The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2053-27

Advanced Workshop on Evaluating, Monitoring and Communicating Volcanic and Seismic Hazards in East Africa

17 - 28 August 2009

Active- and passive-source seismic imaging of crustal architecture and magmatism in East Africa

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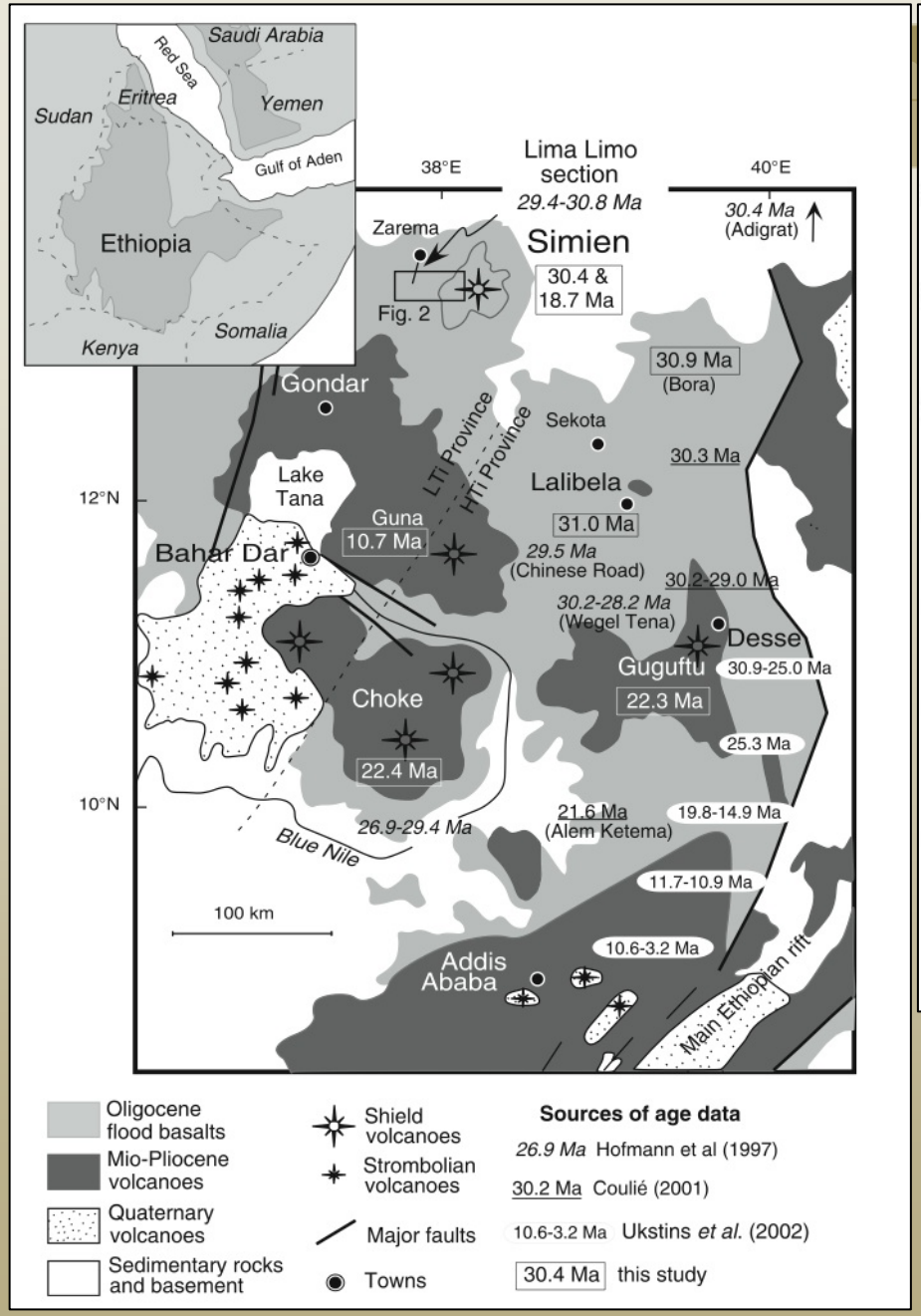
Active-source seismic imaging of crustal structure in East Africa

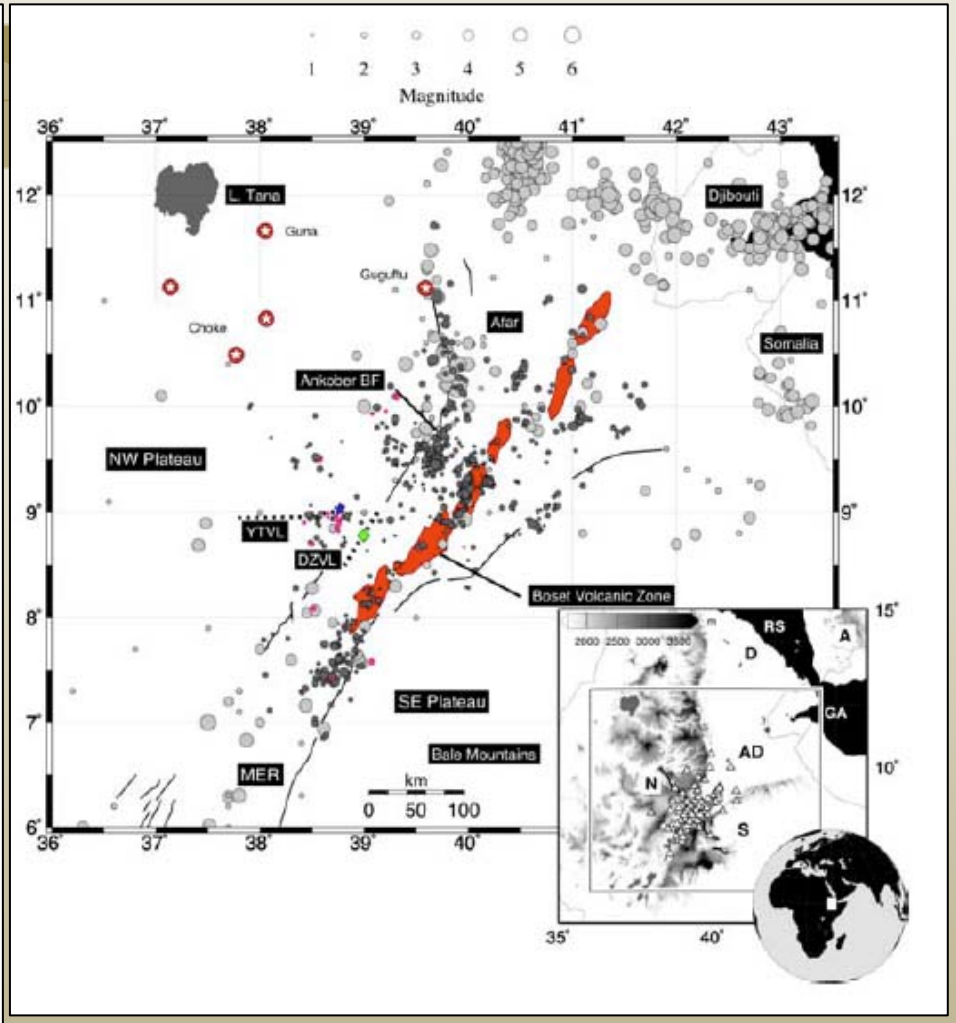
(the 2001-2003 EAGLE project in Ethiopia)

Katie Keranen (keranen@ou.edu)
School of Geology and Geophysics, University of Oklahoma
With results achieved by the entire EAGLE team

Workshop goals

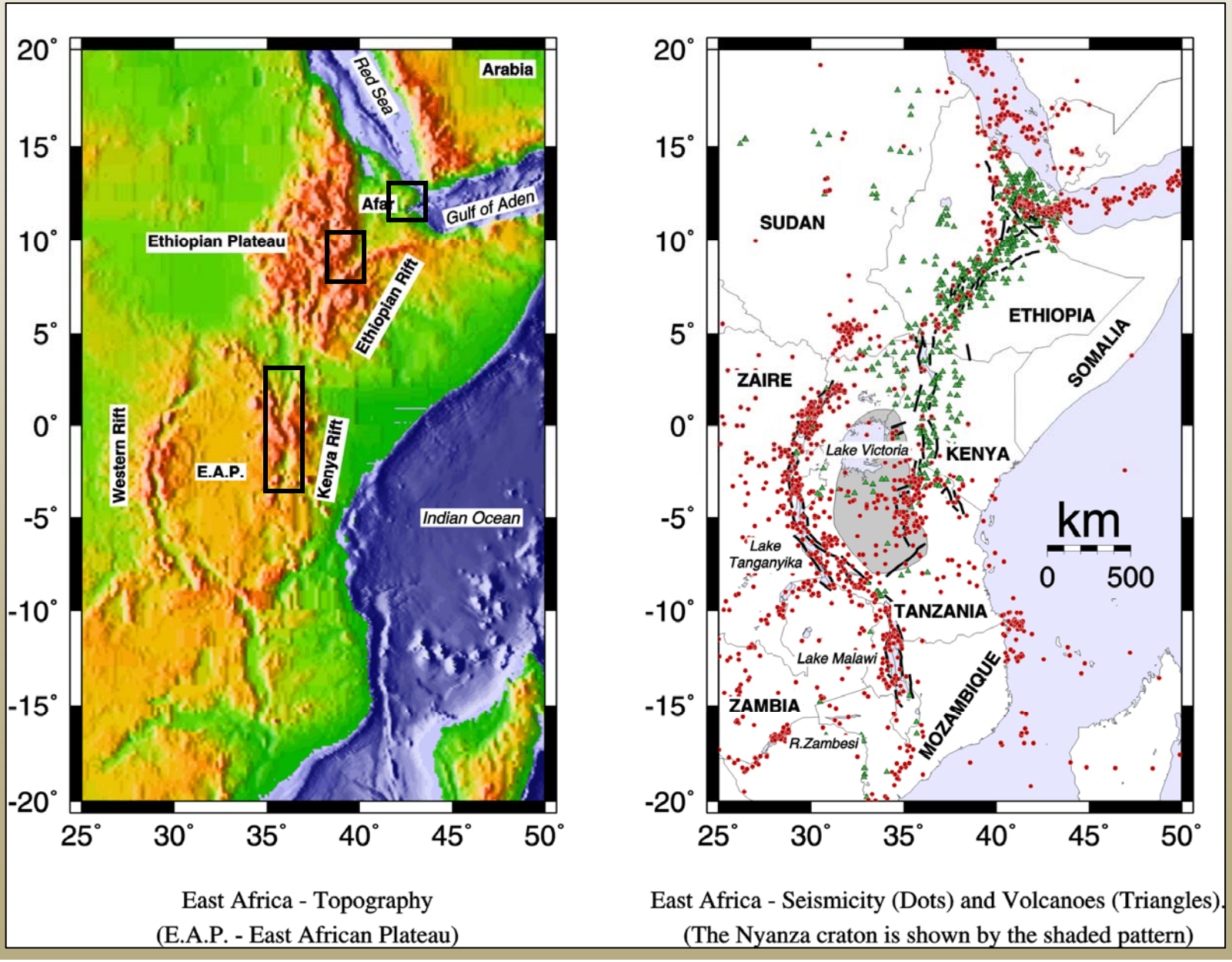
- “Develop and enhance plans for investigations of **processes** leading to volcanic eruptions and large earthquakes in continental rift zones”





Seismicity and volcanism in Ethiopia

The East African Rift System



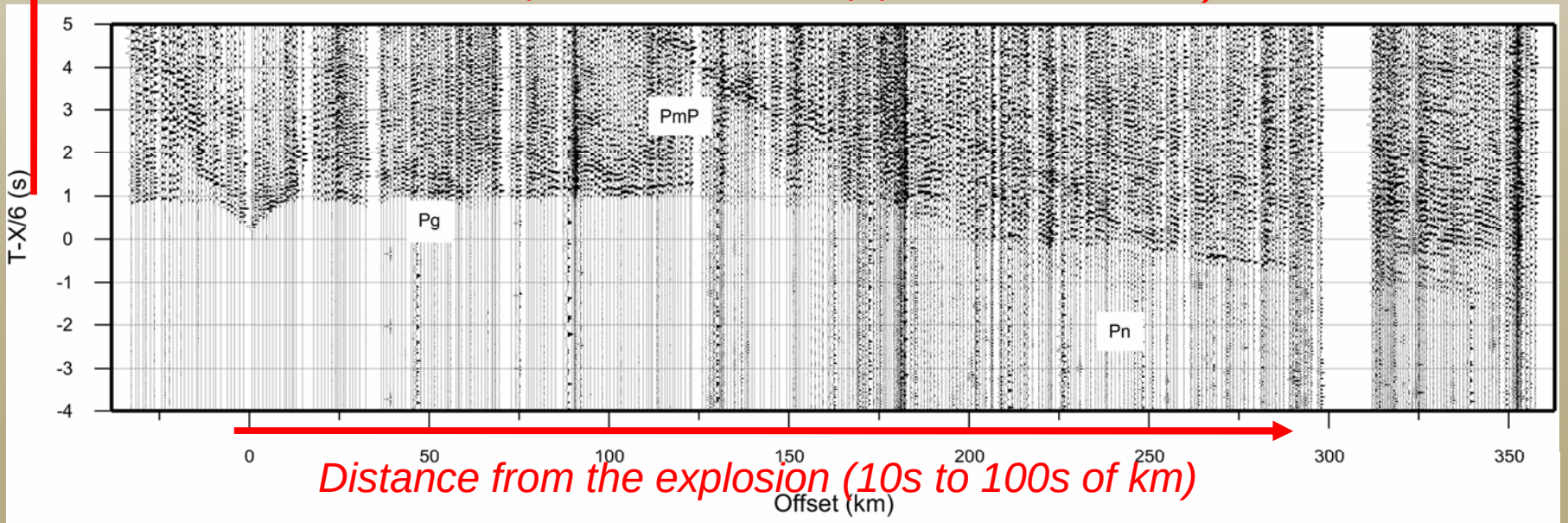
East Africa - Topography
(E.A.P. - East African Plateau)

East Africa - Seismicity (Dots) and Volcanoes (Triangles).
(The Nyanza craton is shown by the shaded pattern)

What is active-source seismic data?

Shots **Instruments**

Time after the shot was fired (seconds to minutes) (“reduced” at 6 km/s)

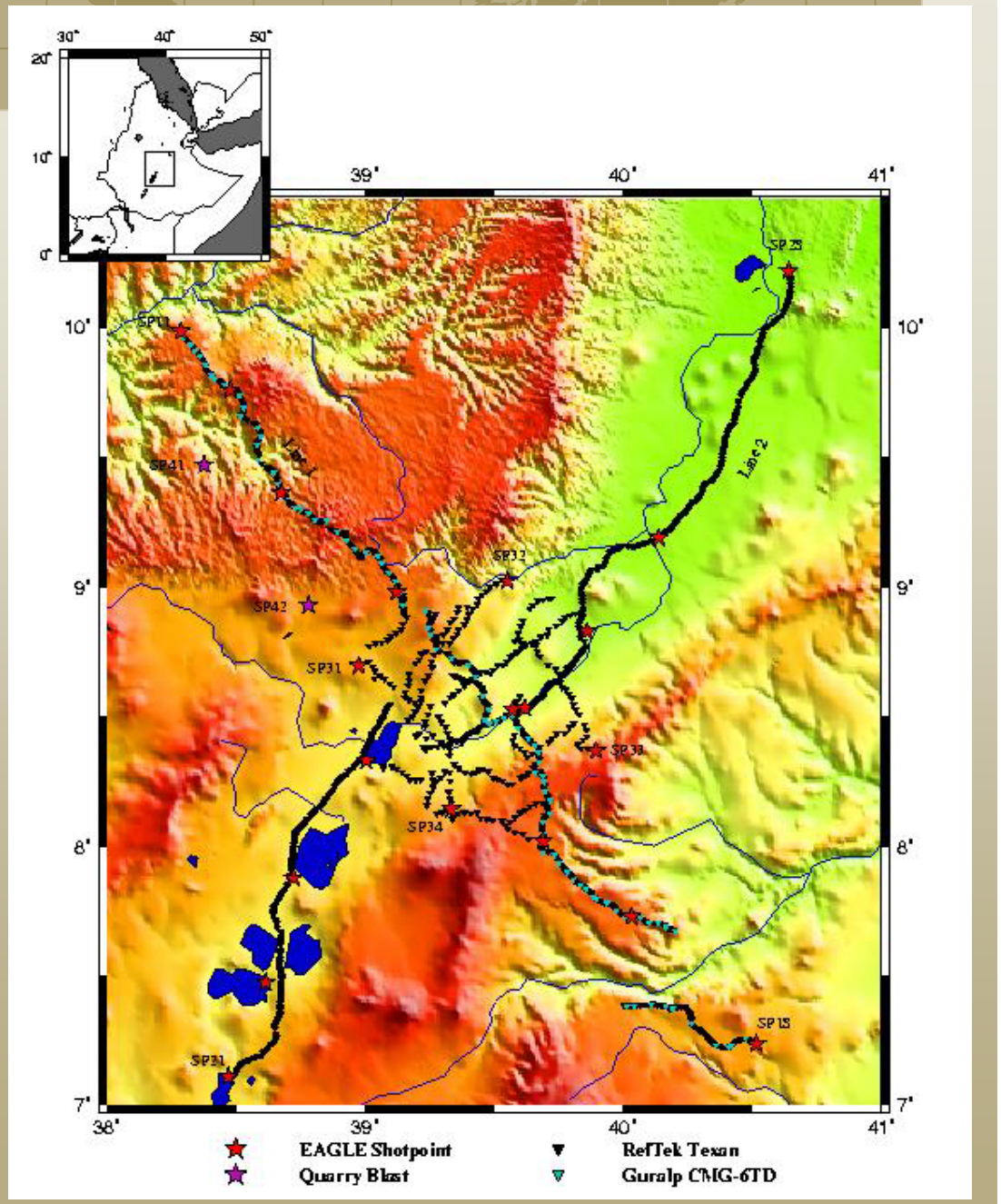


Distance from the explosion (10s to 100s of km)

What is active-source seismic data?

EAGLE:

- *24 shots*
- *1000 instruments*

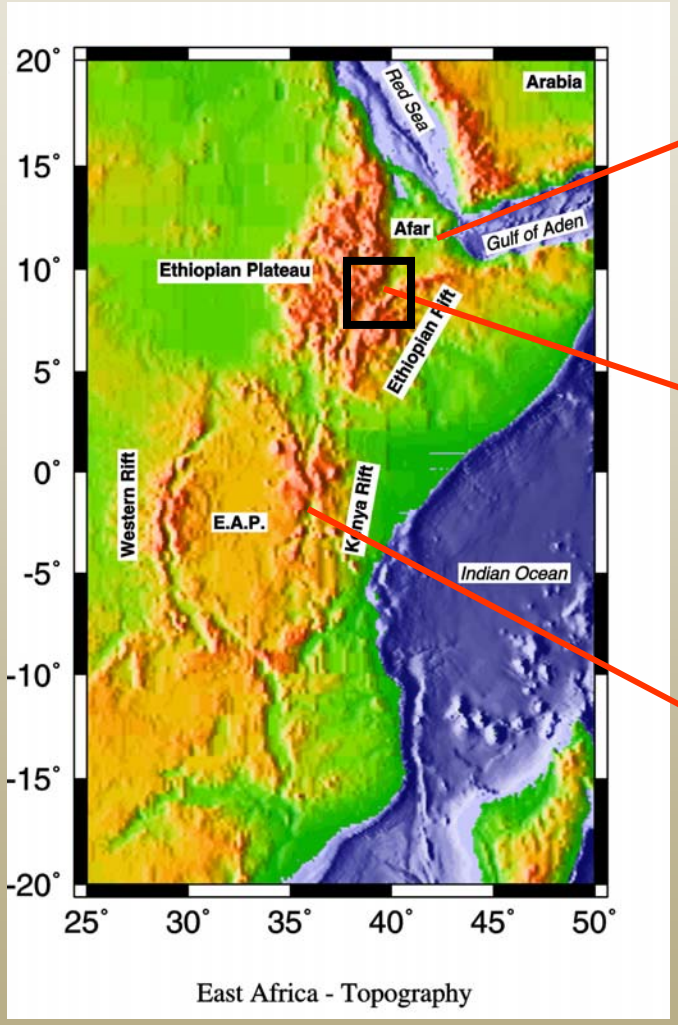


Common active-source (refraction) objectives

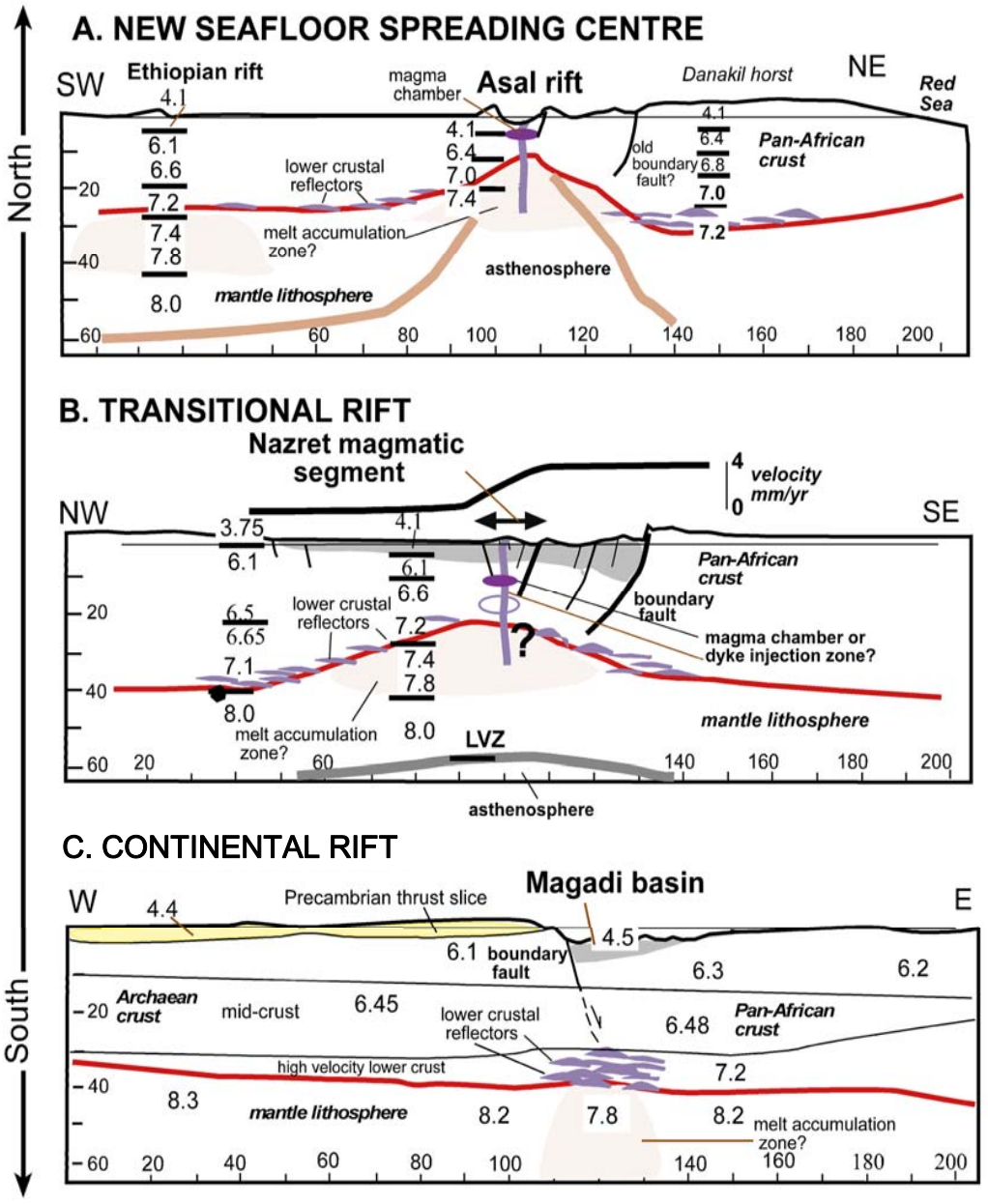
To image variations in crustal and upper mantle structure

- ***Crustal thickness**, spatial variations*
- ***Lithology** (inferred from seismic velocity)*
- *Amount of **magmatic modification** of the crust*
- *Distribution of magmatic modification*
- *Amount of **extension/crustal thinning***
- *Major crustal boundaries*
- *Magmatic chambers*
- *Thickness and location of **sedimentary basin** fill*

Rift Evolution



East Africa - Topography



EAGLE

Ethiopia **A**far **G**eoscientific **L**ithospheric **E**xperiment

EUROPE

University of Leicester, UK
University of Leeds, UK
Royal Holloway, University of London
Copenhagen University, Denmark
Dublin Institute for Advanced Studies

US

Stanford University
University of Texas at El Paso
Southwest Missouri State University
Penn State

ETHIOPIA

Commission of Science and Technology
The University of Addis Ababa
Ministry of Mines
Ethiopian Geological Survey

Funded by:

NSF

NERC

EAGLE Active-source Participants

January Experiment Personnel

Executive		
	P Maguire (UK)	Leicester
	S Klemperer (US)	Stanford
Explosives		
	M.A. Khan	Leicester
Equipment, Computers, Troubleshooting		
	Alex Brisbourne	Leicester
	A Ross	Copenhagen
	Galen Kalp	UTEP
Recording Deployment Manager		
	G Mackenzie	Leicester
Shooting Parties		
Party 1	G Wallace	DIAS
	B O'Reilly	DIAS
Party 2	T Burdette	USGS
	C Cunningham	Leicester
Party 3	R.Brinkman	Stuttgart
	G.R Keller	UTEP
Party 4	P Joergensen	Copenhagen
	K Aric	Austria
Party 5	G Jensen	USGS
	Nicolas Marlita	UTEP
Party 6	S Harder	UTEP
	P A Depret	UTEP
Boat		
	Teasdale	Leicester
Deployment		
1	G Stuart	Leeds
2	M Kendall	Leeds
3	I Bastow	Leeds
4	N Teanby	Leeds
5	J Tomlinson	Leicester
6	A Kelly	Leicester
7	D Cornwell	Leicester
8	P Denton	Leicester
9	A Myers	Leicester
10	D Waltham	RHUL
11	A.Page	RHUL
12	D Keir	RHUL
13	M Fowler	RHUL
14	K Keranen	Stanford
15	K Walker	Stanford
16	E Chetwin	Stanford
17	B Bendick	Colorado
18	M Cash	Stanford
19	A Les	Stanford
20	K Mickus	SWMSU
21	K Thygesen	Copenhagen
22	Y. Makovsky	Consultant

University of Addis Ababa
Geophysical Observatory
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Dr. Atalay Ayele (Chairman, Project Coordinating Committee)
Ato Abebe Albei
W/o Asnakech Estifanos
Ato Dagmawi Shiferaw

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Dr. Tilahun Mammo
Dr. Tenalem Ayenew
Dr. Gezahegn Yirgu
Dr. Dereje Ayelew
Ato Berehanu Gabrile Egziabher
Dr Endale Ketefo
Ato Mekonnen Uressa
Ato Miruts Hagos
Dr. Mulegeta Alene
Ato Tesfaye Hailu
Ato Wolde Selassie Gabriel Hiwot

Commission of Science and Technology
Ato Mulugeta Amha (Commissioner)
Ato Abebe Mekuriaw (Secretary, Project Coordinating Committee)
Engineer Solomon Zewde (Director, ESTC Equipment Centre)
Ato Fanta Demissie

Ministry of Mines
Ethiopian Geological Survey
Ato Ketema Tadesse (General Manager)
Ato Befekadu Oluma
Ato Geremew Negassa
Ato Jembere Shiferaw
Ato Kifle Damitew
Ato Kimemu Nurie
Ato Mamushek Zewge
Ato Mersha Nigussie
W/o Metasebia Demissie
Ato Mohammed Nur Dissassa
Ato Tadesse Lema
Ato Tesfaye Kassaye
Ato Wondwossen Shiferaw
Ato Yomuma Oli

Petroleum Operations Department
Ato Abiy Hunegnaw (Head)
Ato Ketsela Tadesse

Oromia Council
Ato Asefa Kumsa
Ato Waliyi Sheka
W/t Yodit Tefere

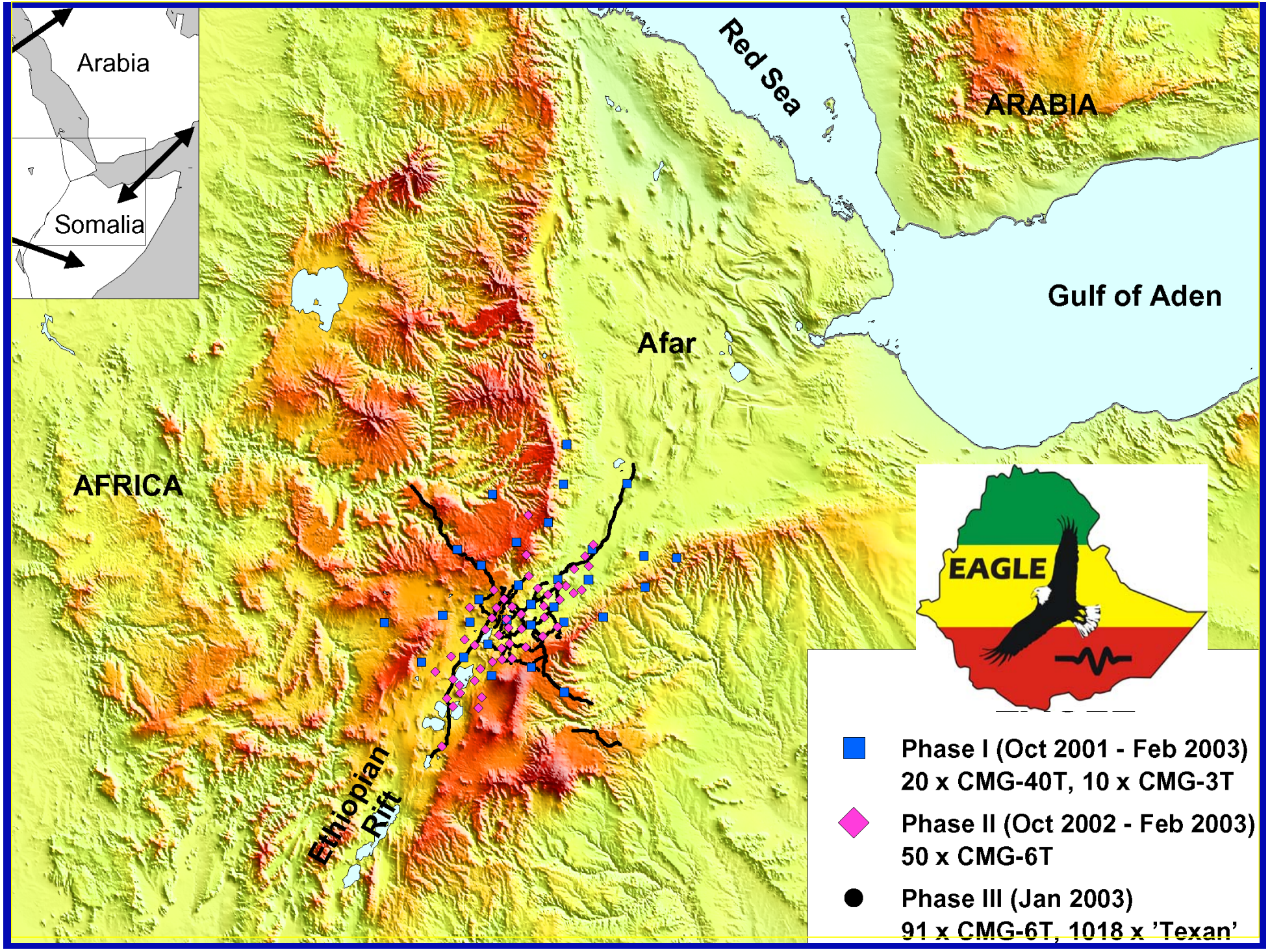
Southern Nations, Nationalities and Peoples Region
Ato Ewenet Gashaw

EAGLE active-source objectives

To image variations in crustal and upper mantle structure

To characterise the distribution of strain and magmatism across a transitional rift segment and along the rift axis

- *Crustal thickness, spatial variations*
- *Lithology (inferred from seismic velocity)*
- *Amount of magmatic modification of the crust*
- *Distribution of magmatic modification*
- *Amount of extension/crustal thinning*
- *Major crustal boundaries*
- *Magmatic chambers*
- *Thickness and location of sedimentary basin fill*


Arabia
Somalia
Red Sea
ARABIA
Gulf of Aden
Afar
AFRICA
Ethiopian Rift
EAGLE
Phase I (Oct 2001 - Feb 2003)
20 x CMG-40T, 10 x CMG-3T
Phase II (Oct 2002 - Feb 2003)
50 x CMG-6T
Phase III (Jan 2003)
91 x CMG-6T, 1018 x 'Texan'

Controlled source effort

January 2003 (3 weeks in total)

2 x 400 km profiles (Cross Rift and Axial)

19 Borehole Shotpoints (5 shooting teams)

2 Lake Shotpoints (1 shooting team)

~1000 seismic instruments (20 teams)

~40 Foreign Scientists

~30 Ethiopian Scientists

2 Days Equipment Deployment

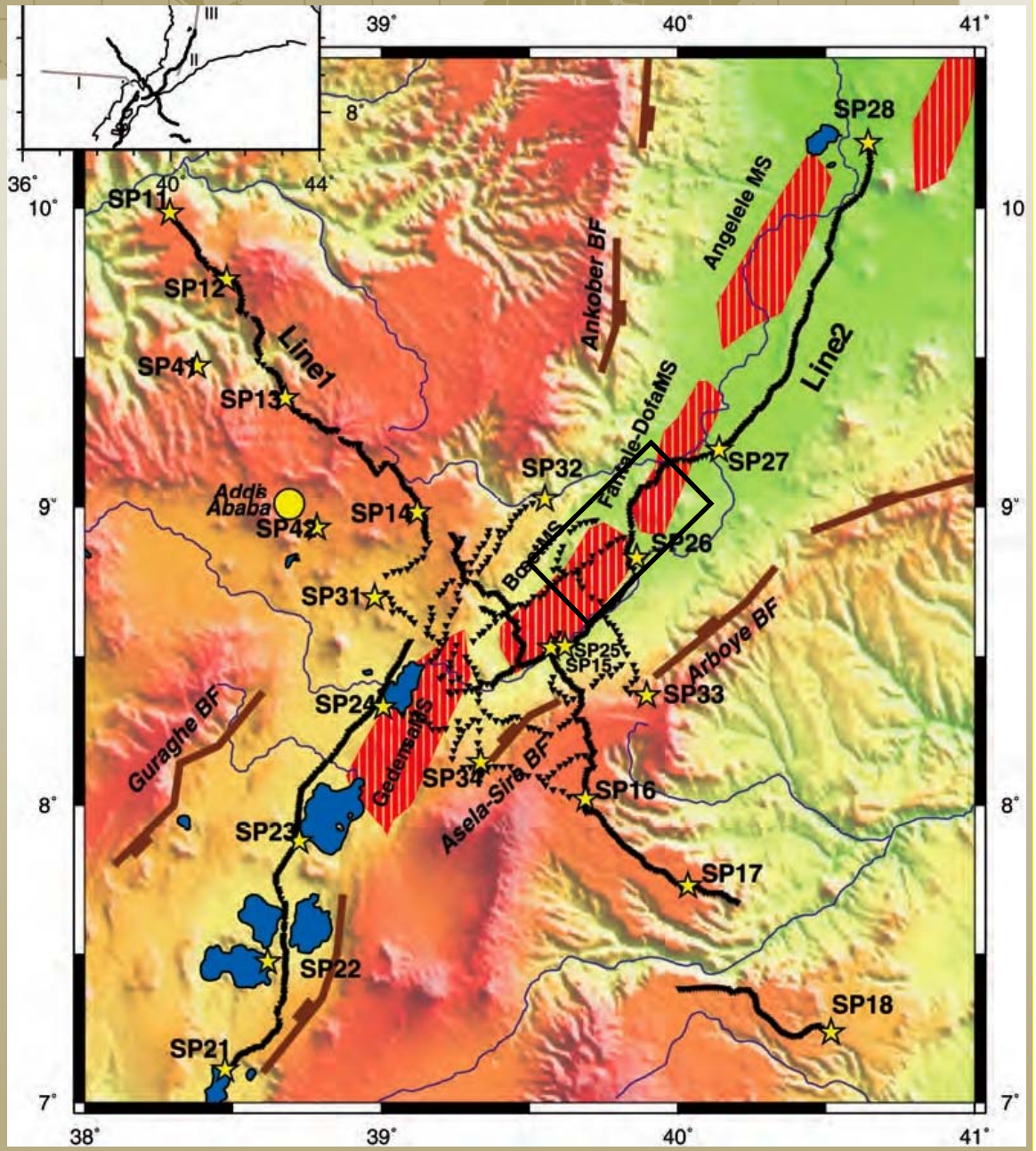
19 Shots in 4 Days

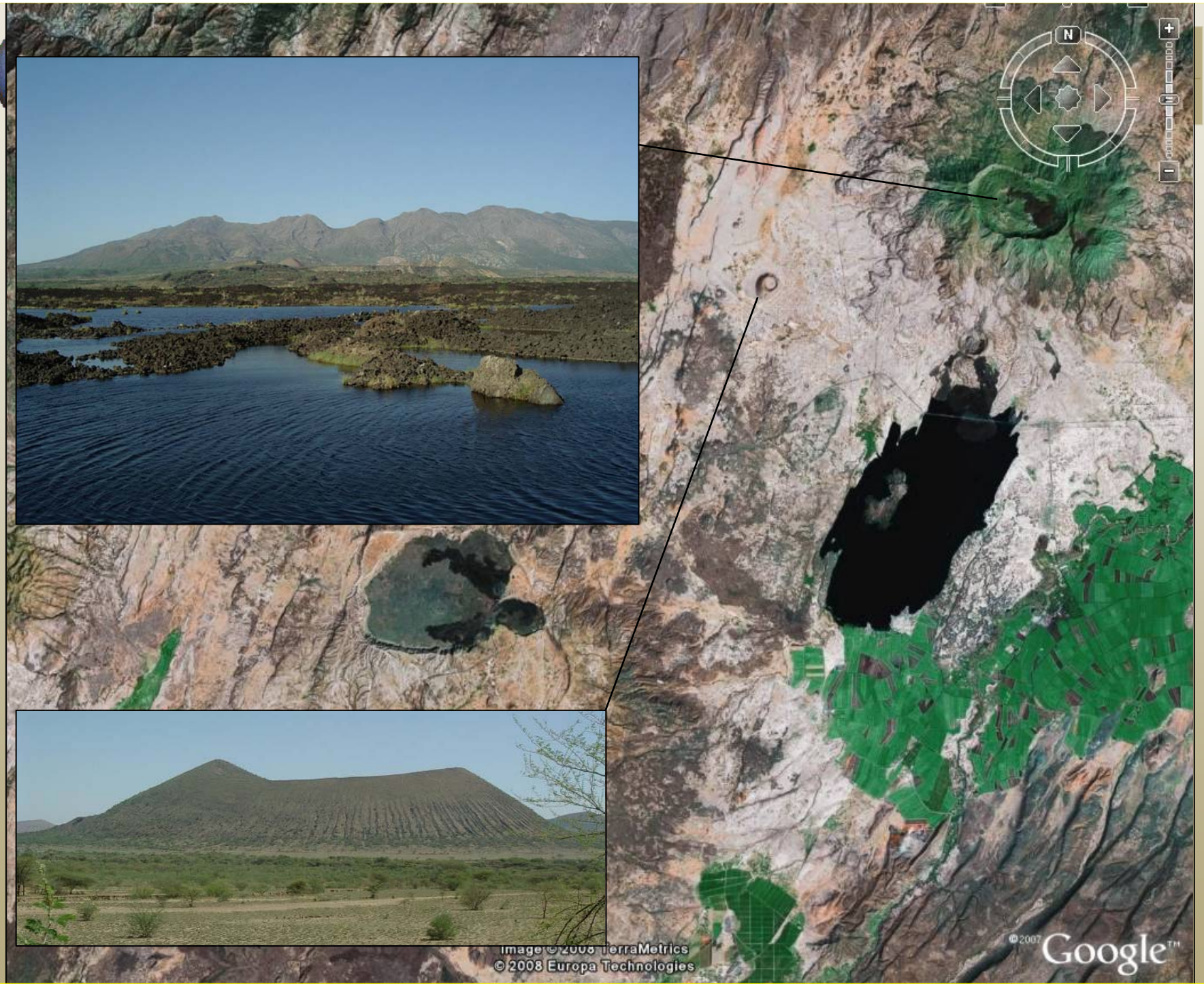
2 Days Equipment Pickup

EAGLE active-source:

At 24 places we fired large explosions (multiple drill rigs were mobilized for three months over long distances in remote areas)

Our 1000 recorders were laid out in two main lines, across the rift, and along the rift (that's 1000 separate sites to be located, surveyed and permitted).




N
Image © 2008 TerraMetrics
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Drilling rig

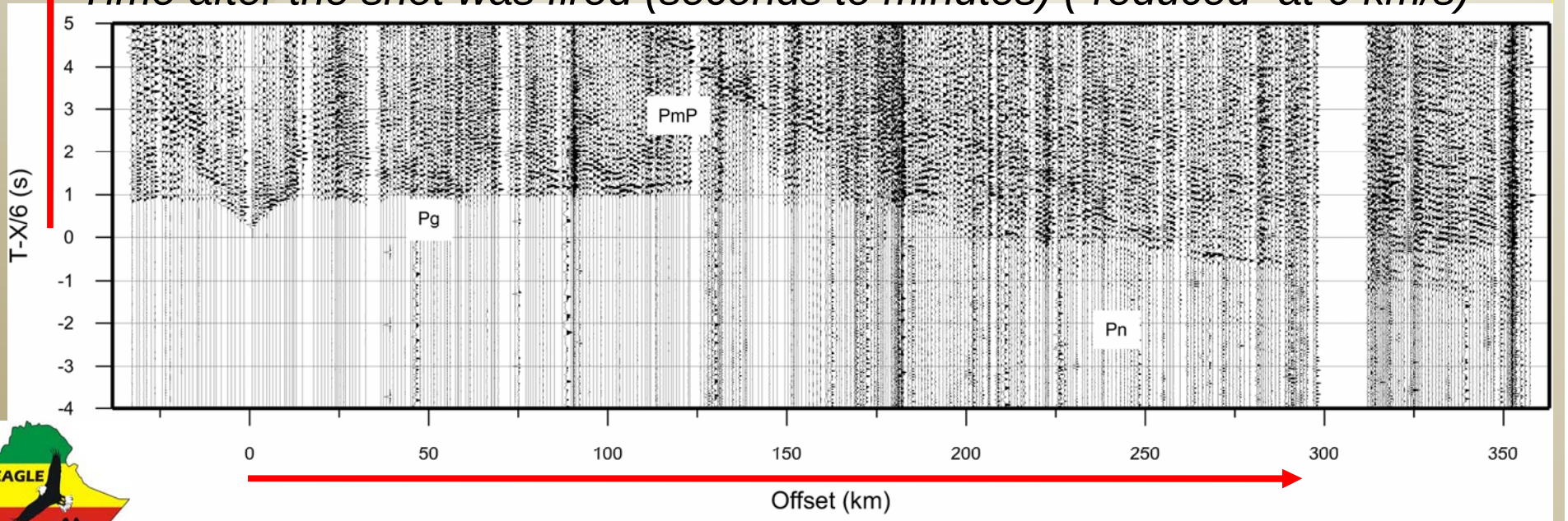
Shots

Controlled-source seismology:

~1000 1C RT-125 (Texan) recorders

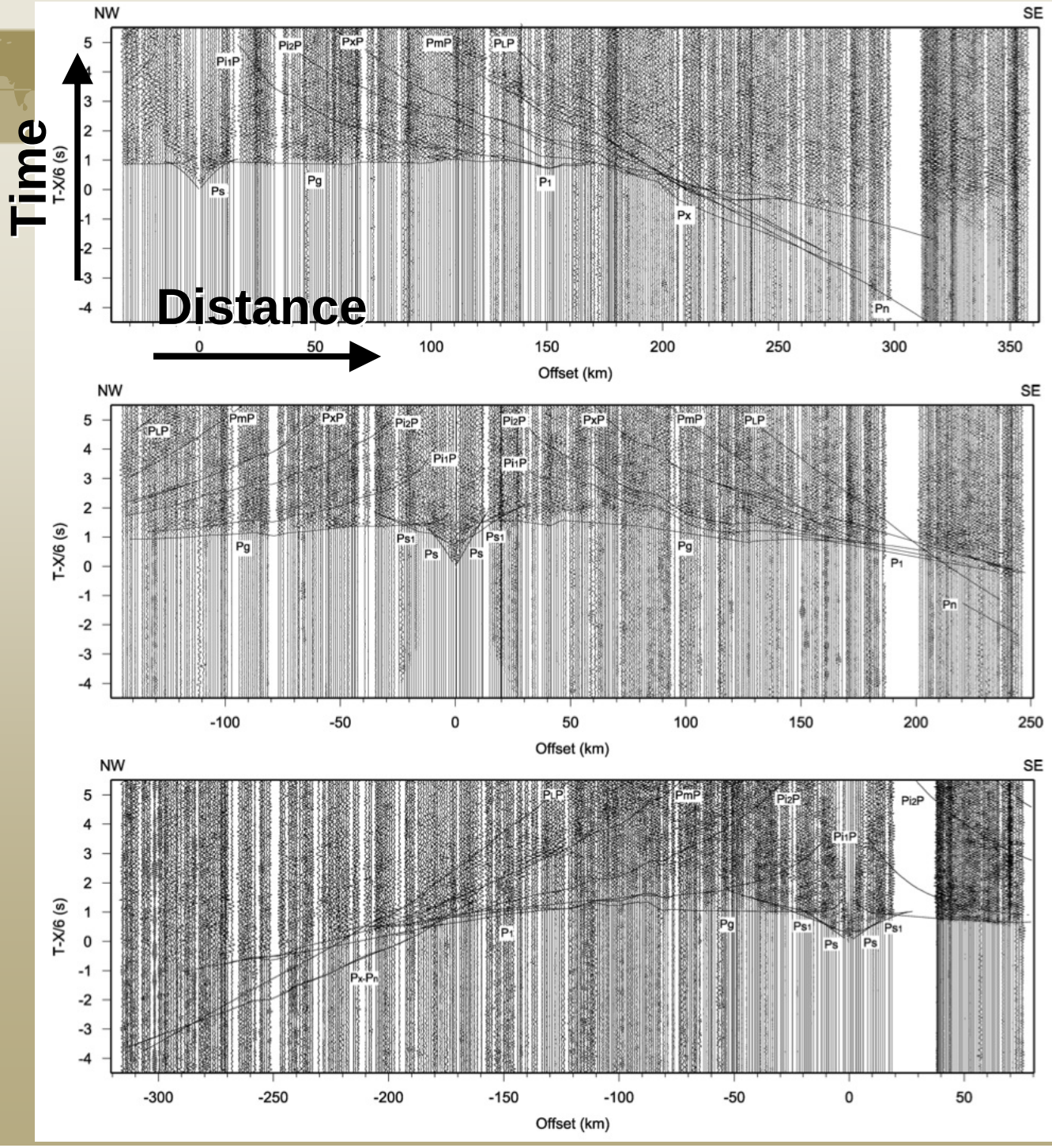
~twenty ~1 tonne detonations

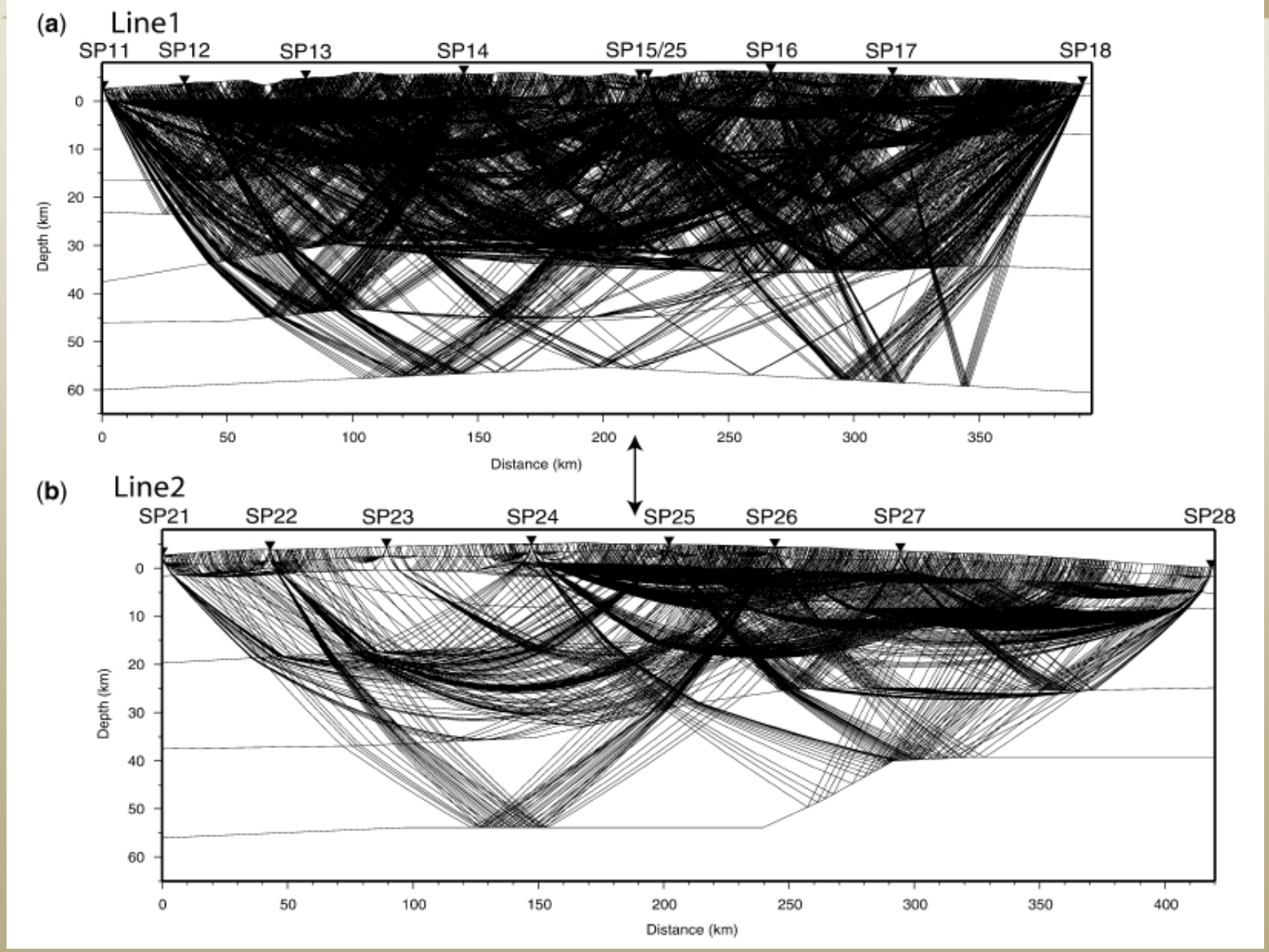
Time after the shot was fired (seconds to minutes) (“reduced” at 6 km/s)



Distance from the explosion (10s to 100s of km)

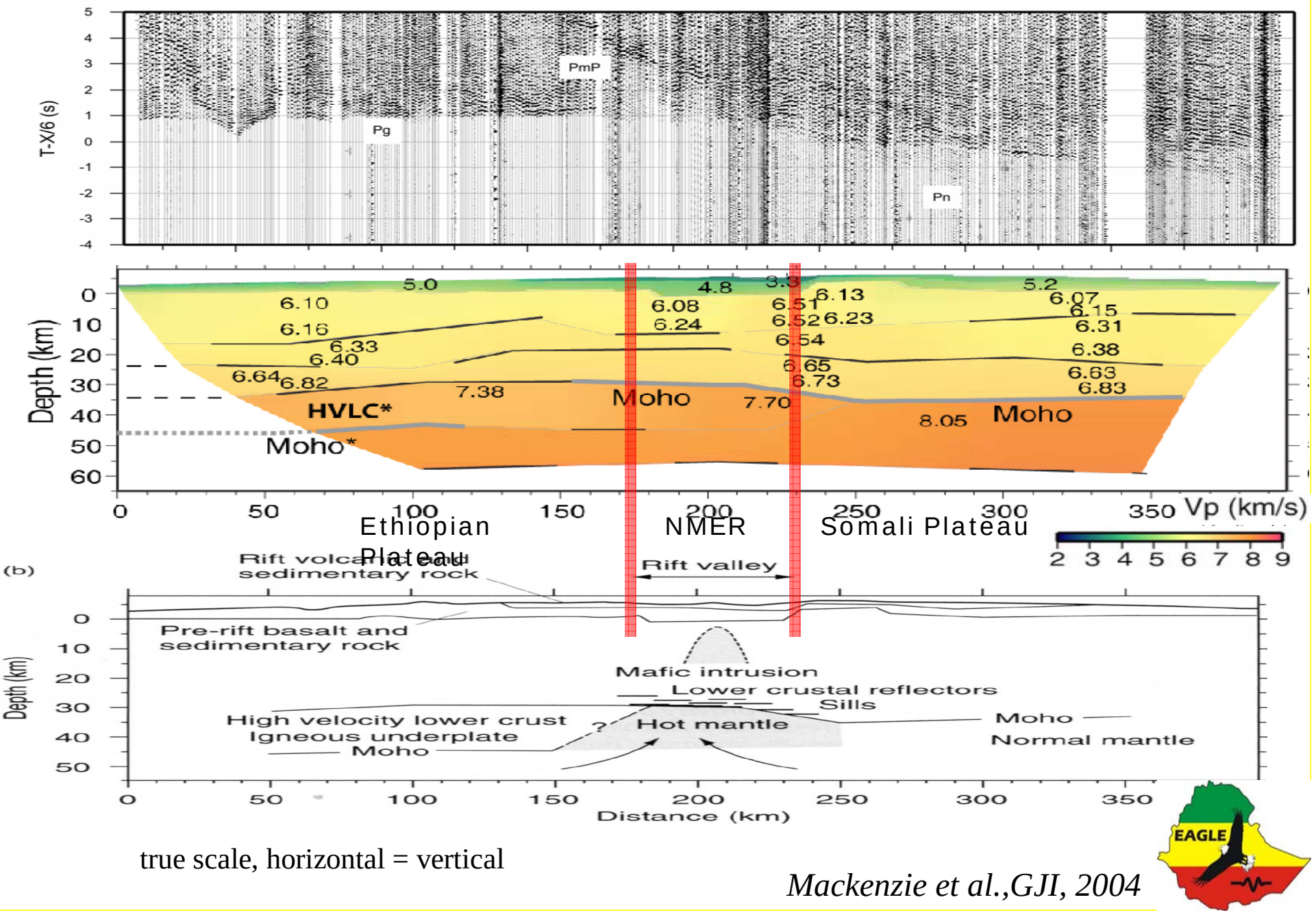
What do we do with the data?





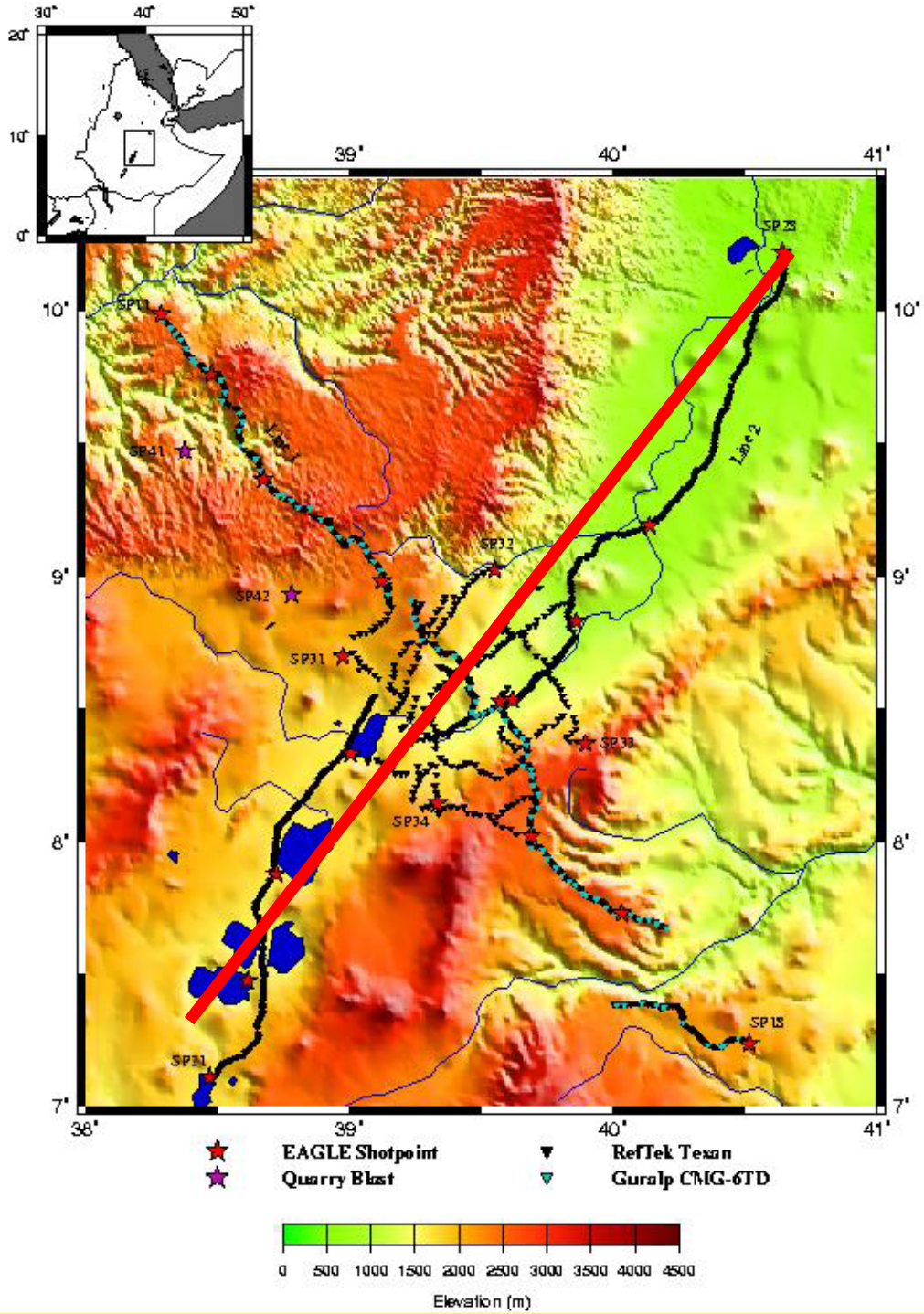
Travel-time modeling: RayInvr

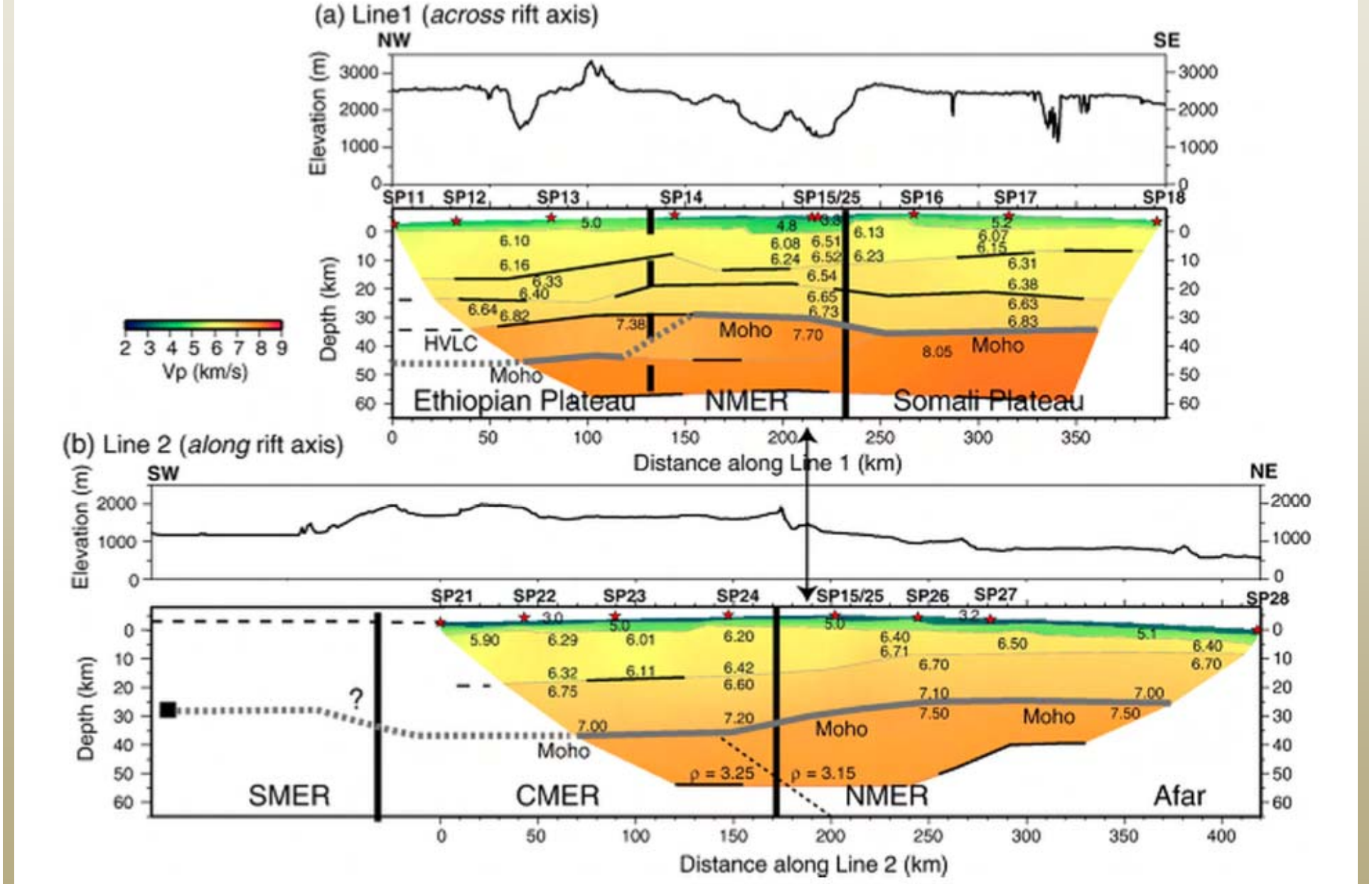
Very uniform Precambrian crust extends into the rift

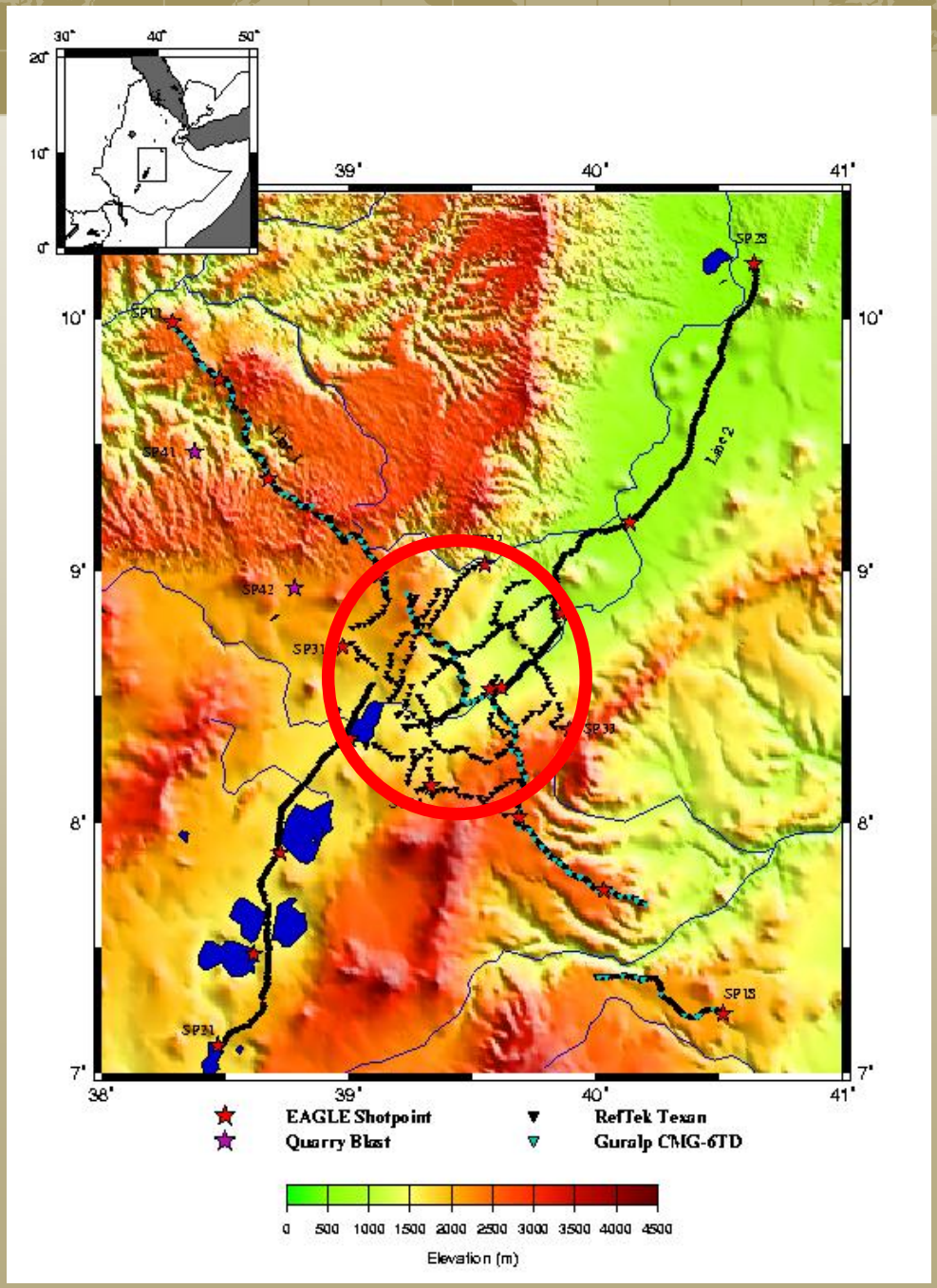


true scale, horizontal = vertical

Mackenzie et al.,GJI, 2004


30°
40°
50°
20°
10°
0°
39°
40°
41°
10°
9°
8°
7°
38°
39°
40°
41°
SP11
SP41
SP42
SP31
SP32
SP33
SP34
SP35
SP21
SP25
Line 2
EAGLE Shotpoint
Quarry Blast
RefTek Texan
Guralp CMG-6TD
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Elevation (m)


(a) Line1 (across rift axis)
NW
SE
Elevation (m)
SP11 SP12 SP13 SP14 SP15/25 SP16 SP17 SP18
Depth (km)
HVLC
Moho
Ethiopian Plateau
NMER
Somali Plateau
Vp (km/s)
Distance along Line 1 (km)
(b) Line 2 (along rift axis)
SW
NE
SP21 SP22 SP23 SP24 SP15/25 SP26 SP27 SP28
SMER
CMER
NMER
Afar
ρ = 3.25
ρ = 3.15
Distance along Line 2 (km)


30°
40°
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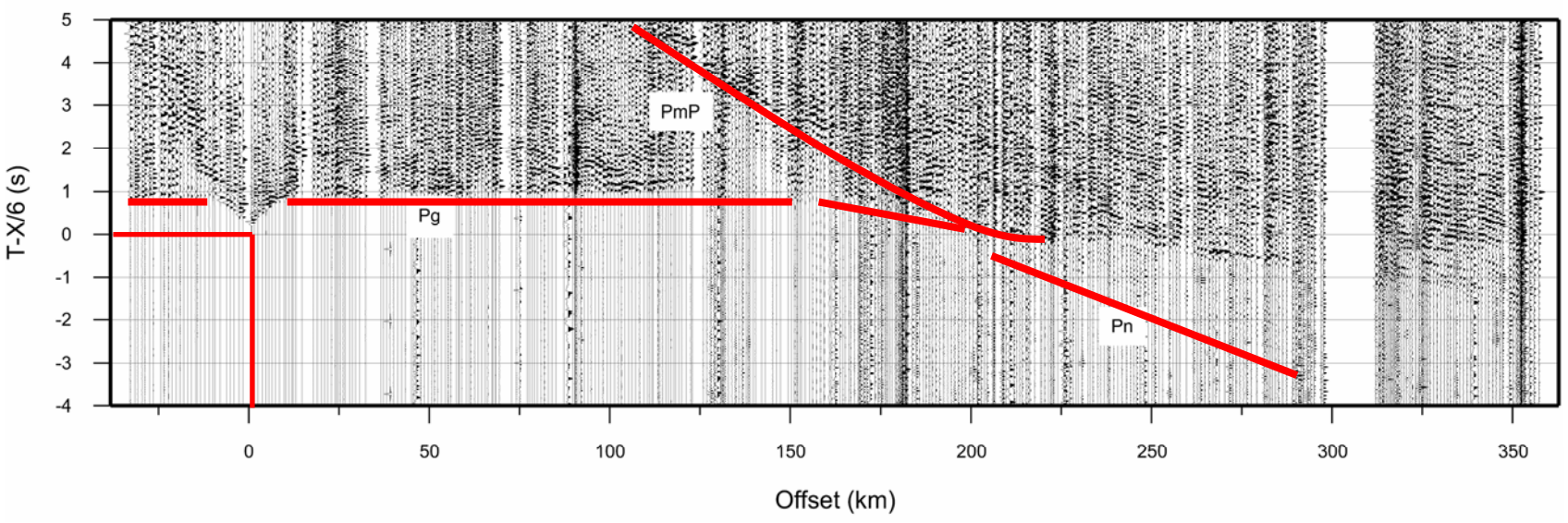
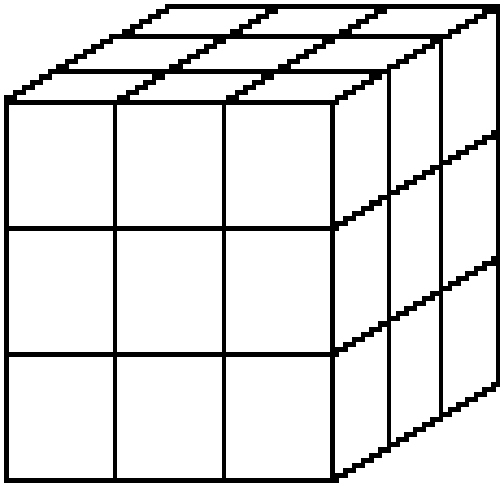
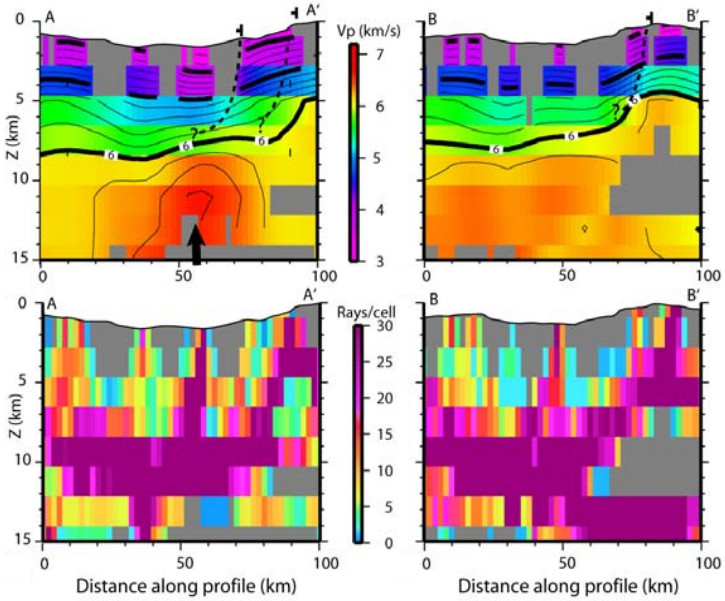
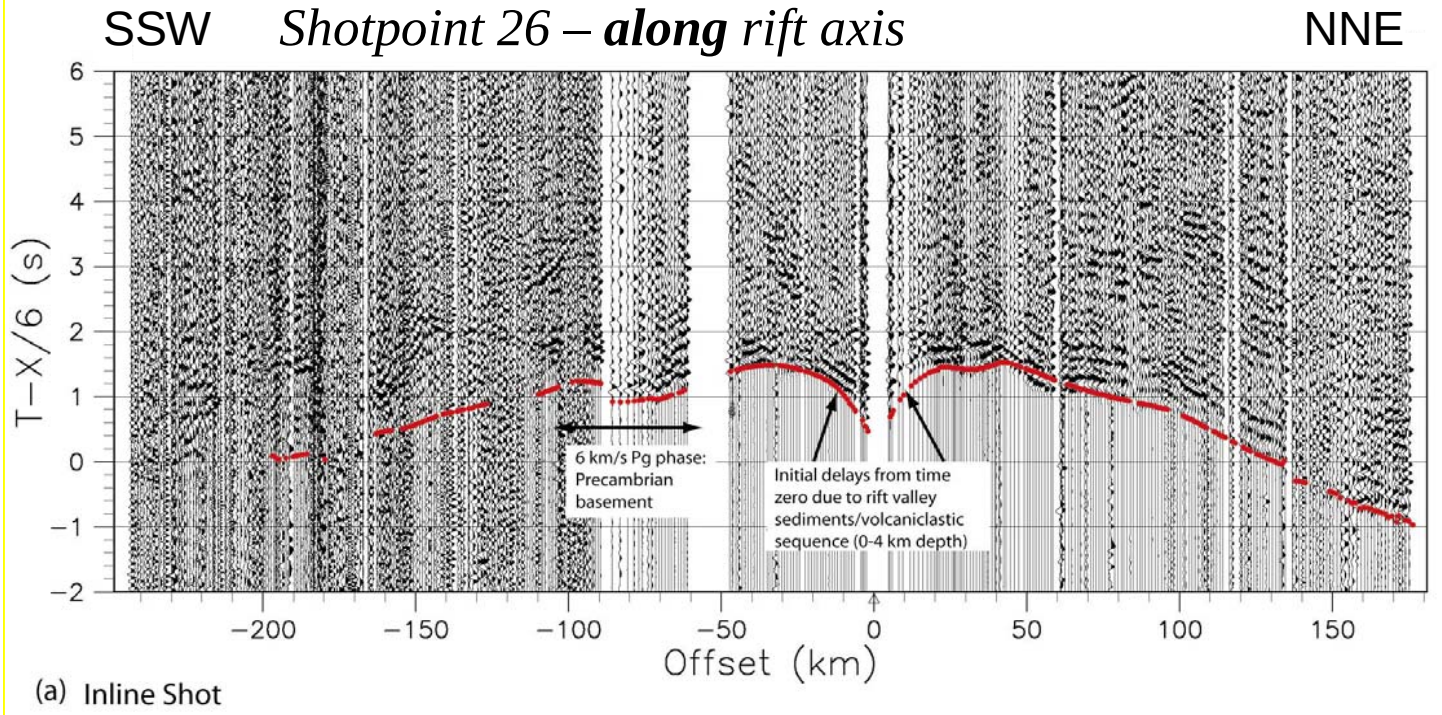
41°
10°
9°
8°
7°
38°
39°
40°
41°
SP28
SP13
SP41
SP42
SP31
SP38
SP15
SP34
Lake 2
EAGLE Shotpoint
Quarry Blast
RefTek Texan
Guralp CMG-6TD
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Elevation (m)

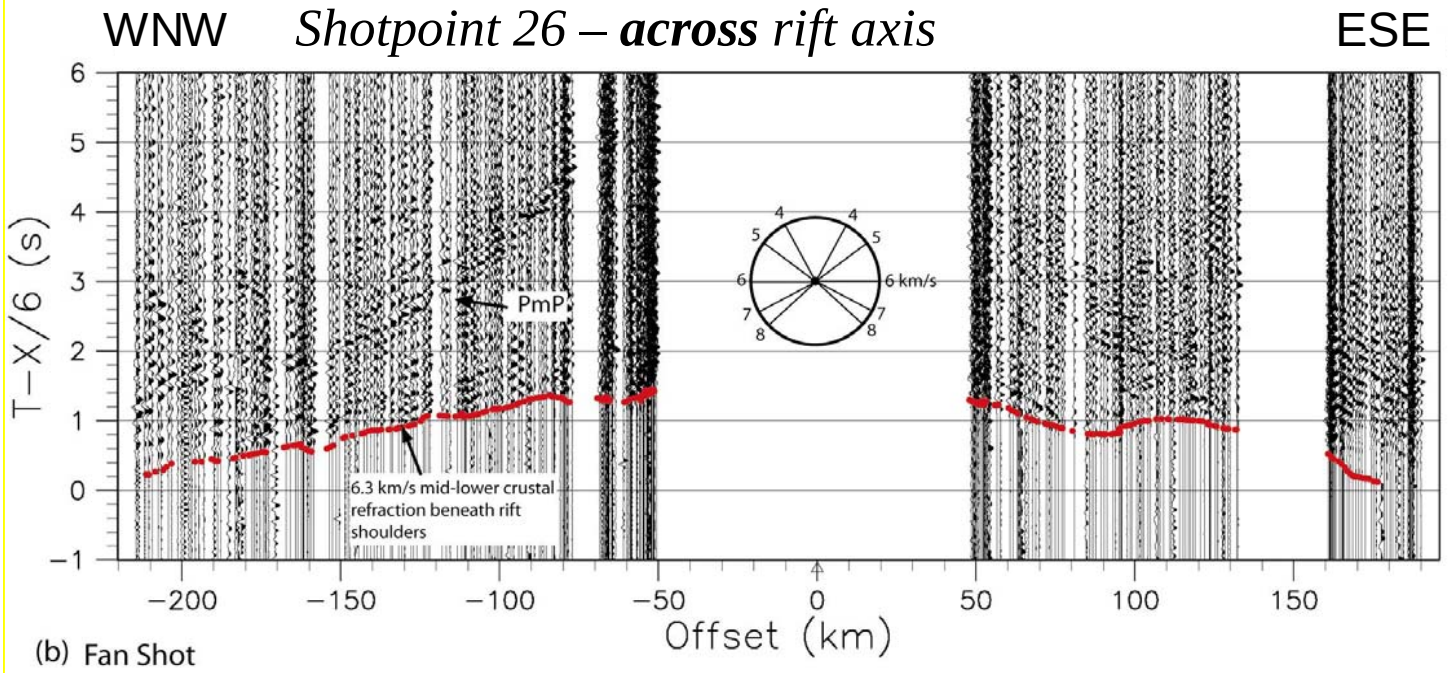
Controlled-source seismic tomography











First arrival travel-time tomography

7450 arrival times

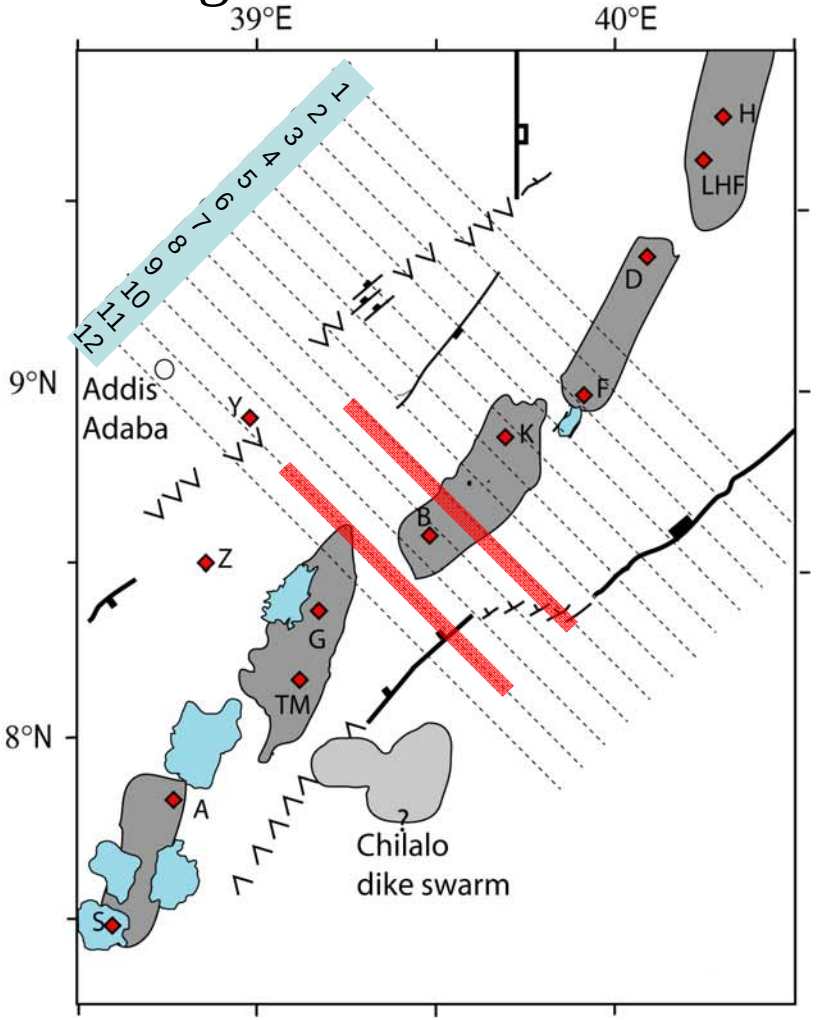
400x400x80km inversion space

2-km voxels

Output: smooth velocity model (3D)

EAGLE

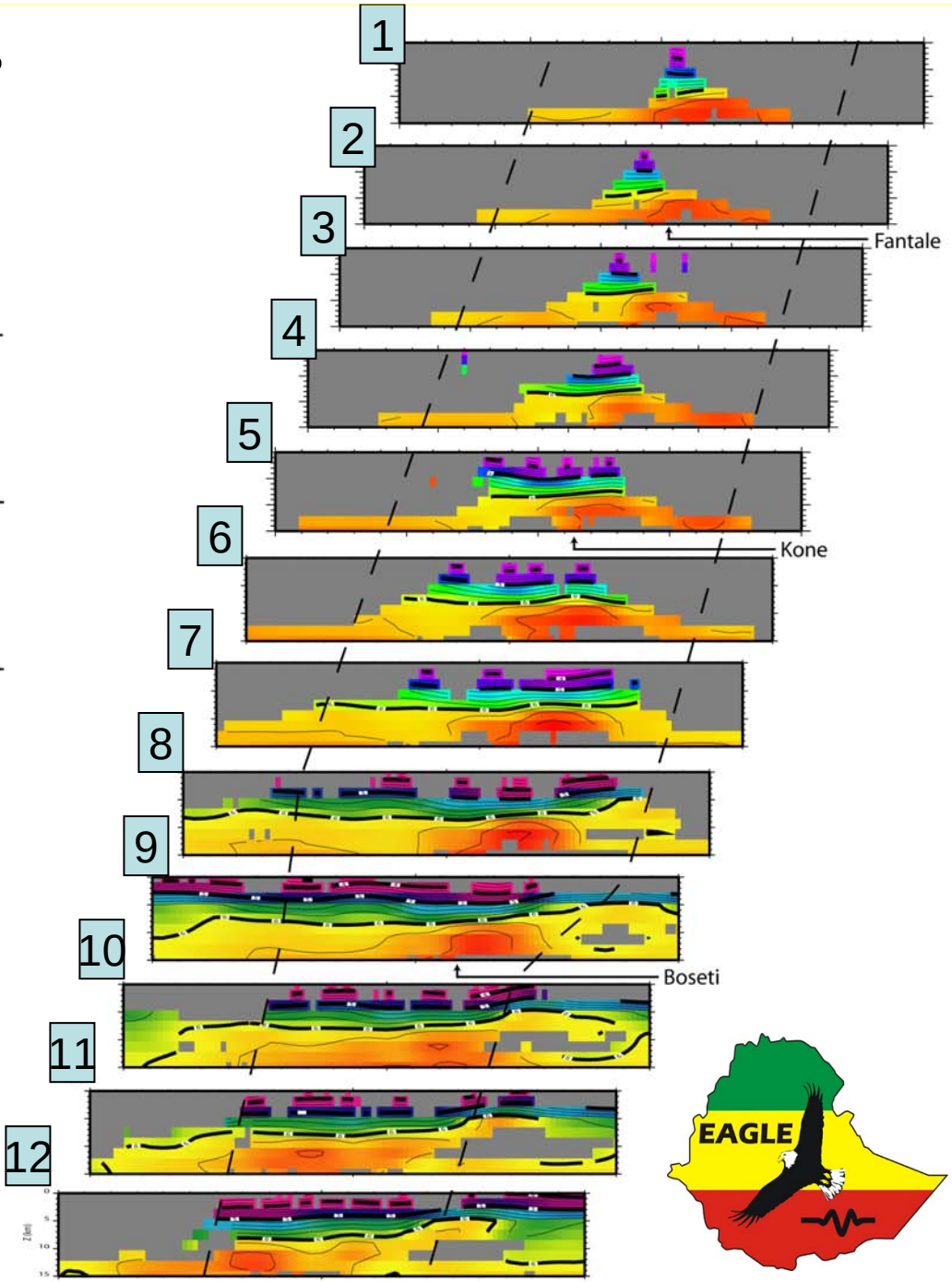
A series of 2D cross-sections through the 3D model:



Location of cross-sections and depth-slice

Tectono-magmatic segment

Volcanic center

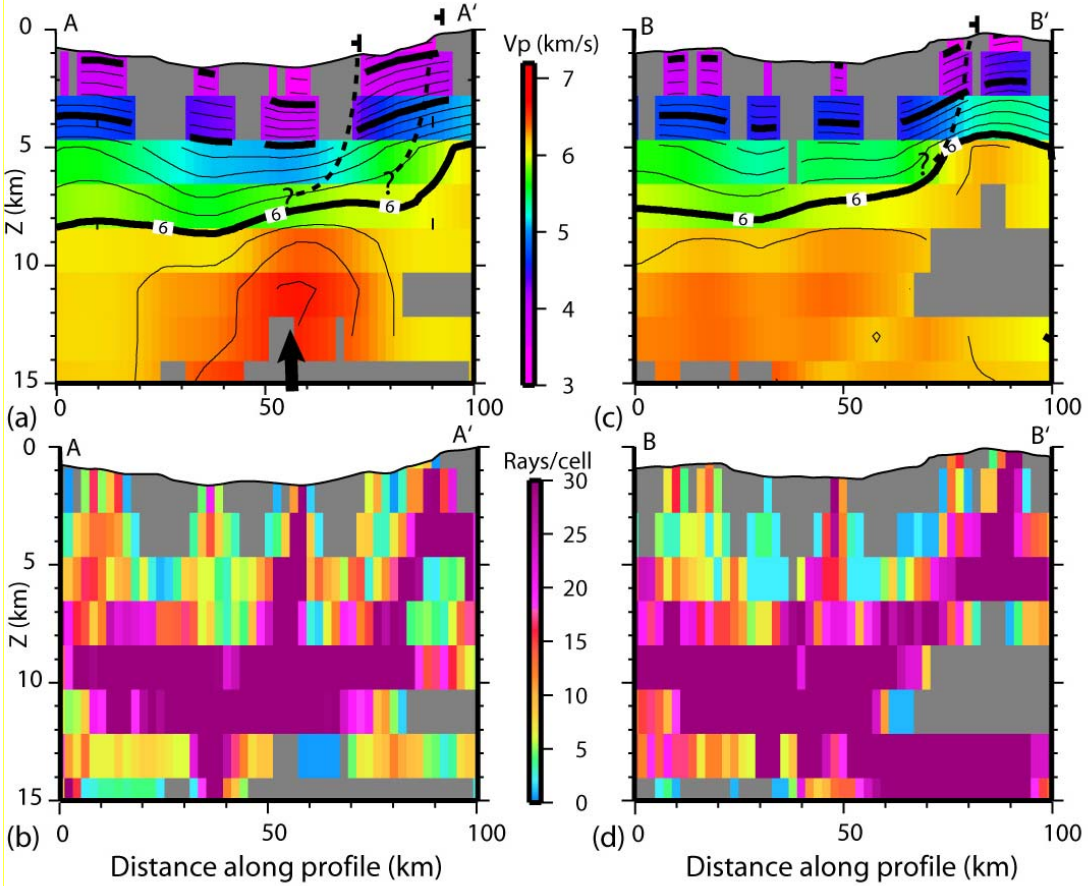


EAGLE

Cross-sections:

A-A': *Across* magmatic segment

B-B': *Between* magmatic segments

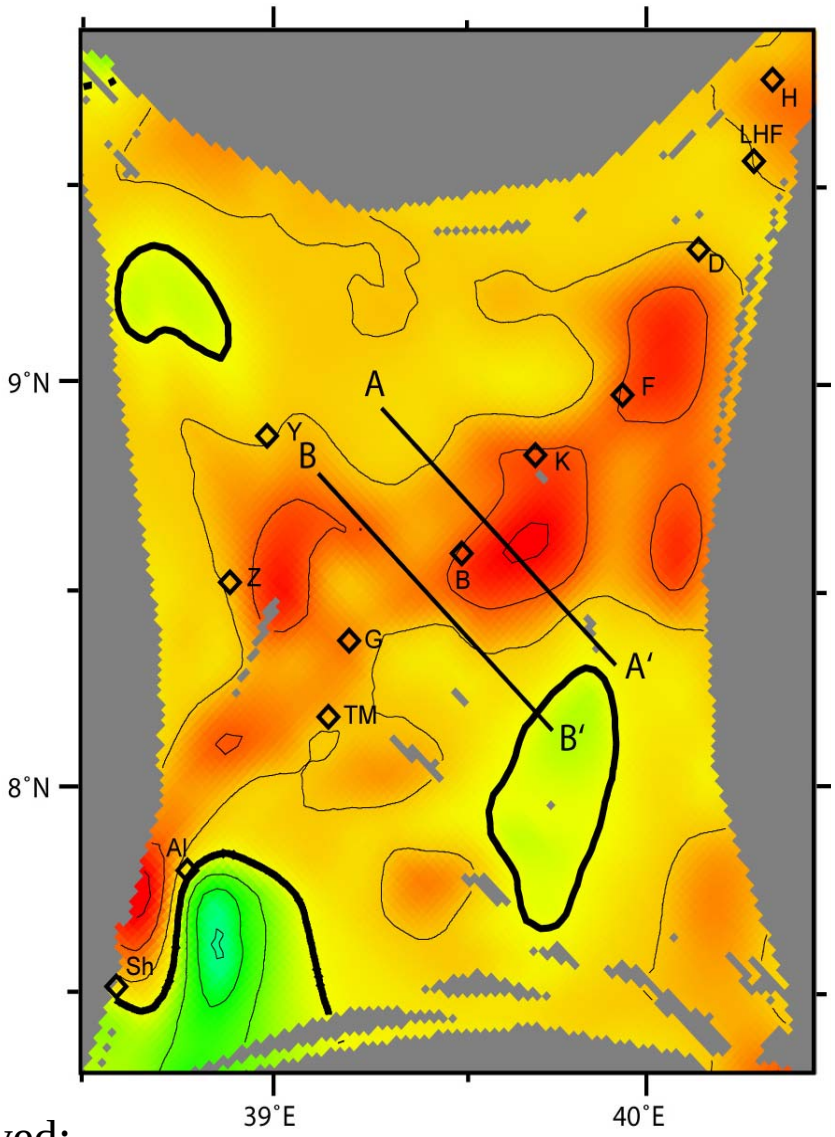


~ 5x vertical exaggeration

color is rays per 2-km voxel:
magenta: > 30 rays,
velocity well resolved;
gray: unresolved

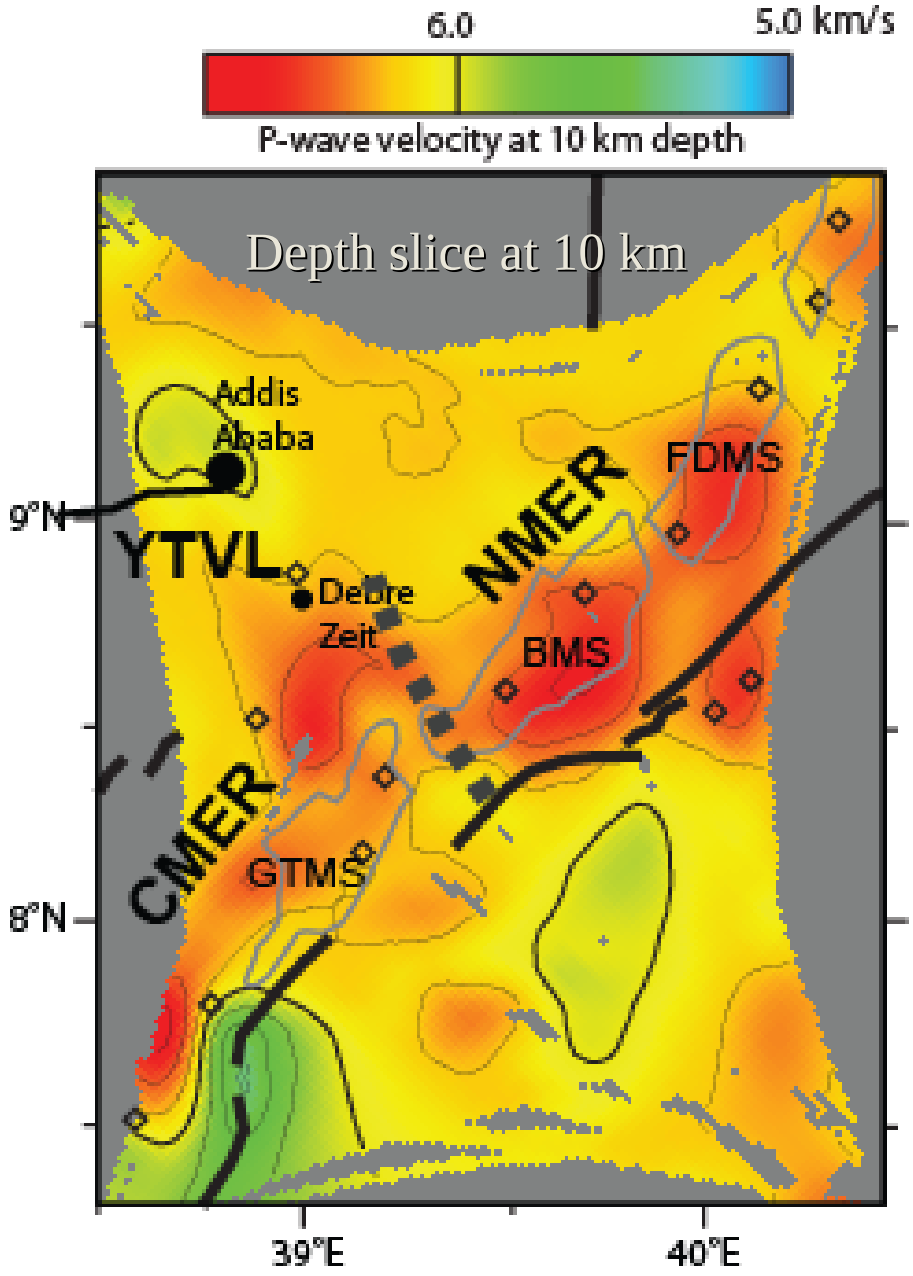
Depth slice:

at 10 km

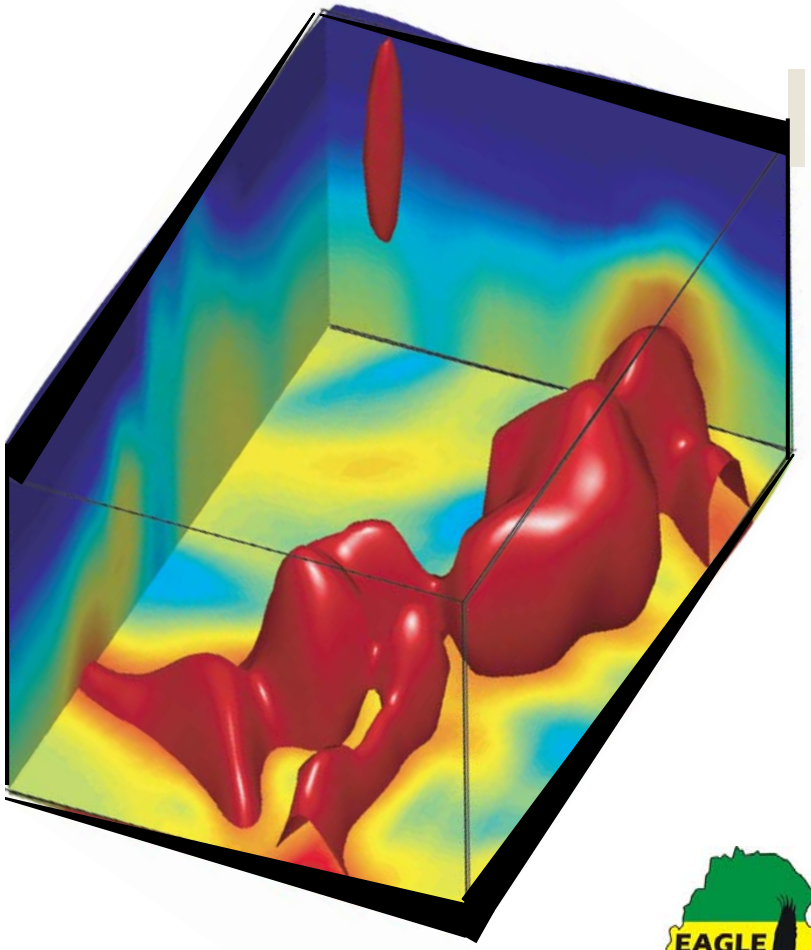


Keranen et al., Geology, 2004

3D tomographic inversion



- Discrete high-Vp bodies ~6.7km/s (solidified gabbros) underlie the rift
- Bodies are indeed offset en-echelon along the rift axis and oriented perpendicular to extension



Keranen et al., Geology, 2004

EAGLE

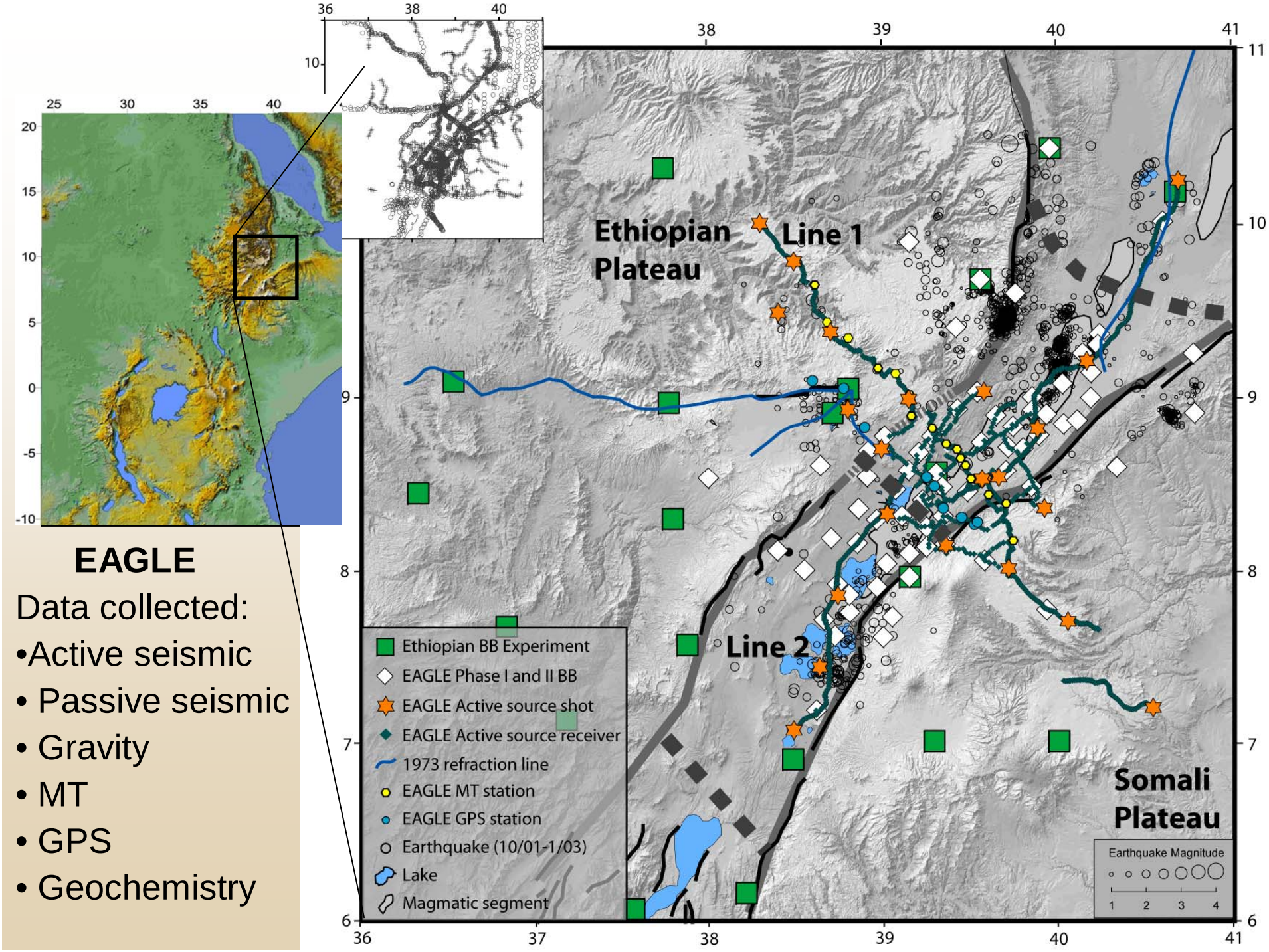
What did we learn from active-source?

- Magmatism is narrowly concentrated within ~20-km-wide bodies within the rift valley
- Crust away from these bodies is largely continental in character
- Magmatic bodies are offset en-echelon along the rift axis, similar to surface patterns
- Crust thins abruptly along the rift axis
- Crustal thinning across the rift occurs primarily in the upper-crust
- A high-velocity body at the base of the crust is modeled on the across-rift line, reflects off-axis magmatic processes (but details unclear)

➢ **Crustal thickness, crustal thinning, extension, magmatic modification, spatial distribution of processes, relative roles of faulting and magmatism**

EAGLE is MUCH more than active-source data

- ✓Seismicity
- ✓EQ 3D crustal tomography
- ✓Magnetotellurics
- ✓Geochemistry
- ✓Geodetics
- ✓Crustal gravity models
- ✓Shear-wave splitting
- ✓Receiver functions
- ✓Mantle tomography
- ✓Surface-wave tomography

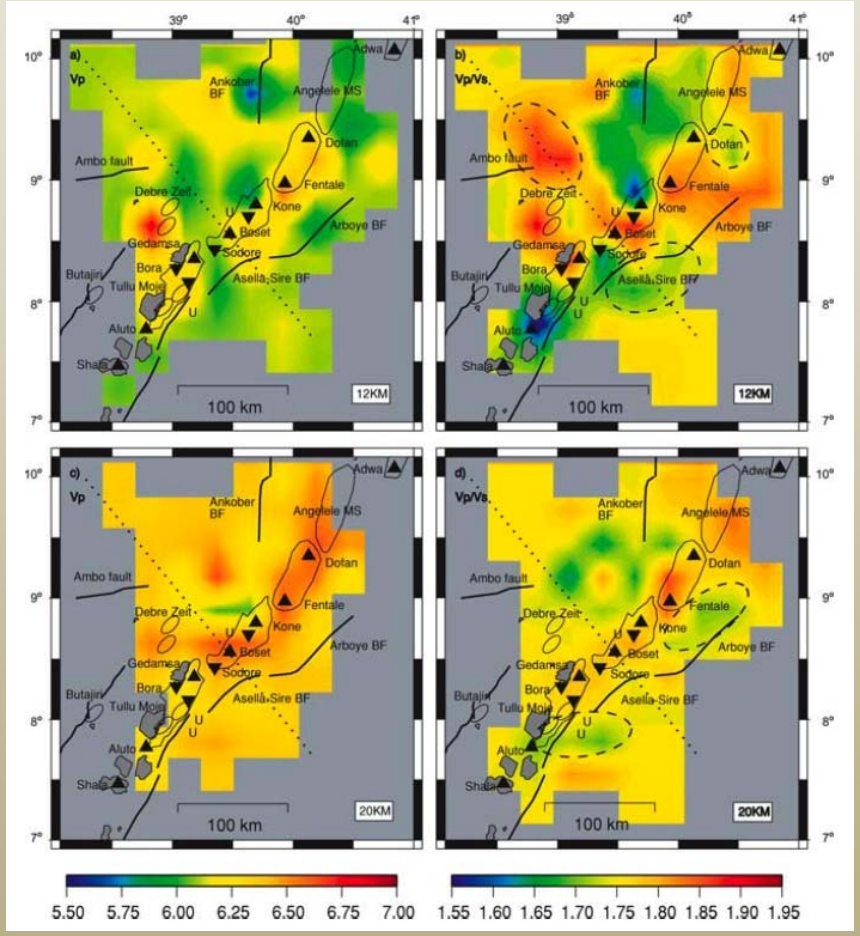


EAGLE

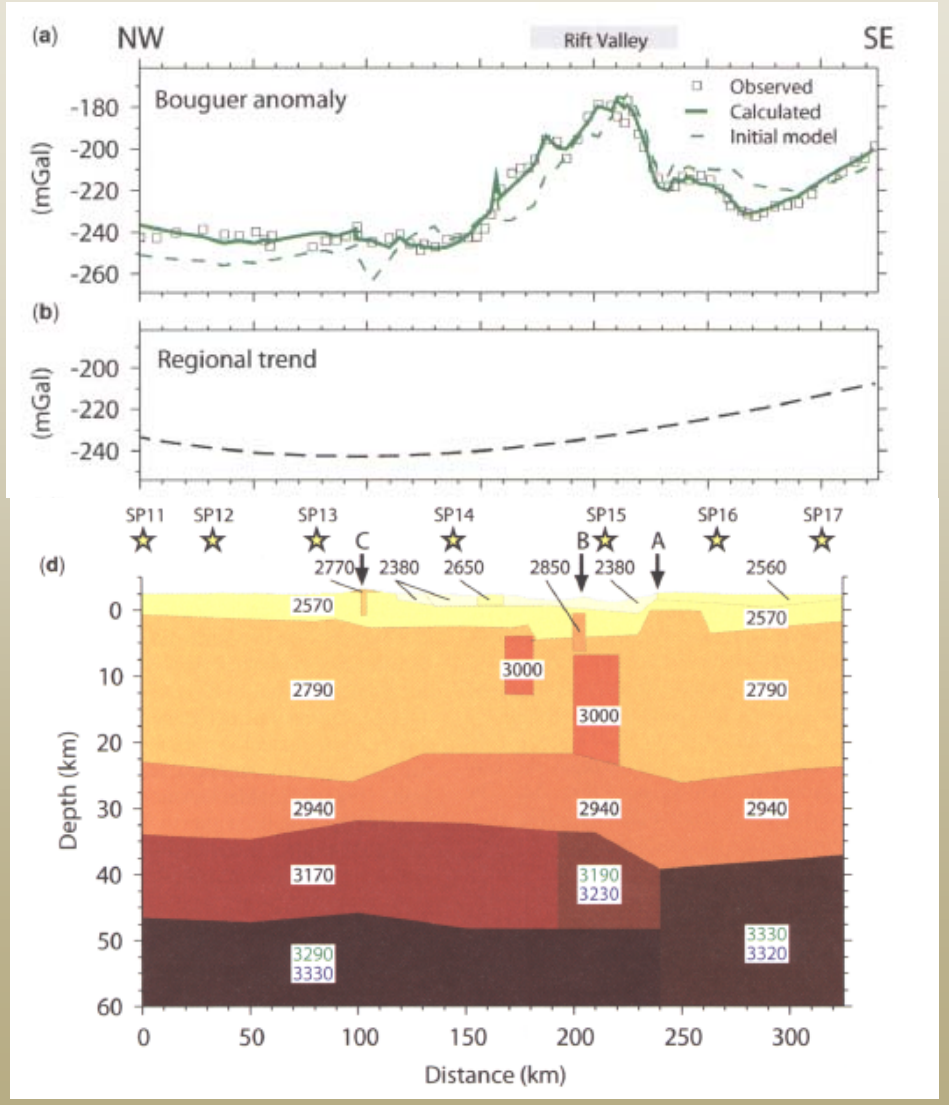
Data collected:

- Active seismic
- Passive seismic
- Gravity
- MT
- GPS
- Geochemistry

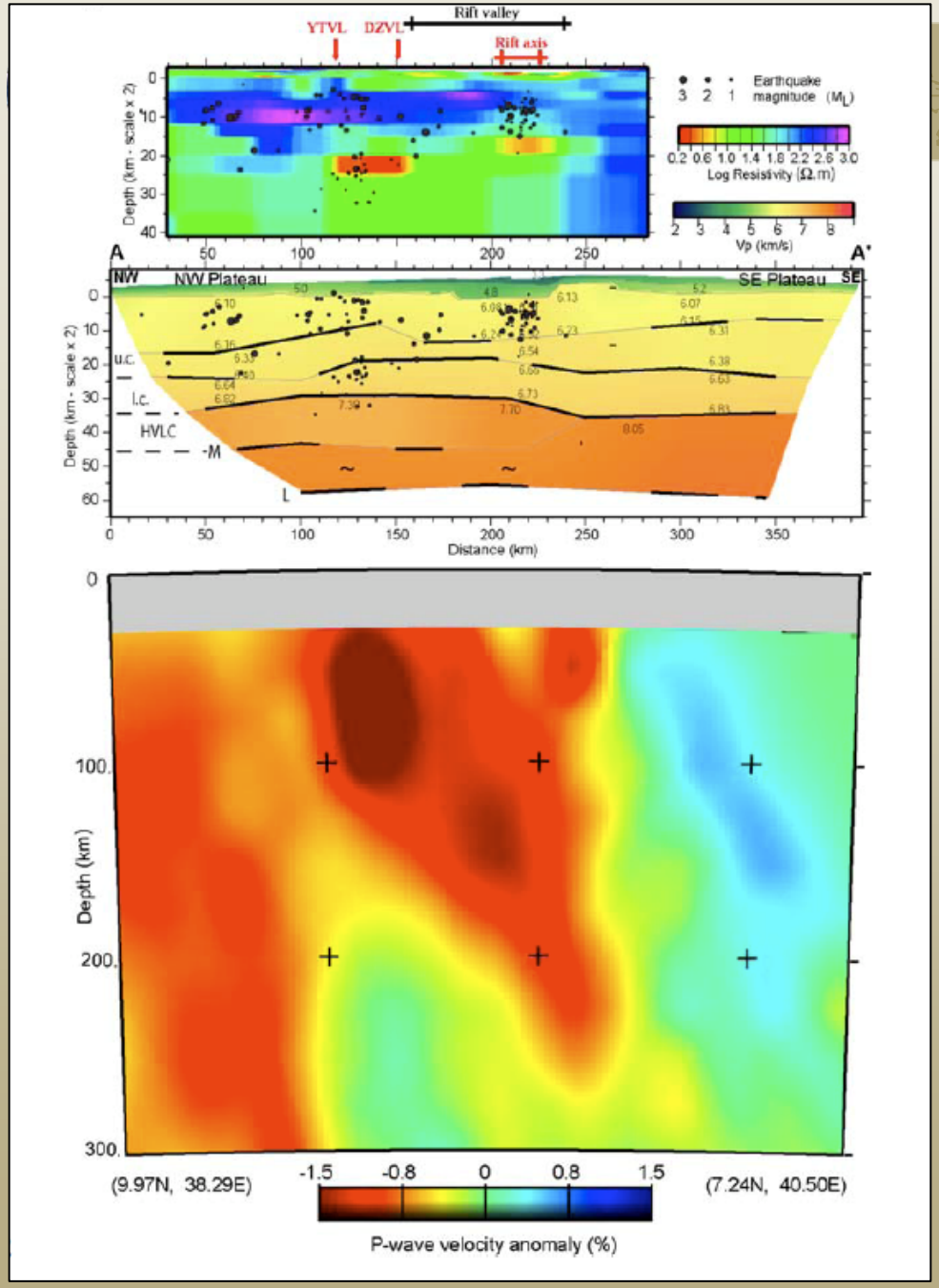
Passive-source tomography; gravity

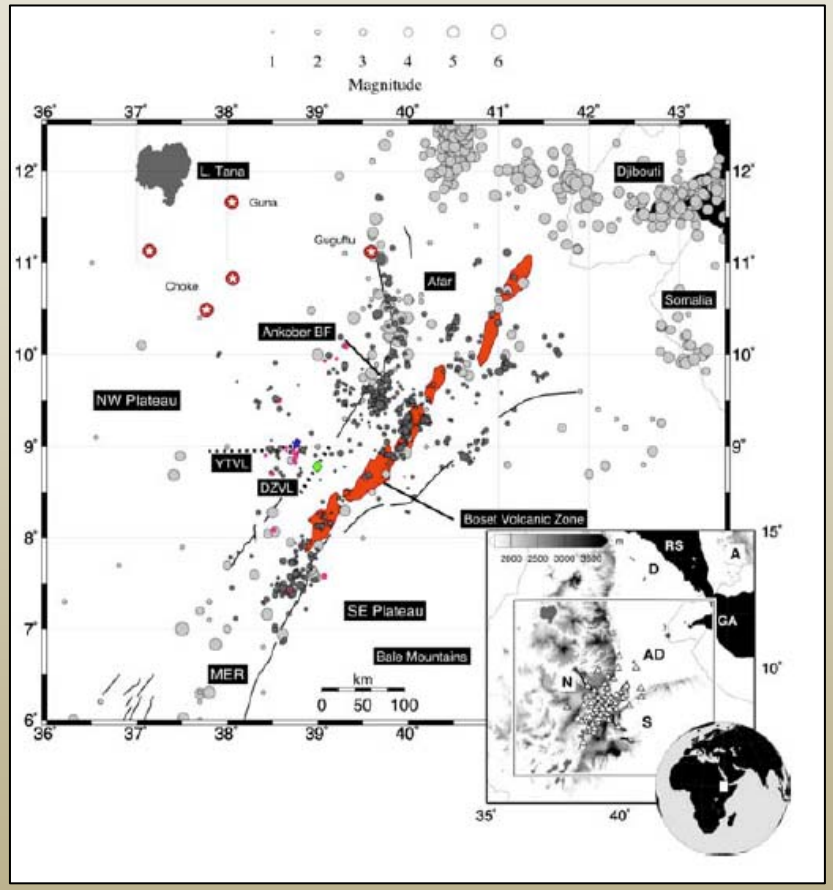


Daly et al., 2008



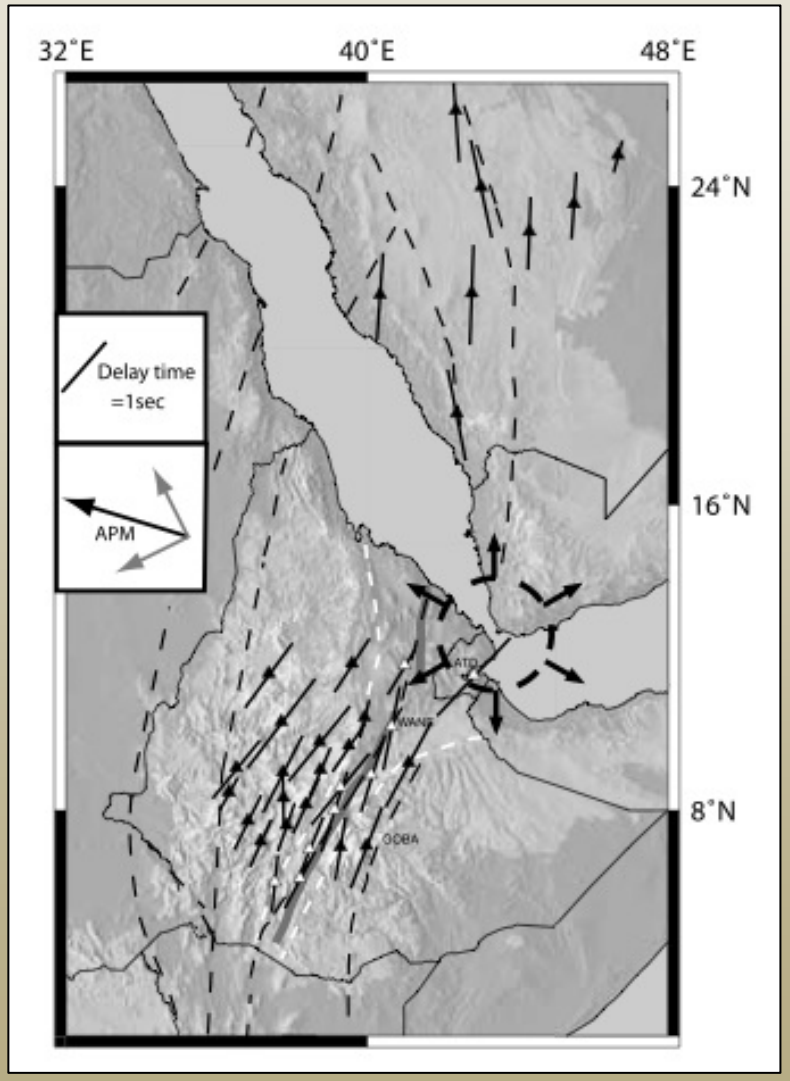
Cornwell et al., 2006



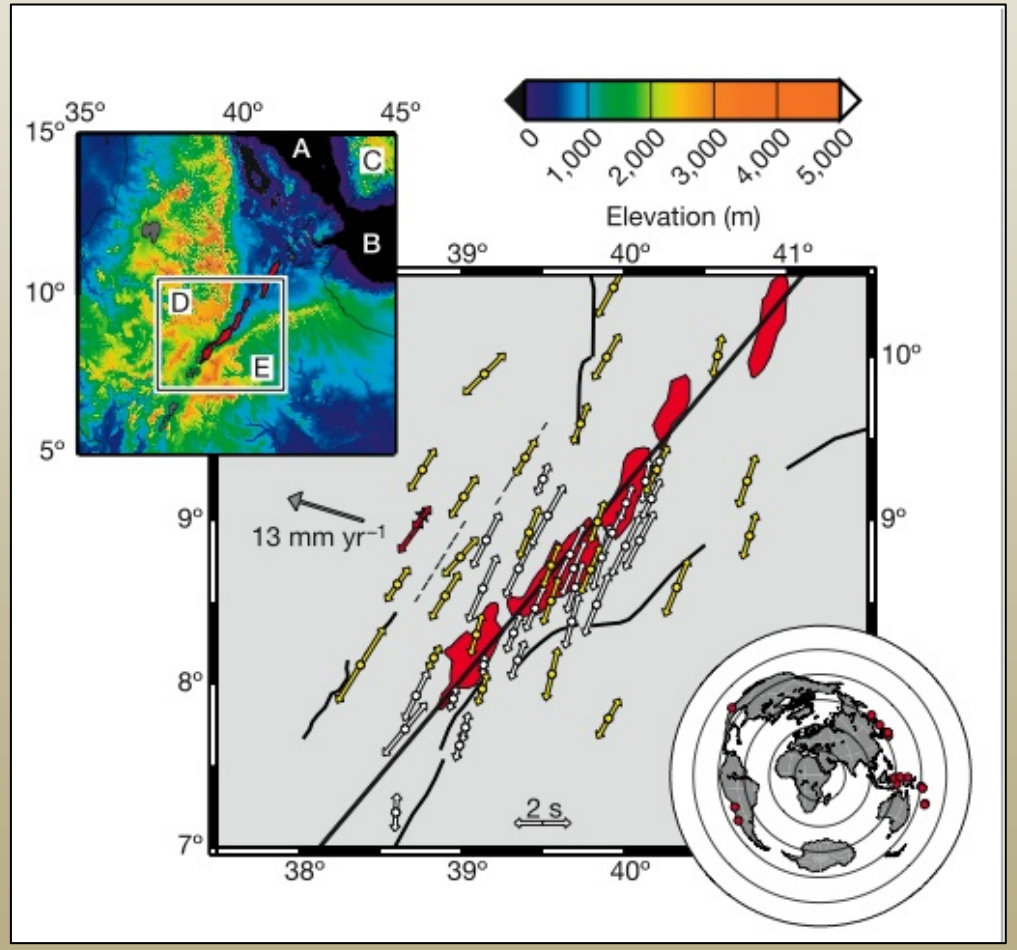


Whaler and Hautot, 2006
Bastow et al., 2008
Keir et al., 2009

Shear-wave splitting



Gashawbeza et al., 2004



Kendall et al., 2004

Sample of exciting EAGLE results

- From EAGLE, we image across a wide range of scales, disciplines within the MER

- Deep earthquakes near Debre Zeit reflect the process of magmatic injection into the lower crust (Keir et al., 2009)
- Low crustal assimilation into magma; distinction between SDFZ and WFB (Rooney et al., 2007)
- Northwestern Ethiopian Plateau is conductive, warm, magmatically modified has seismicity, volcanism, …(many sources)
- Upper mantle low-velocity anomaly is offset from the rift axis (Bastow et al., 2005, 2008; Benoit et al., 2006)

- A huge body of literature is now available!

Sample of exciting EAGLE results

- Ewenet Gashawbeza (Ethiopia)
  - Shear-wave splitting, now at ExxonMobil
- Ketsela Tadesse (Ethiopia)
  - Active-source seismology, now at Ethopian Ministry of Mines, Petroleum Operations
- Mehari Melak (Ethiopia)
  - Now starting a Ph.D. program at Univ. of Memphis, USA
- Derek Keir (UK)
  - Seismicity, now at Leeds
- Ian Bastow (UK)
  - Tomography, now at Bristol
- Dave Cornwell (UK)
  - Gravity, rec. functions, now at Leeds
- Katie Keranen (U.S.)
  - Active-source seismology, now at Univ. of Oklahoma
- Tyrone Rooney (U.S. via the UK)
  - Geochem/petrology, now at Michigan State Univ.
- Eve Daly (UK, post-doc)
  - Seismicity, passive-source tomography, now at Galway

EAGLE Students, Post-docs

Data, etc.

- EAGLE seismic data are freely available through IRIS/PASSCAL (or through PIs)
- I can help, Cindy can help, etc.
- Field notes
- Derivative information, i.e. my travel-time picks

- Ask us…

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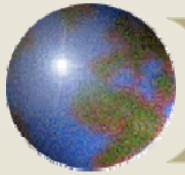
Logistics – what made EAGLE a success?

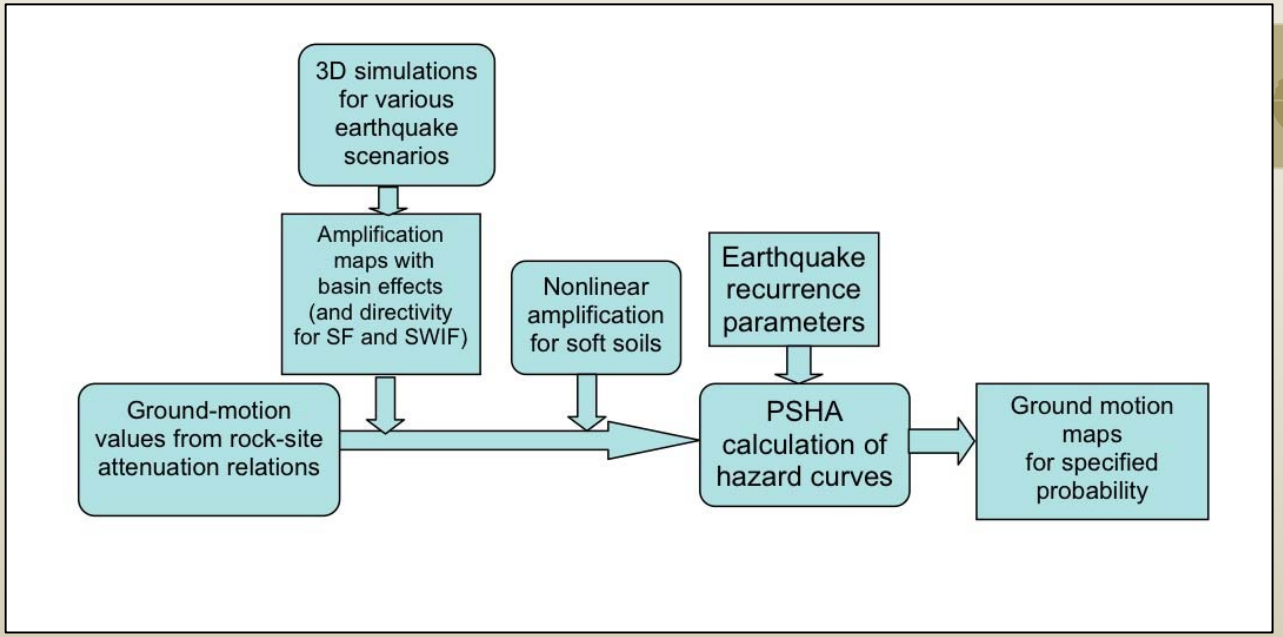
- **IRIS/PASSCAL**
  - Technicians, instruments, expertise, data management, data archival, shots
- Community of scientists, collaboration from pre-fieldwork to well post-fieldwork; face-to-face meetings
- Strong support from Ethiopian colleagues, government, citizens
- Data processing codes: Freely available, advice plentiful from authors of codes and experienced users



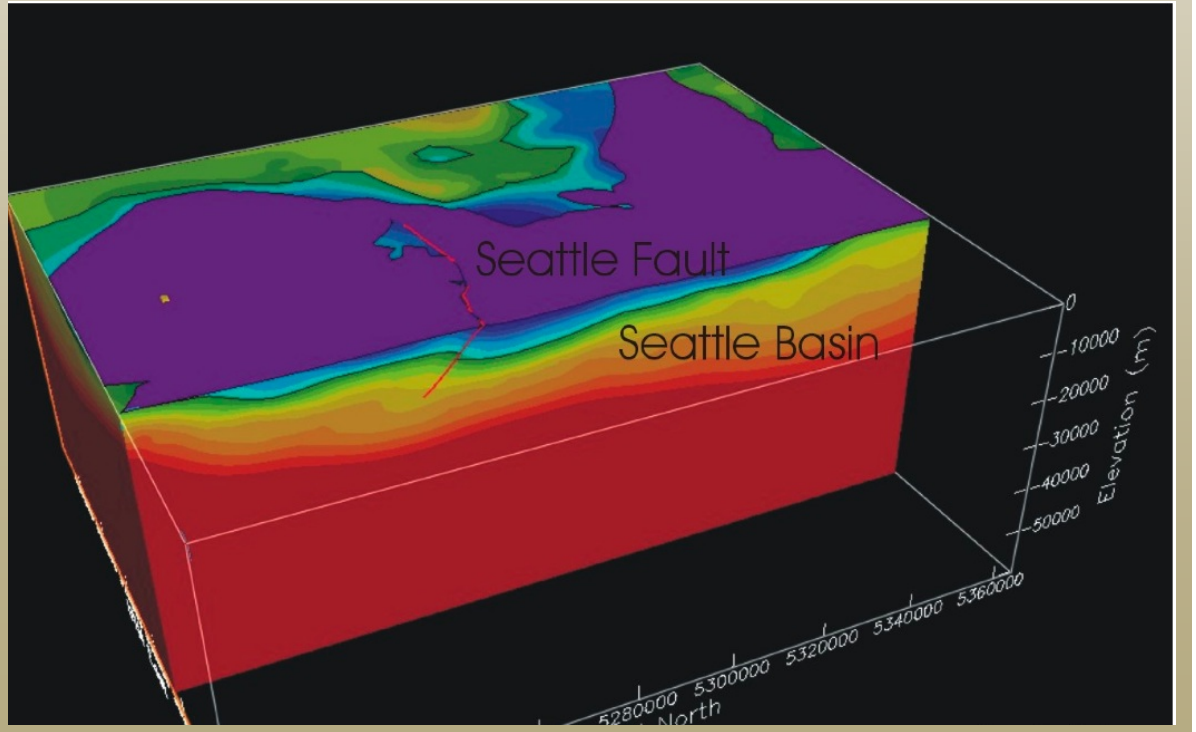
IRIS – www.iris.edu

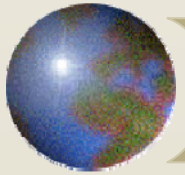
- Support from the National Science Foundation
- IRIS is a consortium of over 100 US universities
- Dedicated to the operation of science facilities for the acquisition, management, and distribution of seismological data.

- Software, data, instruments, expertise, personal networks, tutorials, etc.
- PASSCAL instrument center: http://www.iris.edu/hq/programs/passcal/instrumentation



Probabilistic earthquake hazards: *Inputs from seismic velocity models*





What Have We Learned?

- International, interdisciplinary projects in the EARS have been highly successful
- Career training/development of numerous scientists from Africa, the U.S. & Europe; now in:
  - Industry
  - Government scientific agencies
  - Teaching and research universities
- Integrated understanding of extensional and magmatic processes along the EARS
  - Seismology, potential fields, geochemistry/petrology, structural geology, geodesy, etc.
  - Datasets exist, ready as inputs into seismic hazard models or for future study
- Promoted collaboration and heightened appreciation between geoscience disciplines and nurtured ongoing international collaborations