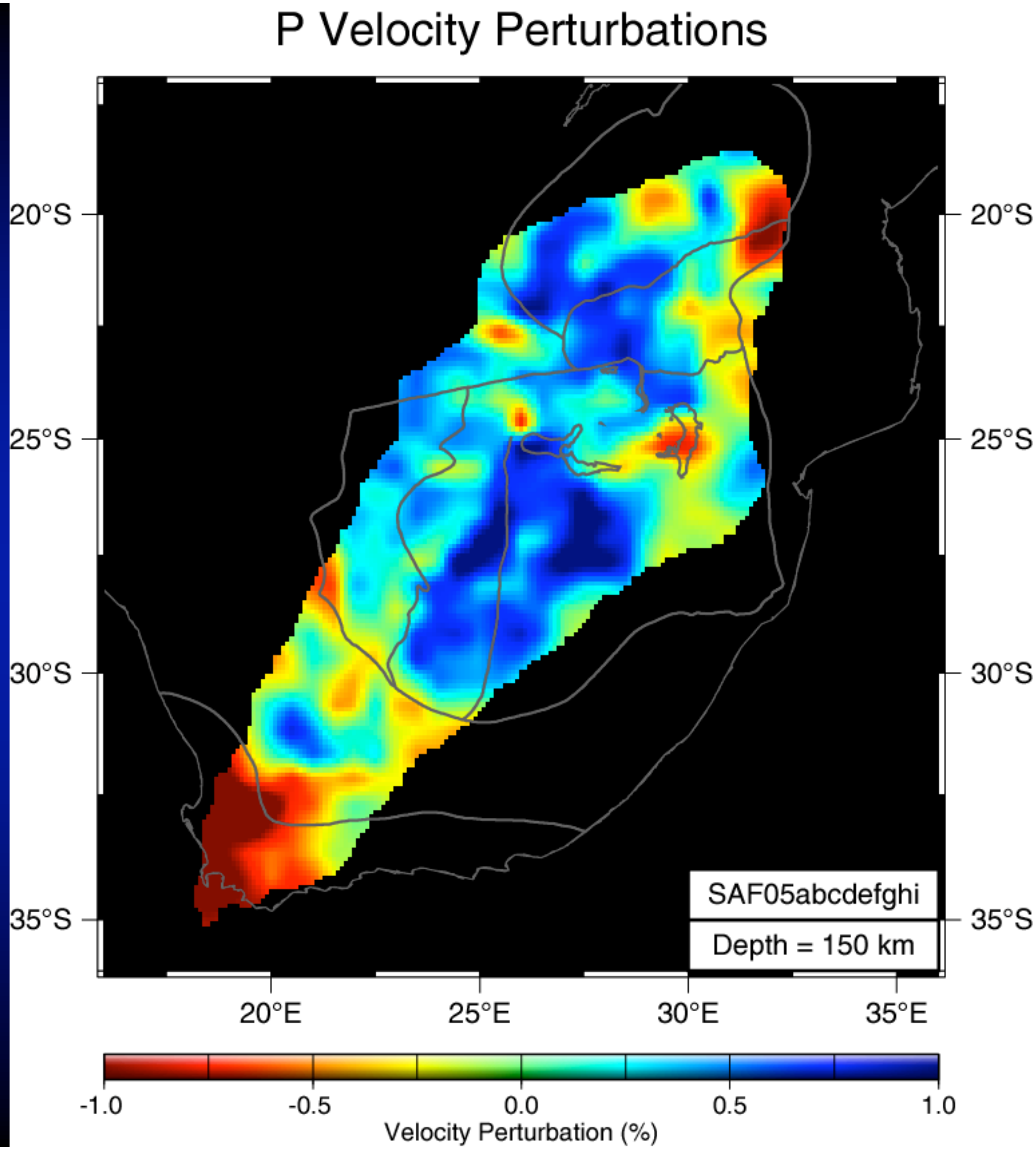


Regional Southern Africa Tomogram

- P-wave model from Kaapvaal Seismic Array data (150 km slice)

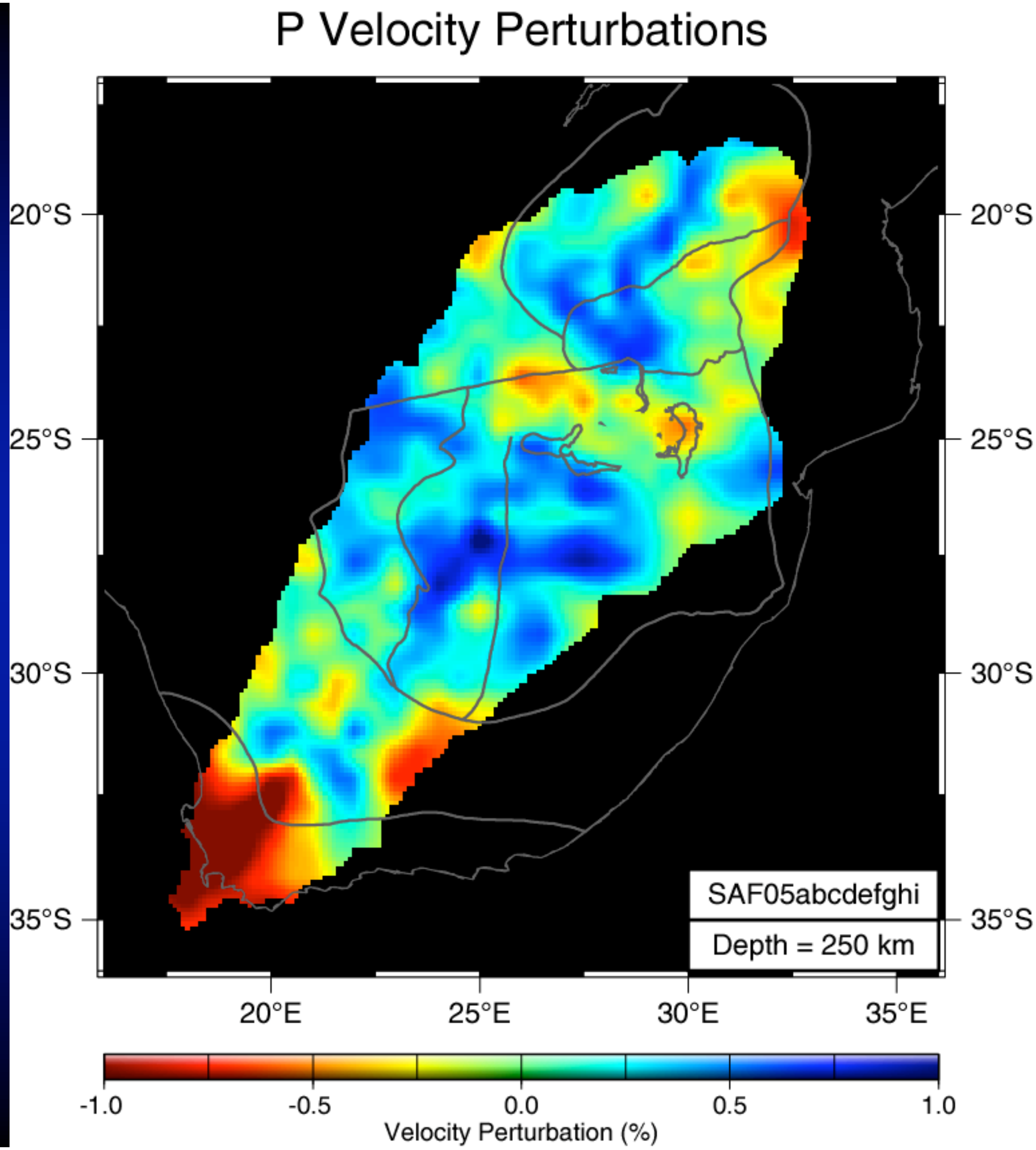
Fouch et al. [2005]



Regional Southern Africa Tomogram

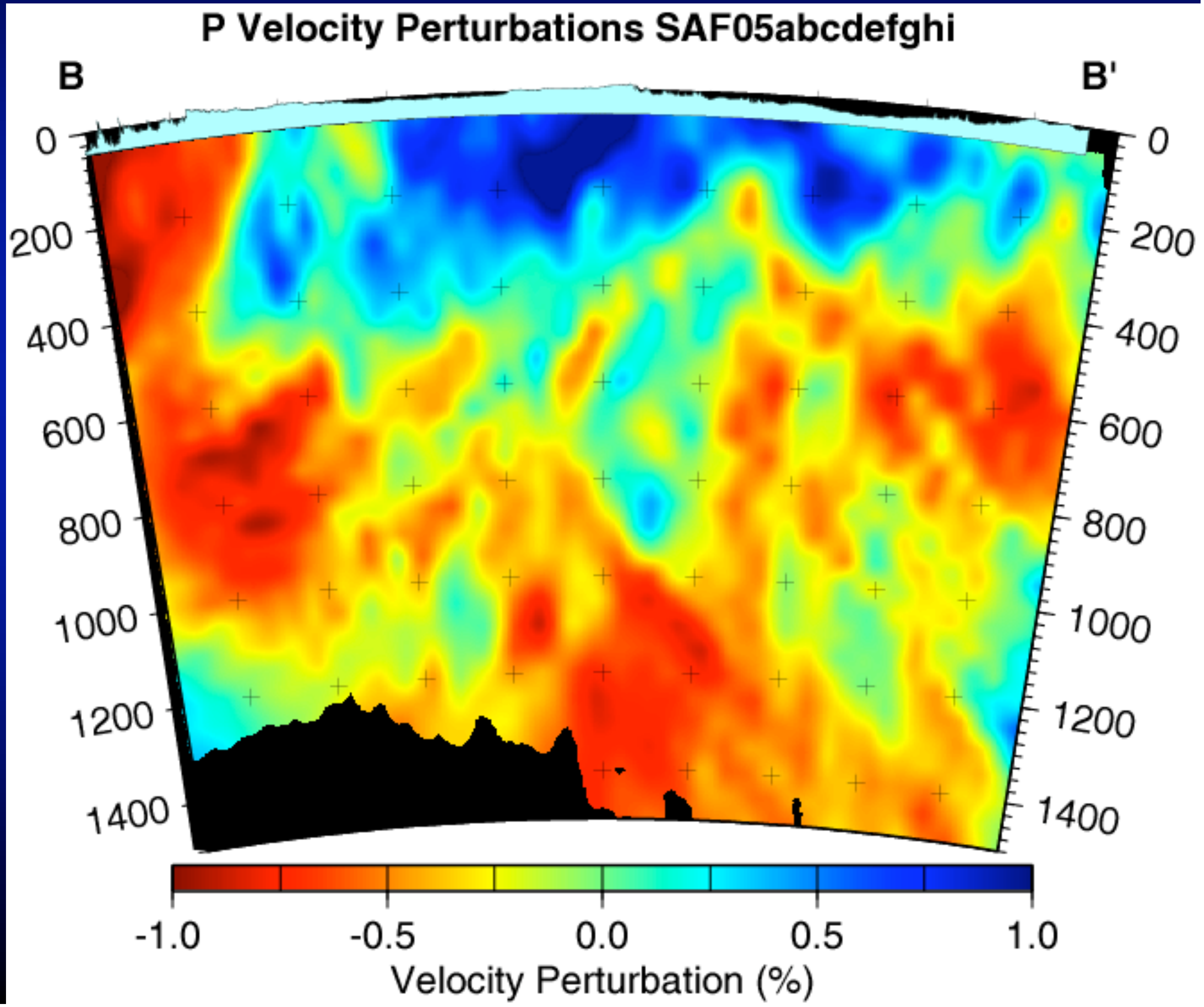
- P-wave model from Kaapvaal Seismic Array data (250 km slice)

Fouch et al. [2005]



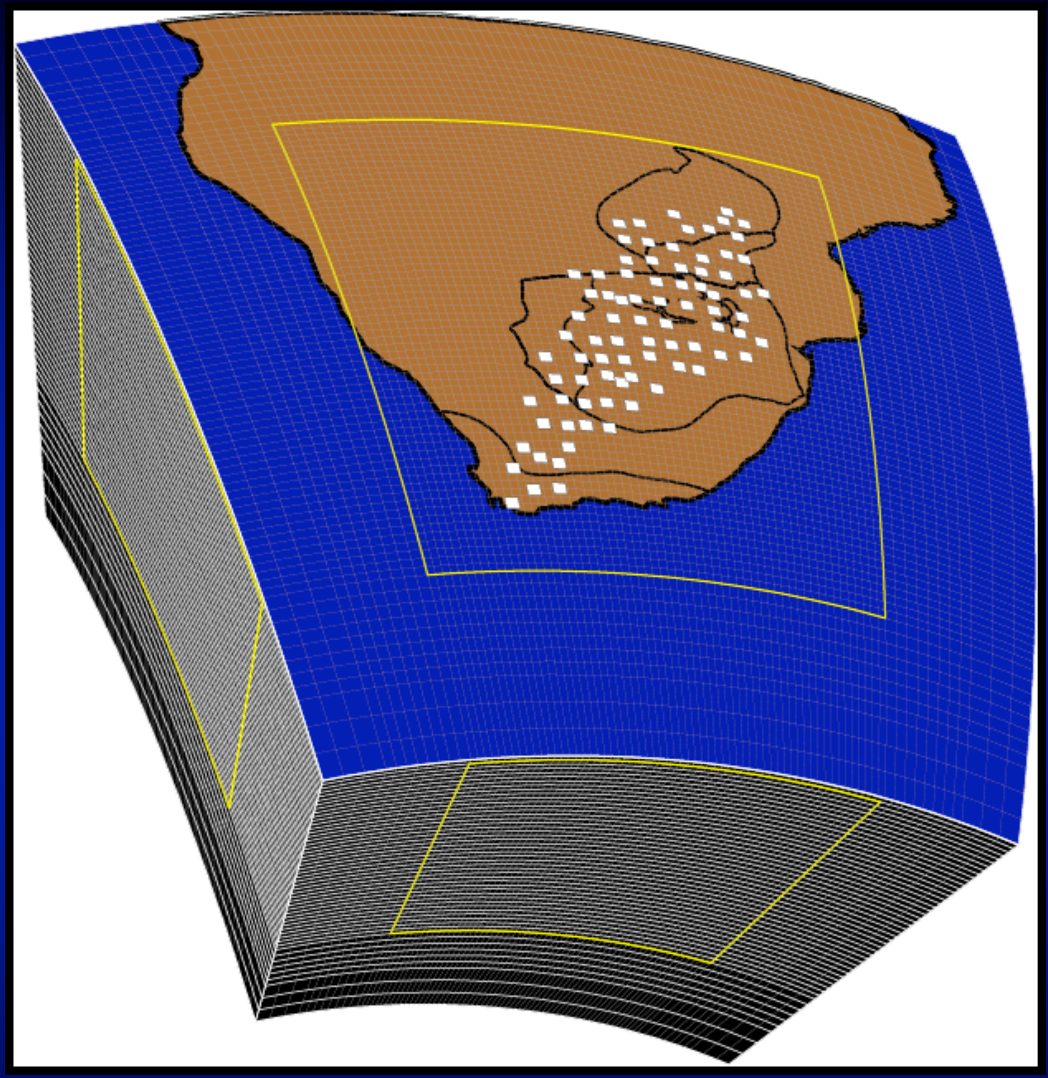
Regional Southern Africa Tomogram

- P-wave model from Kaapvaal Seismic Array data (cross-section)



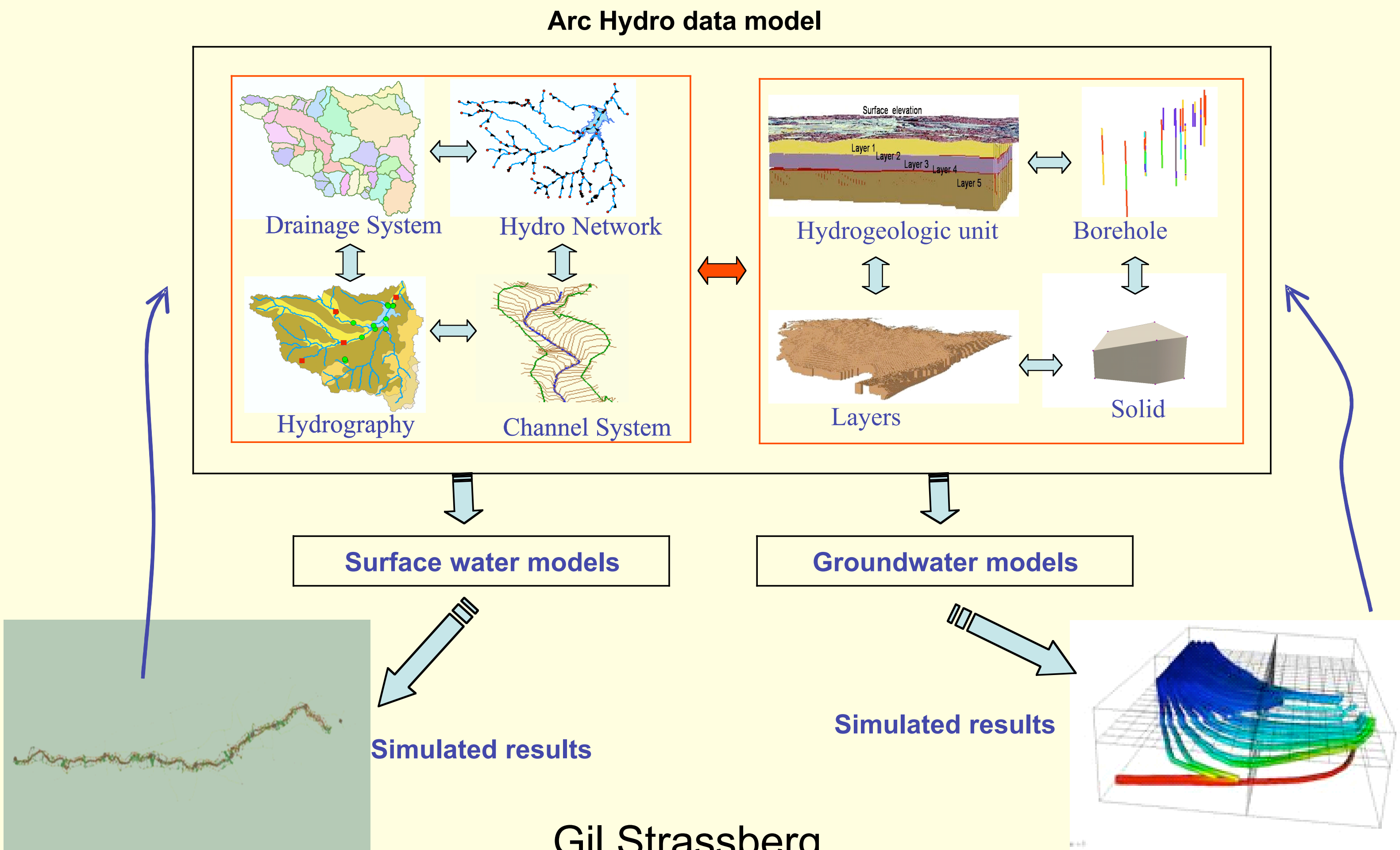
How do we integrate this with other types of data?

We can assign density values to each voxel element based on an established empirical relationship between velocity and density. The trick is what to do if the gravity response does not fit the observed gravity values.



How do we edit and visualize the model?

One way to proceed is to employ GIS technology, and we have developed a conceptual scheme that is based on the recently developed groundwater data model.



Gil Strassberg
Center for Research in Water Resources, UT Austin

Some Elements of the GeoData Model

GeoPoint (Sample locations, GPS control point, instrument location)

Well (Location of a drill hole))

GeoLine (Fault, joint, axis of a fold, lineament, flight line)

BoreLine (Multinode (x,y,z) ine; nodes are interface intersections)

GeoArea (Outcrop of a geologic unit, fault surface, geochemical zone)

GeoSection (Cross-section along a plane with an arbitrary orientation)

WaterArea (An area such as a lake)

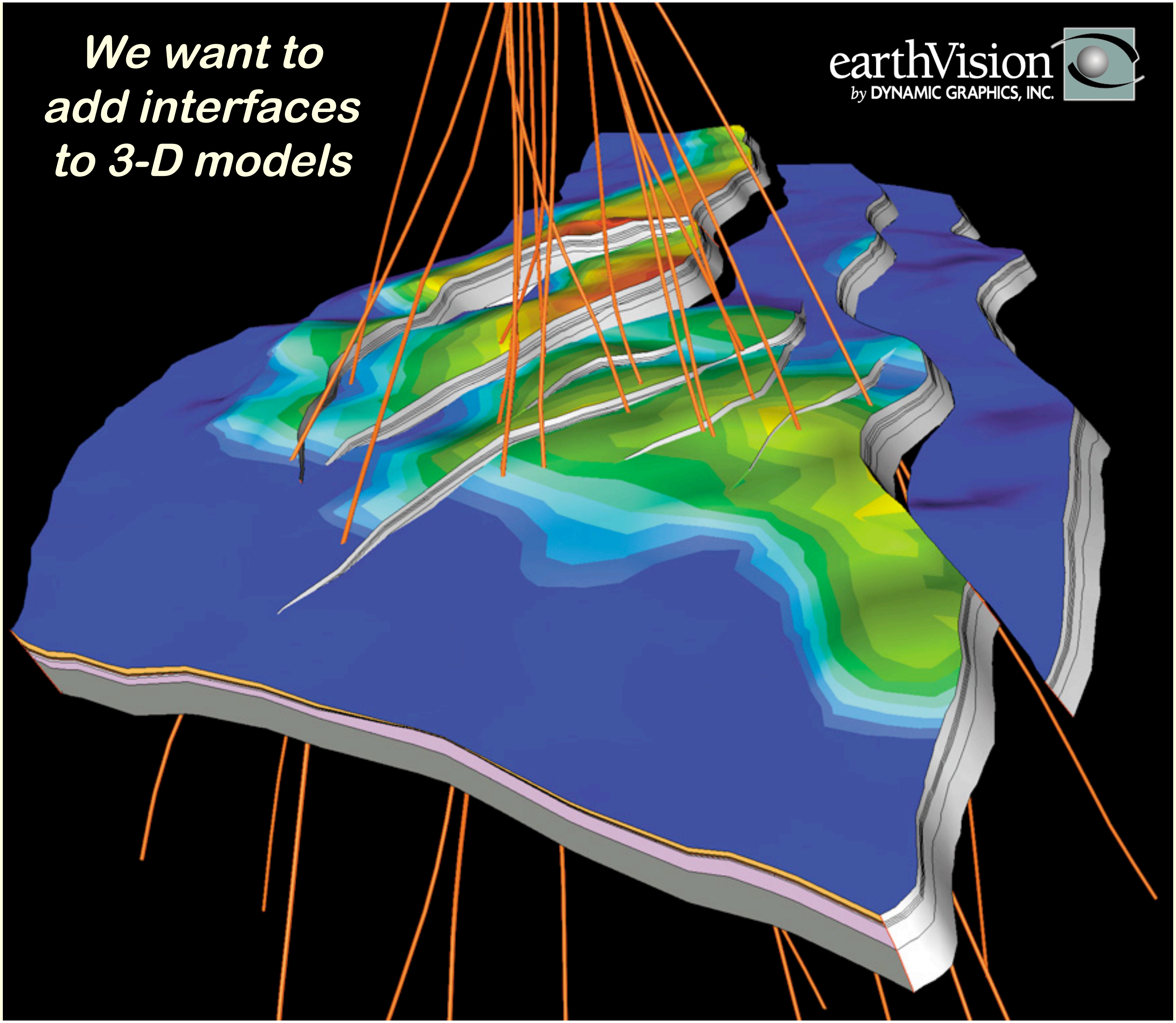
Items matched to the groundwater data model

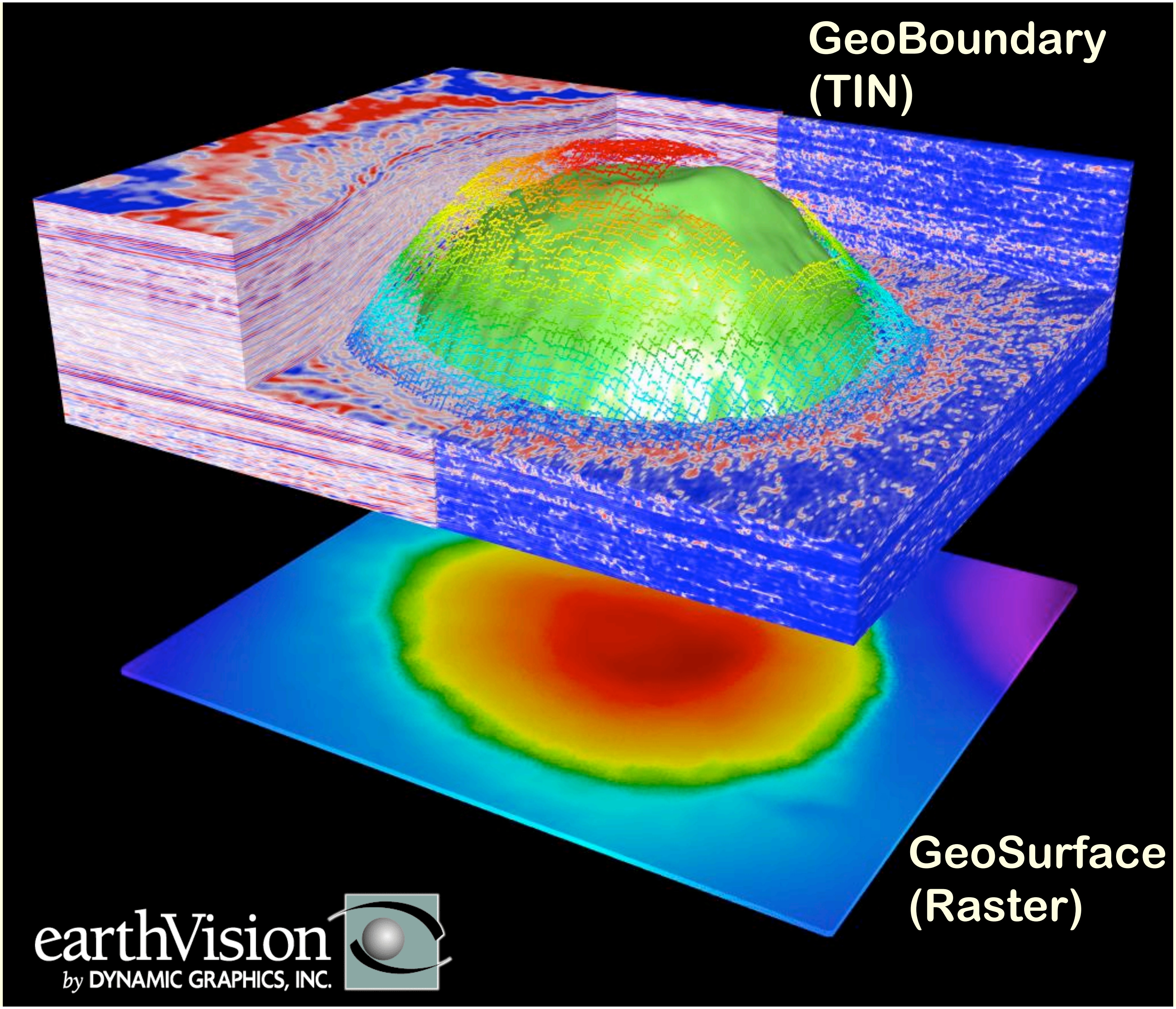
Some Elements of the GeoData Model

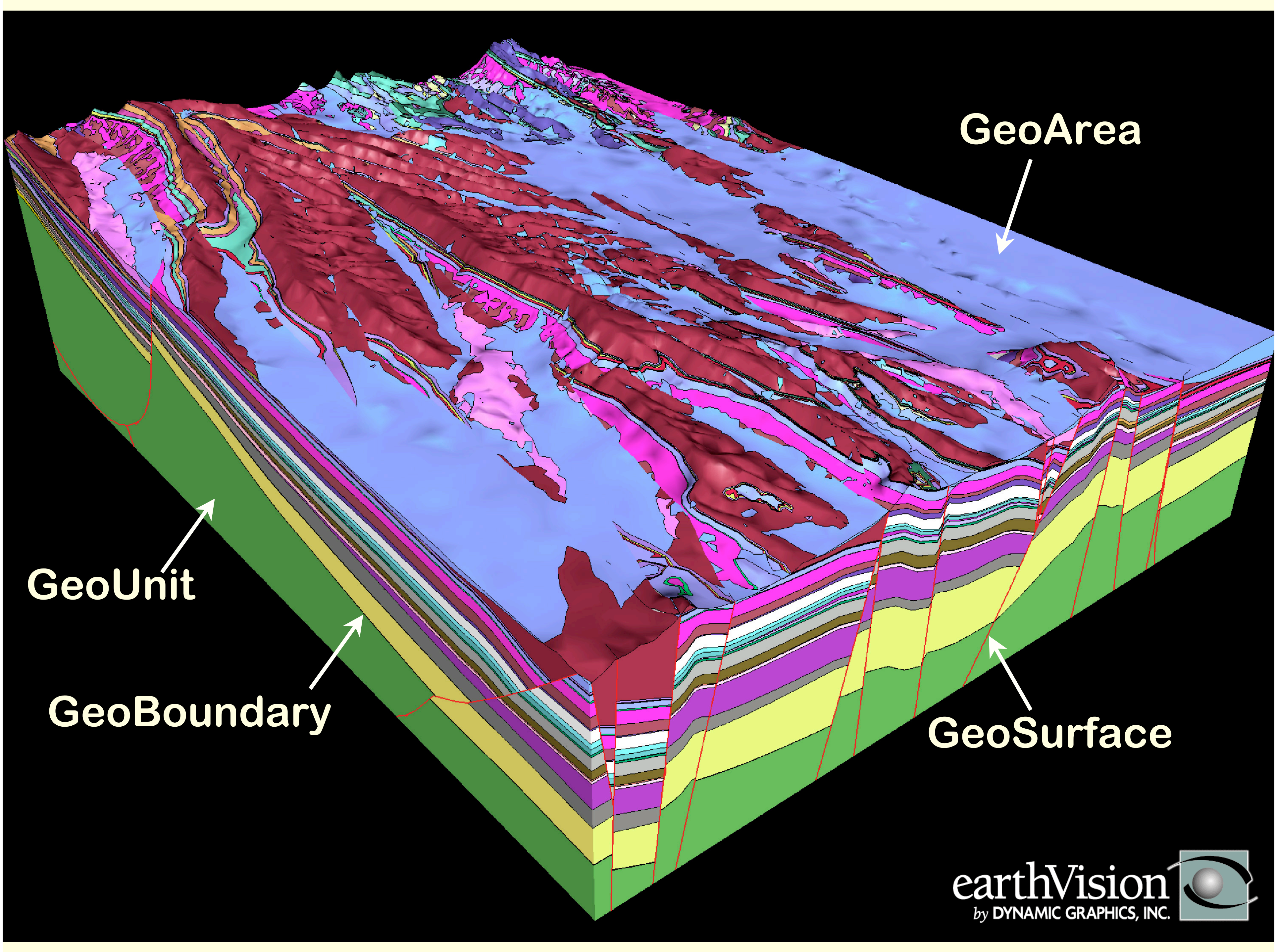
- **GeoSurface** (A raster represenation of a geologic surface - 2.5 D)
- **GeoImage** (A raster image of geological interest)
- **GeoVolume** (A closed surface in 3-D; igneous body, ore body-Multipatch)
- **GeoRaster** (A grid of voxels with physical properties as attributes - 3D)
- **GeoBoundary_T** (A TIN representing a geological surface)
- **GeoBoundary_M** (A Multipatch representing a geological surface)
- **GeoUnit** (A geological unit defined as the region between 2 GeoBoundaries)

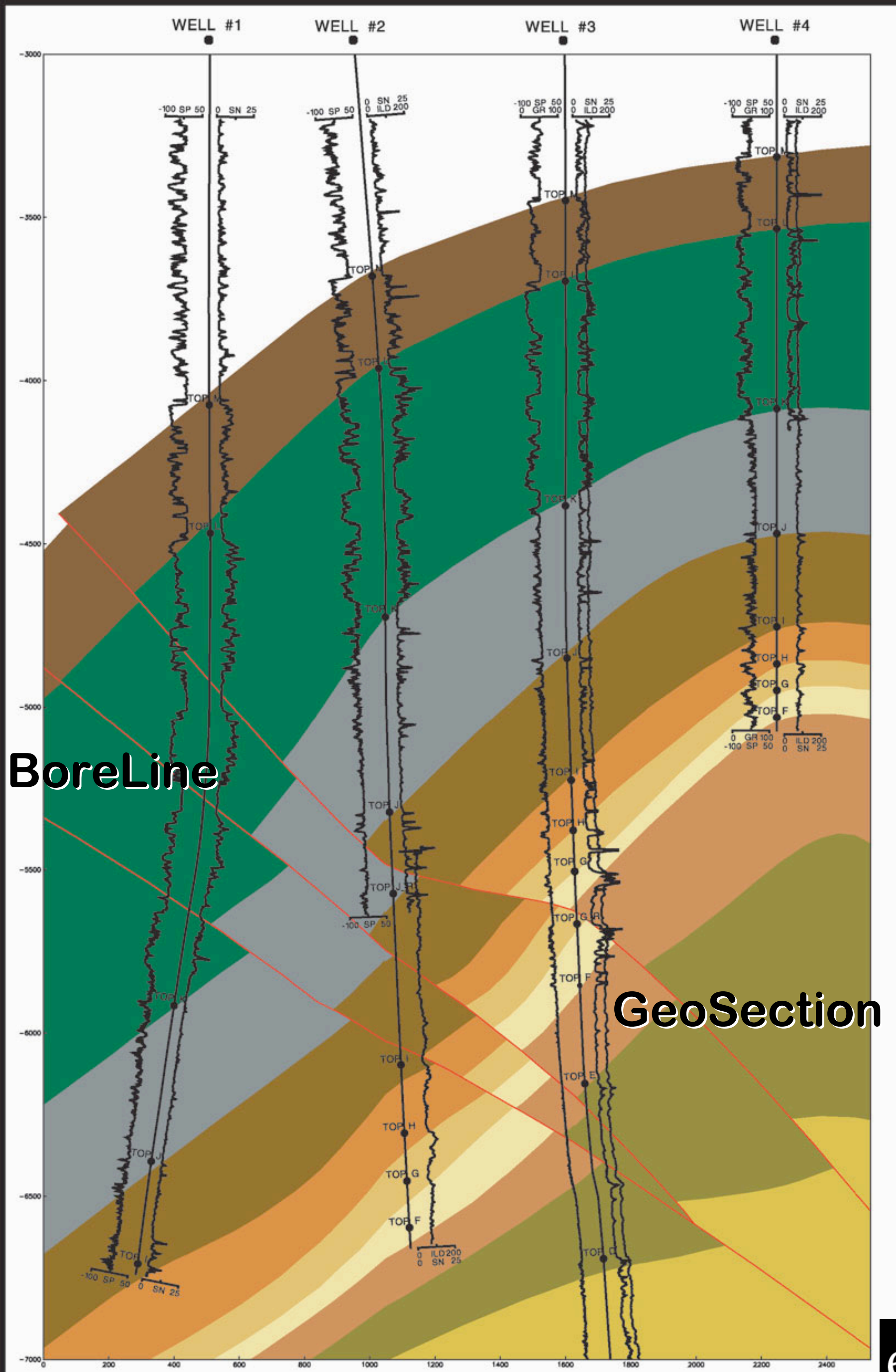
Additional items (GeoVector - GPS, plate motion, fault slip; Geo???)

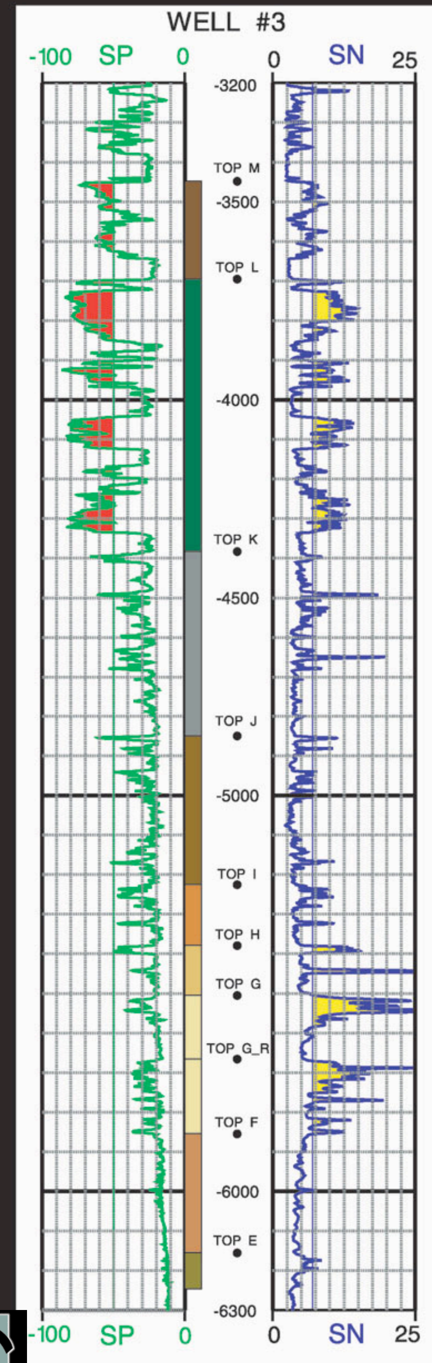
We want to add interfaces to 3-D models



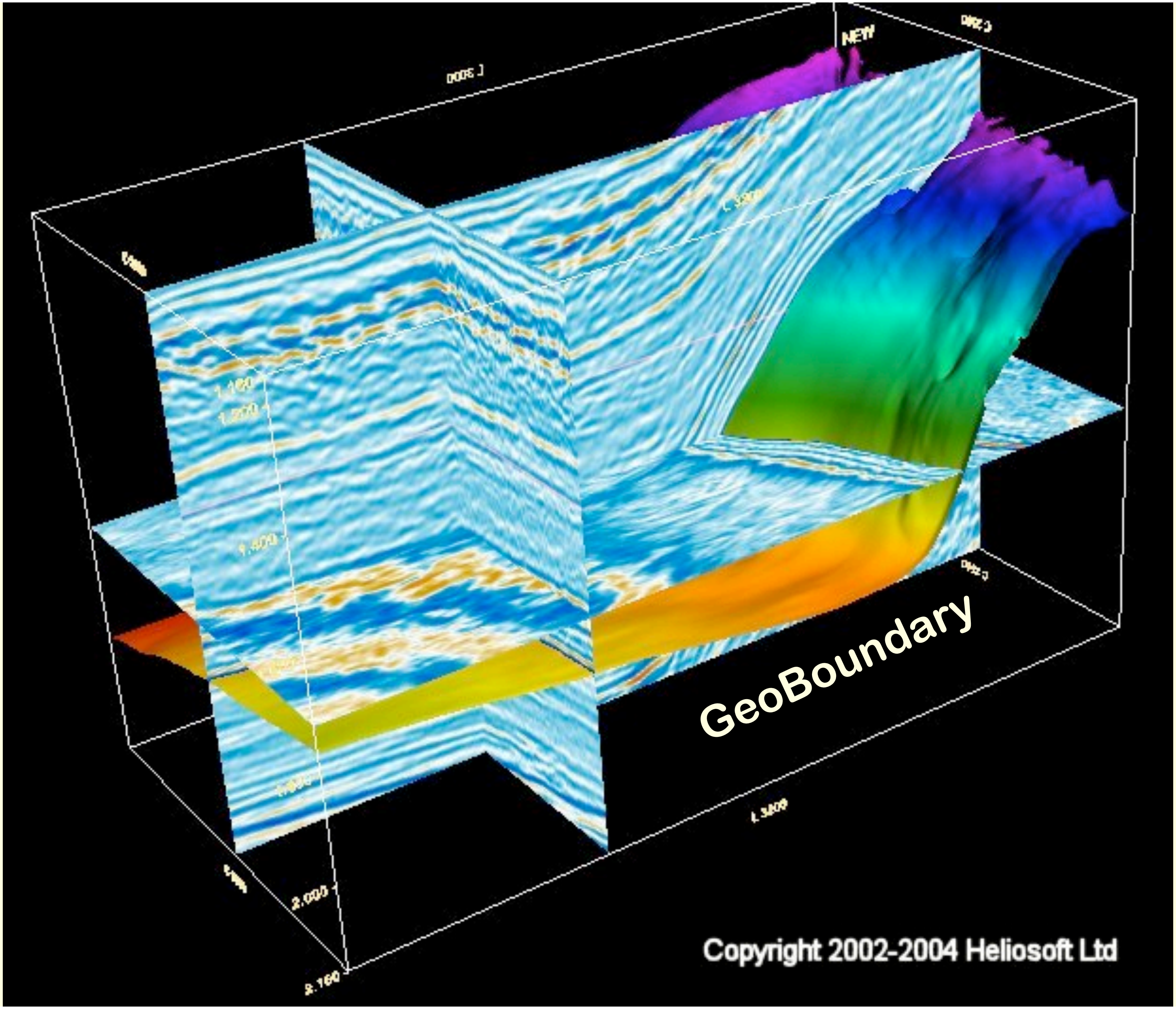

GeoBoundary
(TIN)
GeoSurface
(Raster)
earthVision
by DYNAMIC GRAPHICS, INC.


GeoArea
GeoUnit
GeoBoundary
GeoSurface
earthVision
by DYNAMIC GRAPHICS, INC.

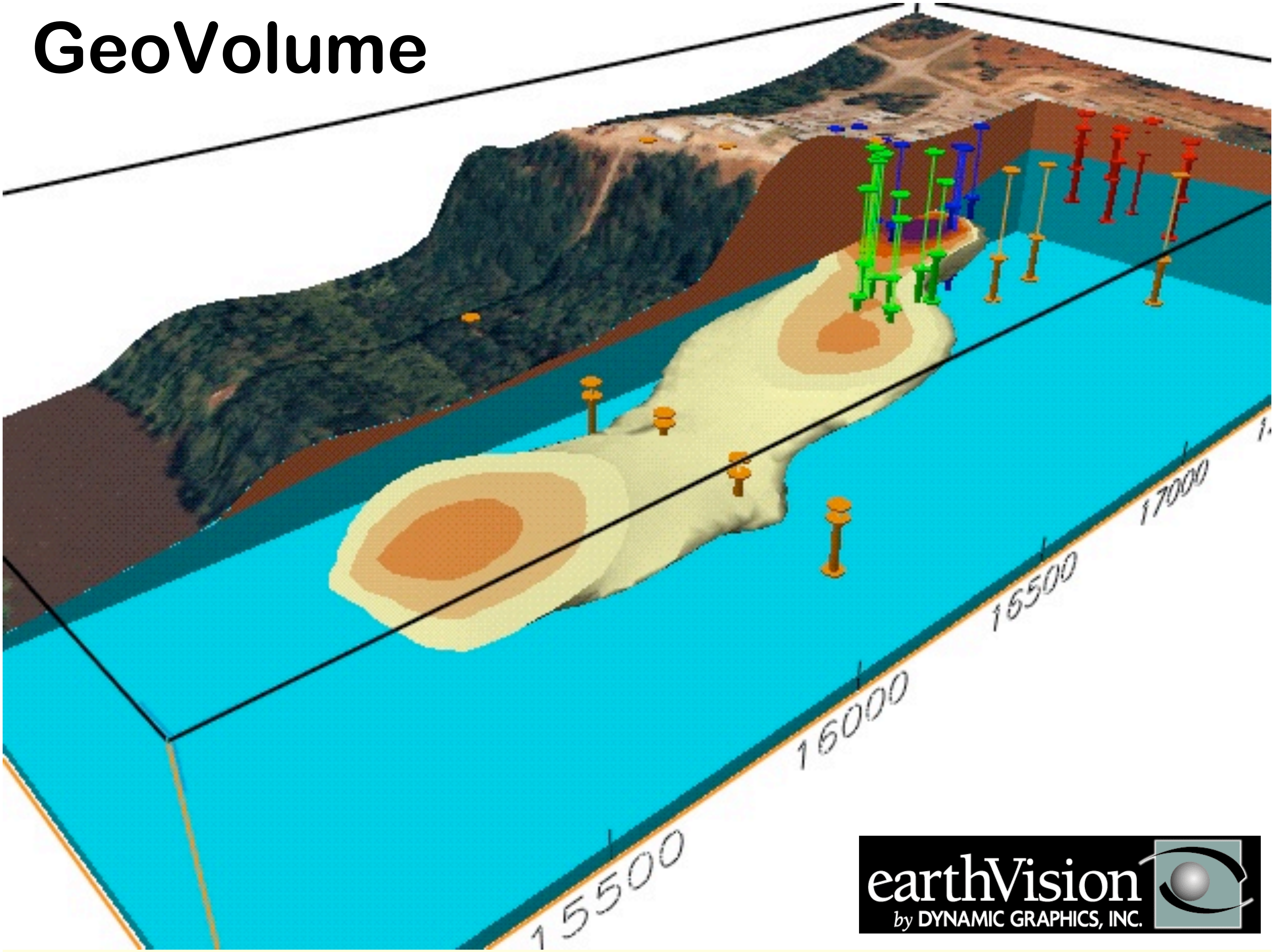




earthVision by DYNAMIC GRAPHICS, INC.

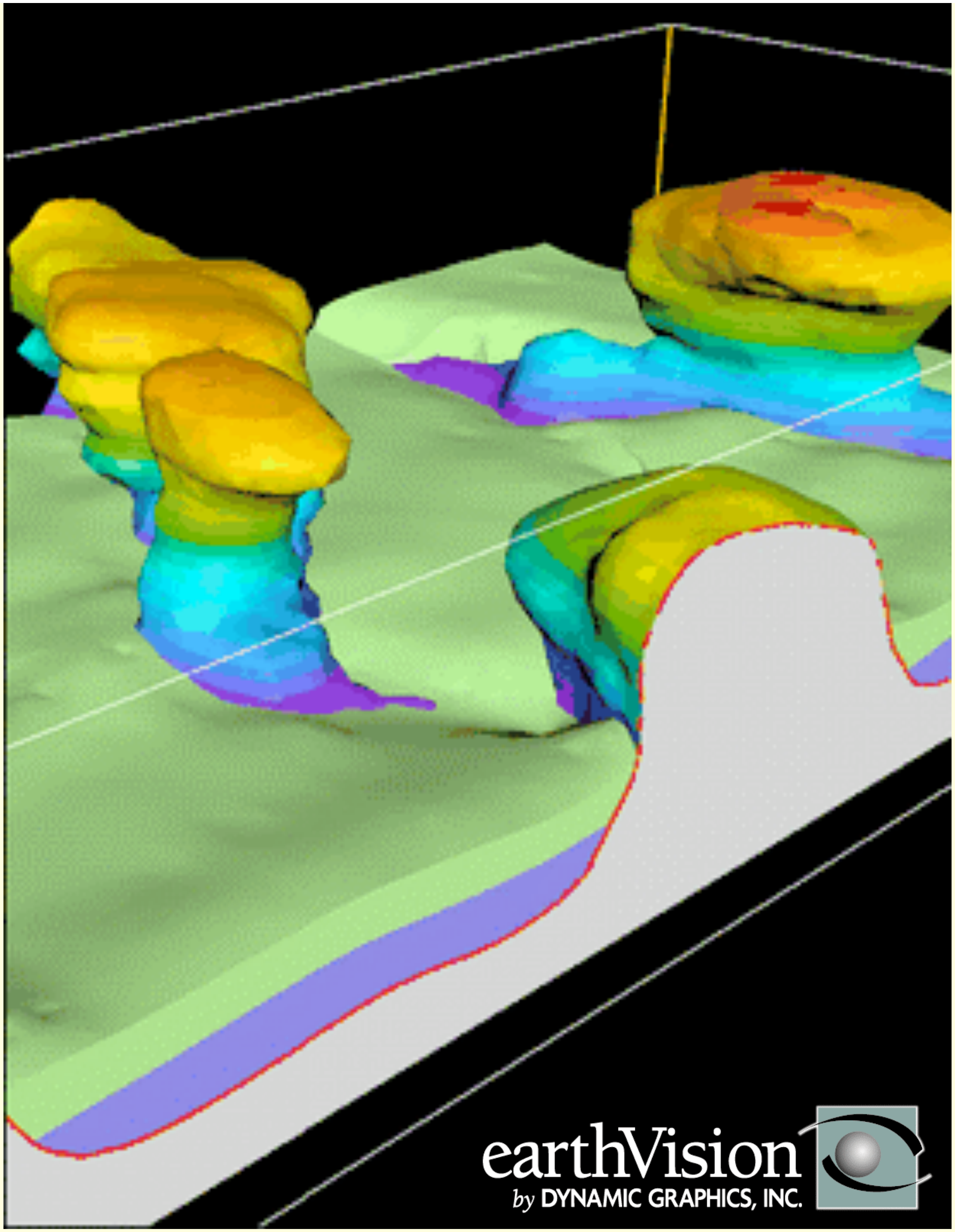

GeoBoundary
Copyright 2002-2004 Heliosoft Ltd

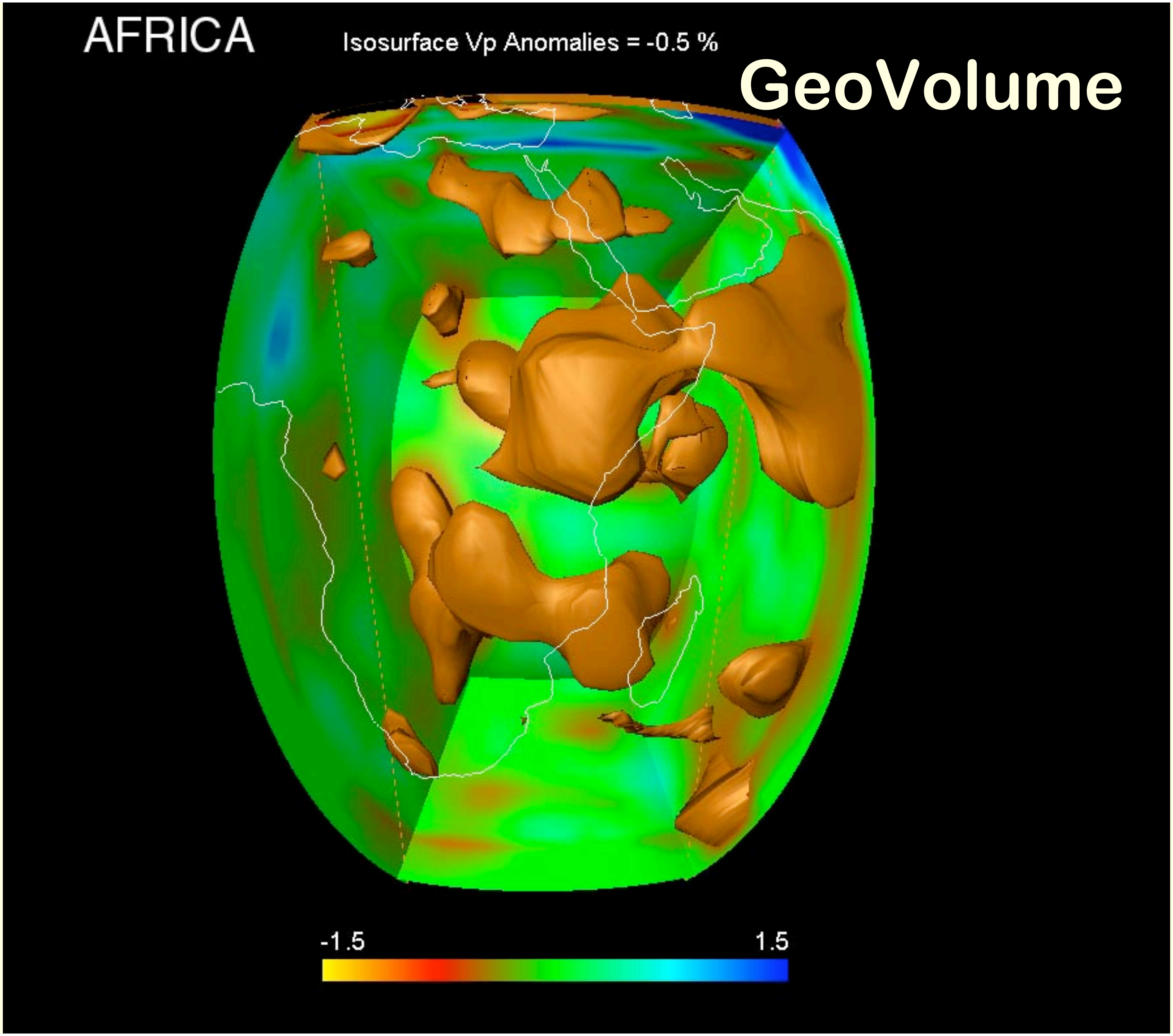
GeoVolume


15500
16000
16500
17000
earthVision
by DYNAMIC GRAPHICS, INC.

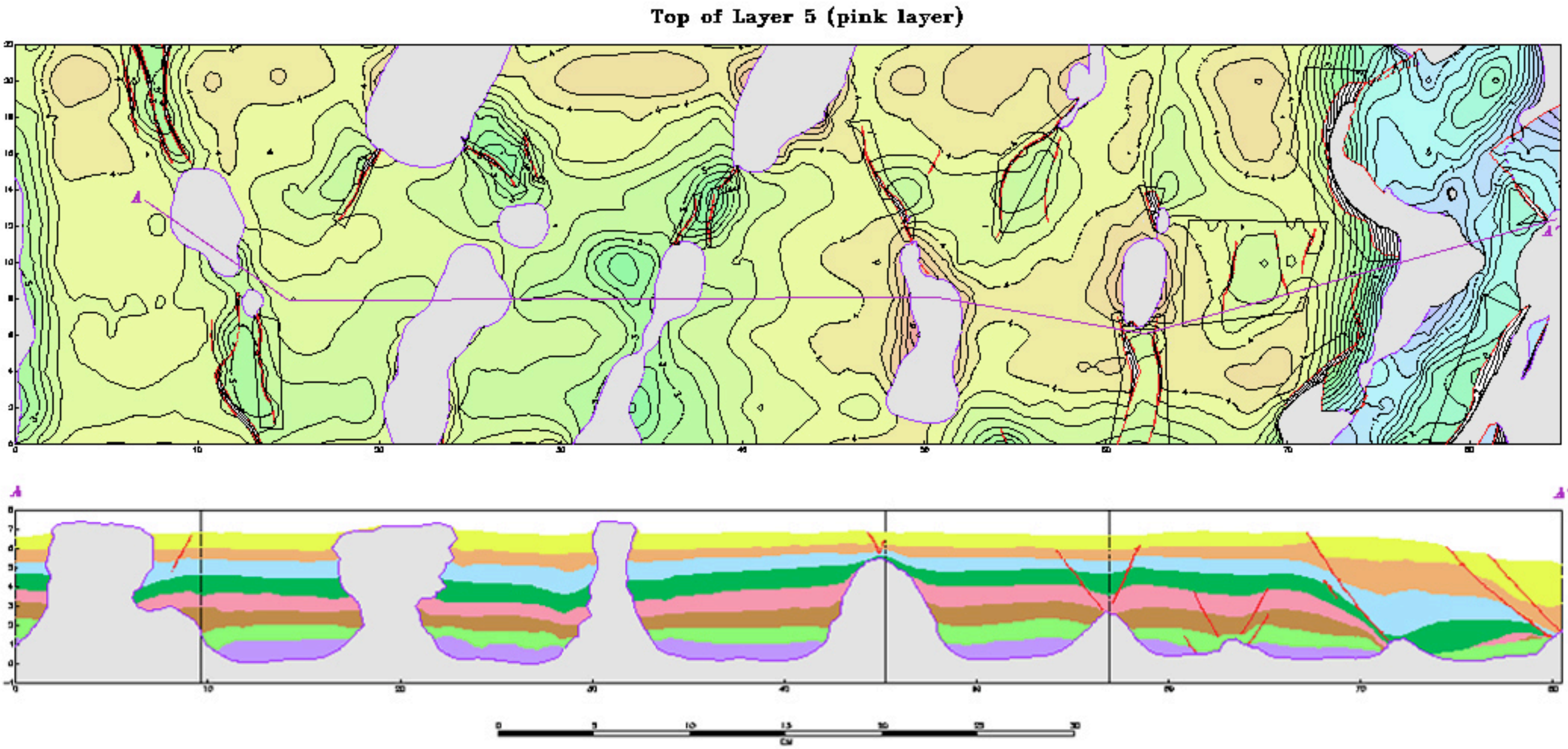
Geovolume

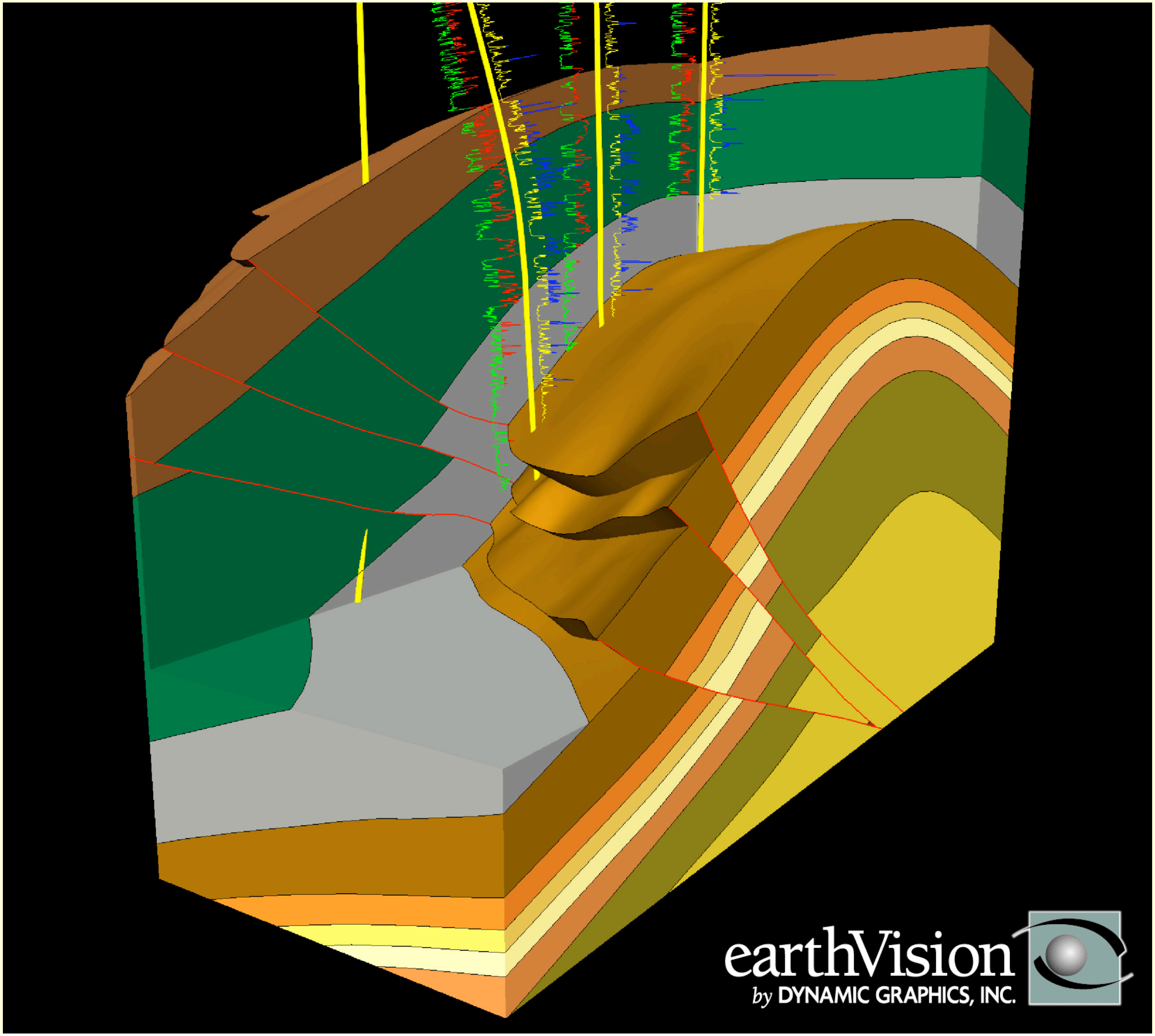
Salt domes




AFRICA
Isosurface Vp Anomalies = -0.5 %
GeoVolume
-1.5
1.5

We also want to slice the data volumes along arbitrary



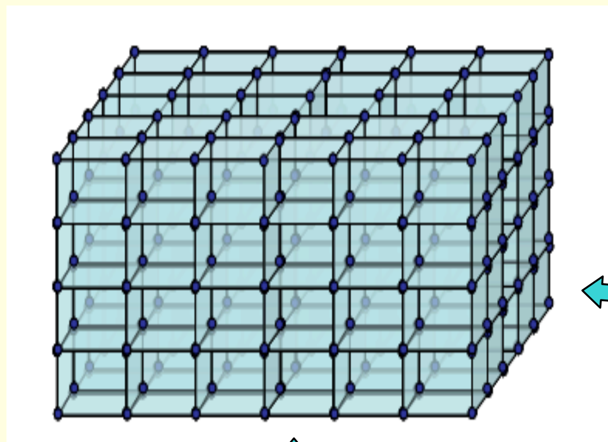

earthVision
by DYNAMIC GRAPHICS, INC.

This type of GIS capability does not exist yet, but it is on the way. It is certainly one way to be able to edit voxel-based models and insert interfaces. A model such as this could be expanded and updated as more data become available.

Integrated modeling scheme

2.5 or 3-D, P-wave tomography (active source, local earthquakes)

Assign densities via Vp - ρ relationship Calculate gravity response



Joint receiver function and surface wave inversion

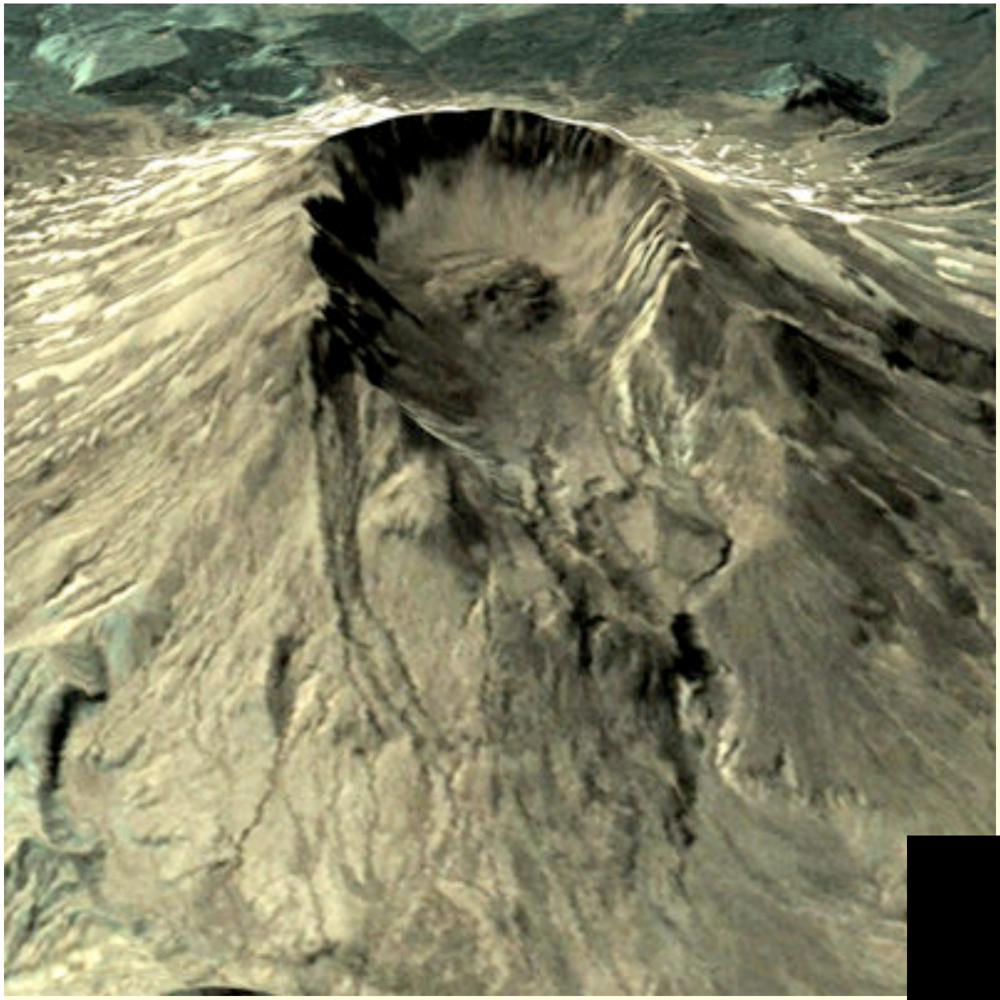
Joint P-wave tomography and receiver function inversion

Magnetic modeling of upper crust

Other seismic properties (e.g., attenuation, anisotropy)

Independent constraints (drill holes, geology, etc.

Integration via visualization is also a useful qualitative option.



Mount St. Helens example of the visual integration of seismic tomography and earthquake hypocenters

The animation was constructed using the GEON IDV using data provided by Greg Waite of the USGS.