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Title: Introduction to Seismic Tomography

Author(s): Rowe, Charlotte Anne

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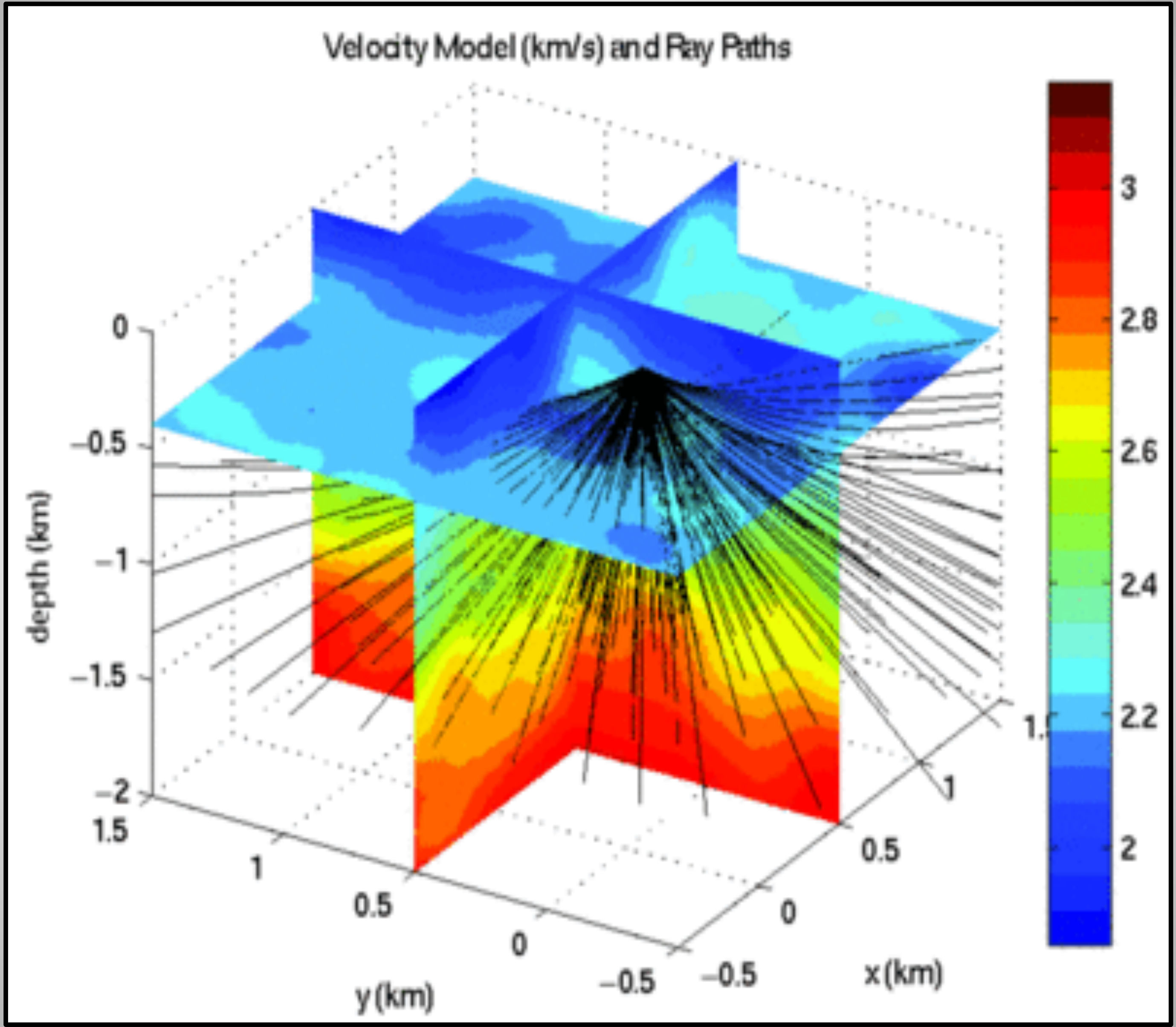
INTRODUCTION TO SEISMIC TOMOGRAPHY



Presented to SisVOc

by CHARLOTTE ROWE

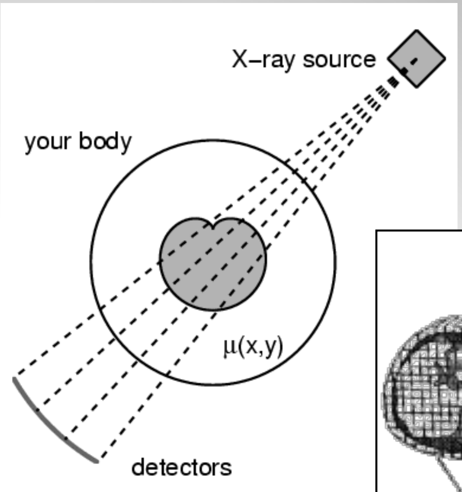
22 Noviembre 2017

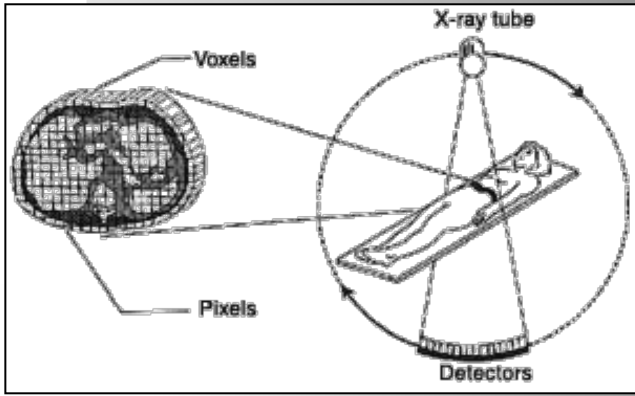
WHAT IS TOMOGRAPHY?

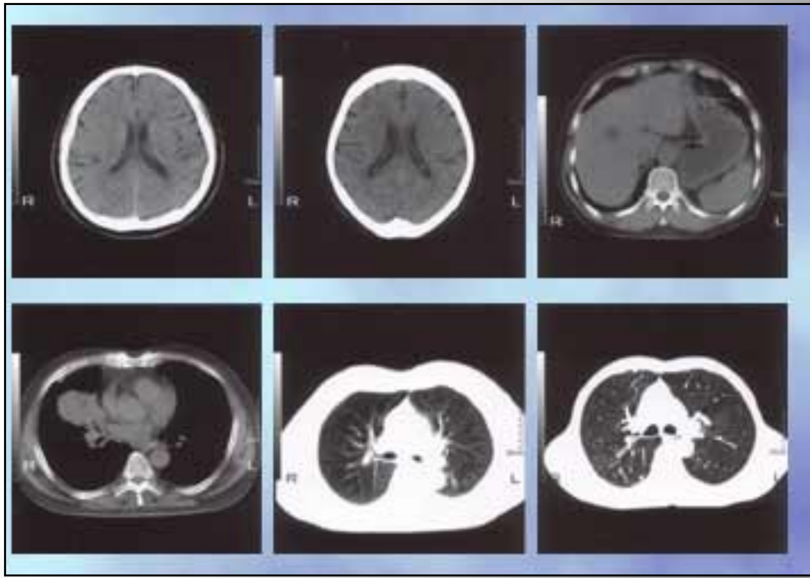
TOMOGRAPHY IS A METHOD OF OBTAINING AN IMAGE OF A 3D OBJECT BY OBSERVING THE BEHAVIOR OF ENERGY TRANSMISSIONS THROUGH THE OBJECT.

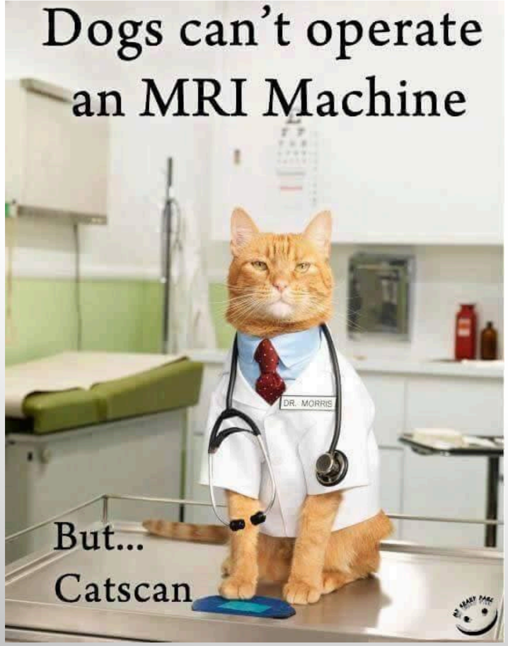
THE IMAGE IS OBTAINED BY INTERROGATING THE OBJECT WITH ENERGY SOURCES AT A VARIETY OF LOCATIONS AND OBSERVING THE OBJECT'S EFFECTS ON THE ENERGY AT A VARIETY OF SENSORS.

TOMOGRAPHY WAS FIRST USED TO BUILD 3-DIMENSIONAL SCANS THROUGH HUMAN BODIES. THESE ARE CALLED COMPUTED TOMOGRAPHIC (CT) SCANS.







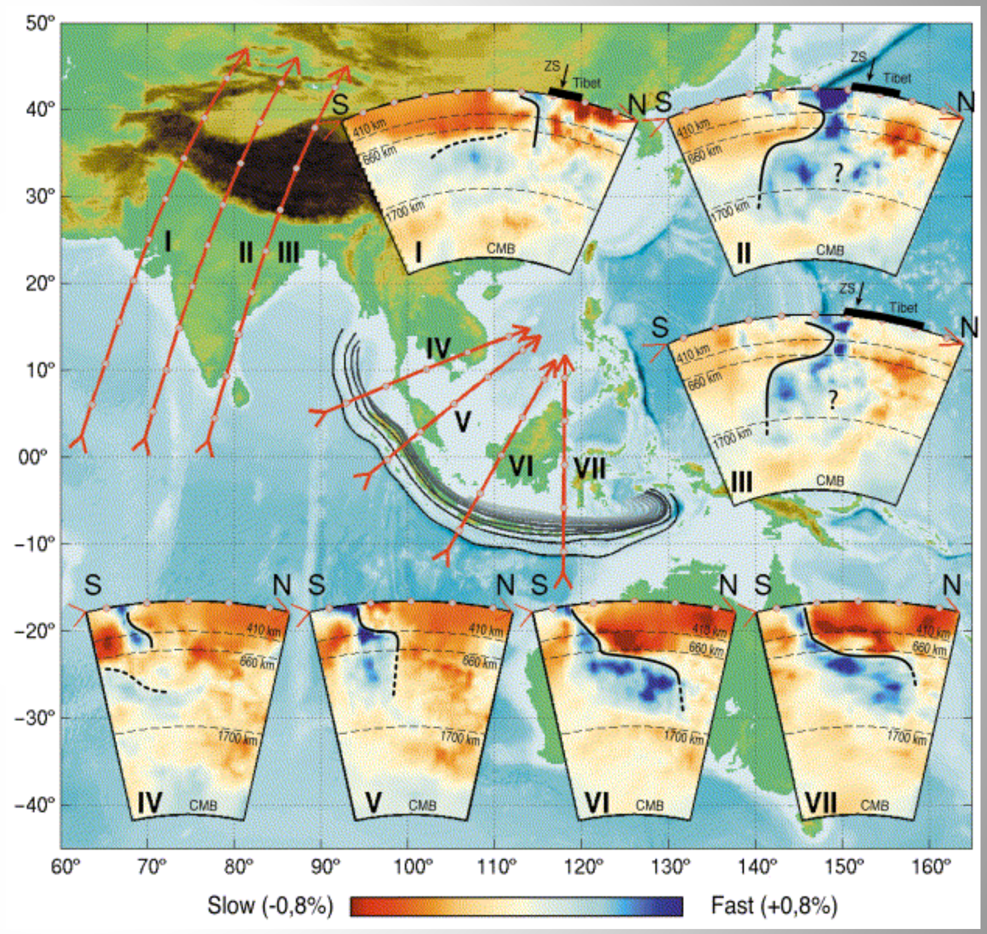


WHAT IS *SEISMIC* TOMOGRAPHY?

WHEN WE TALK ABOUT SEISMIC TOMOGRAPHY WE USUALLY MEAN SEISMIC WAVE SPEED TOMOGRAPHY – WE ARE TRYING TO BUILD A 3D REPRESENTATION OF HOW FAST SEISMIC WAVES PROPAGATE THROUGH THE EARTH.

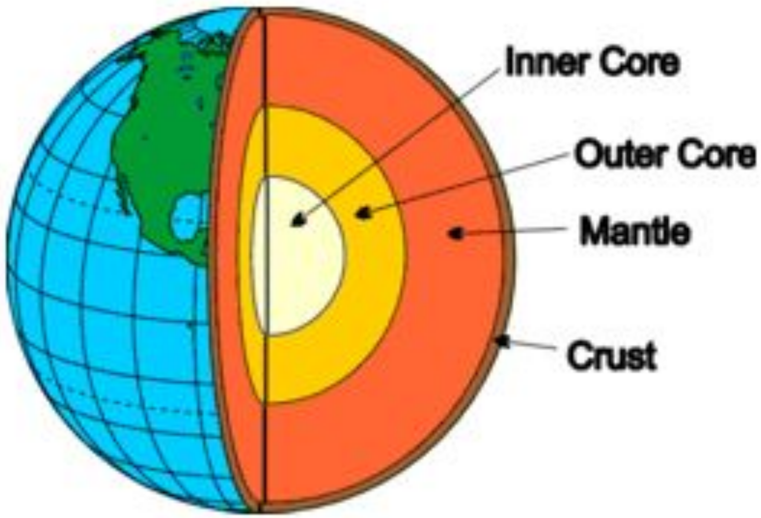
WE CAN ALSO PERFORM TOMOGRAPHY TO FIND SEISMIC ATTENUATION CHARACTERISTICS OF THE EARTH – BUILD A THREE-DIMENSIONAL MODEL OF HOW THE SEISMIC WAVES ARE ATTENUATED AS THEY PASS THROUGH THE EARTH.

BUT TODAY LET'S JUST TALK ABOUT SEISMIC WAVE SPEED.



WHY DO WE NEED TO KNOW SEISMIC WAVE SPEEDS?

1) KNOWING SOMETHING ABOUT SEISMIC WAVE SPEED TELLS US SOMETHING ABUOT THE PROPERTIES OF THE ROCKS
2) WE NEED TO USE SEISMIC WAVE SPEEDS (VELOCITY) IN ORDER TO CALCULATE THE LOCATION OF AN EARTHQUAKE WHOSE SOURCE IS OF INTEREST TO US.



Cross section of the Earth

HOW WELL MUST WE KNOW THE VELOCITY?

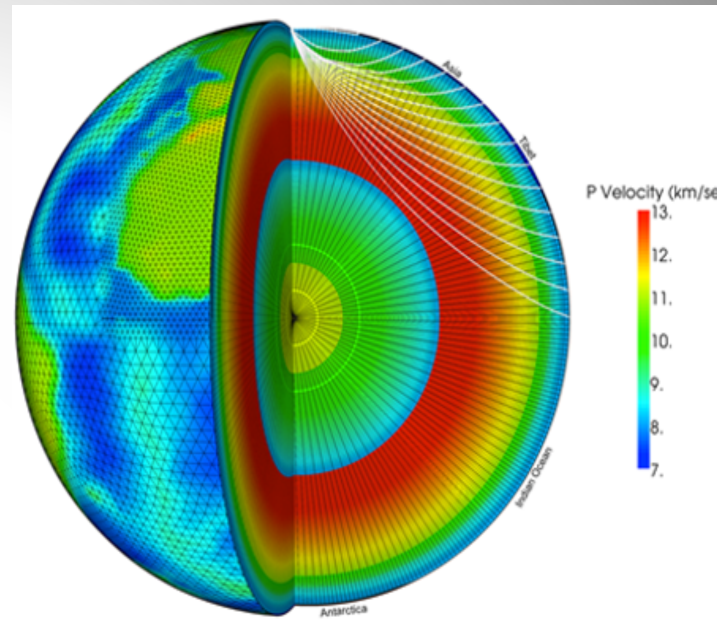
THIS DEPENDS ON WHAT KIND OF PROBLEM WE ARE TRYING TO SOLVE.

TO INTERPRET GENERAL, BULK PROPERTIES OF THE EARTH, IF OUR VELOCITY ESTIMATE IS PRETTY CLOSE TO CORRECT AND IS GENERALIZED OVER A LARGE VOLUME, IT IS PROBABLY GOOD ENOUGH.

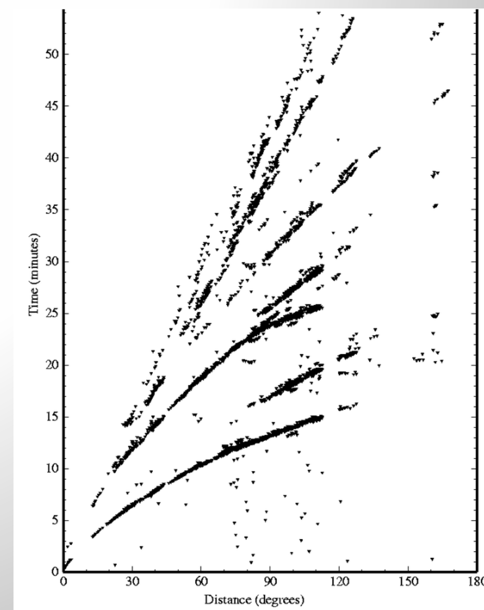
HOW MUCH DO WE NEED TO KNOW ABOUT SEISMIC WAVE SPEEDS IN THE EARTH?

TO OBTAIN A ROUGH IDEA OF WHERE AN EARTHQUAKE HAS OCCURRED, ESPECIALLY AT *TELESEISMIC* DISTANCES, A SIMPLE MODEL IS PROBABLY GOOD ENOUGH.

THE MODEL SHOWN HERE IS WHAT WE CALL A ONE-DIMENSIONAL MODEL. YES, IT IS ACTUALLY A 3D OBJECT, BUT THE SEISMIC VELOCITY ONLY VARIES IN ONE DIRECTION – RADIALLY. WE CALL THIS A RADIAL 1-D MODEL.



SUCH MODELS WERE OBTAINED BY LOOKING AT THE VARIOUS SEISMIC WAVES FROM LARGE, DISTANT EARTHQUAKES, AND MEASURING THE TIME IT TOOK THEM TO TRAVEL FROM THE EARTHQUAKE TO SEISMOMETERS AT MANY DISTANCES AROUND THE WORLD.



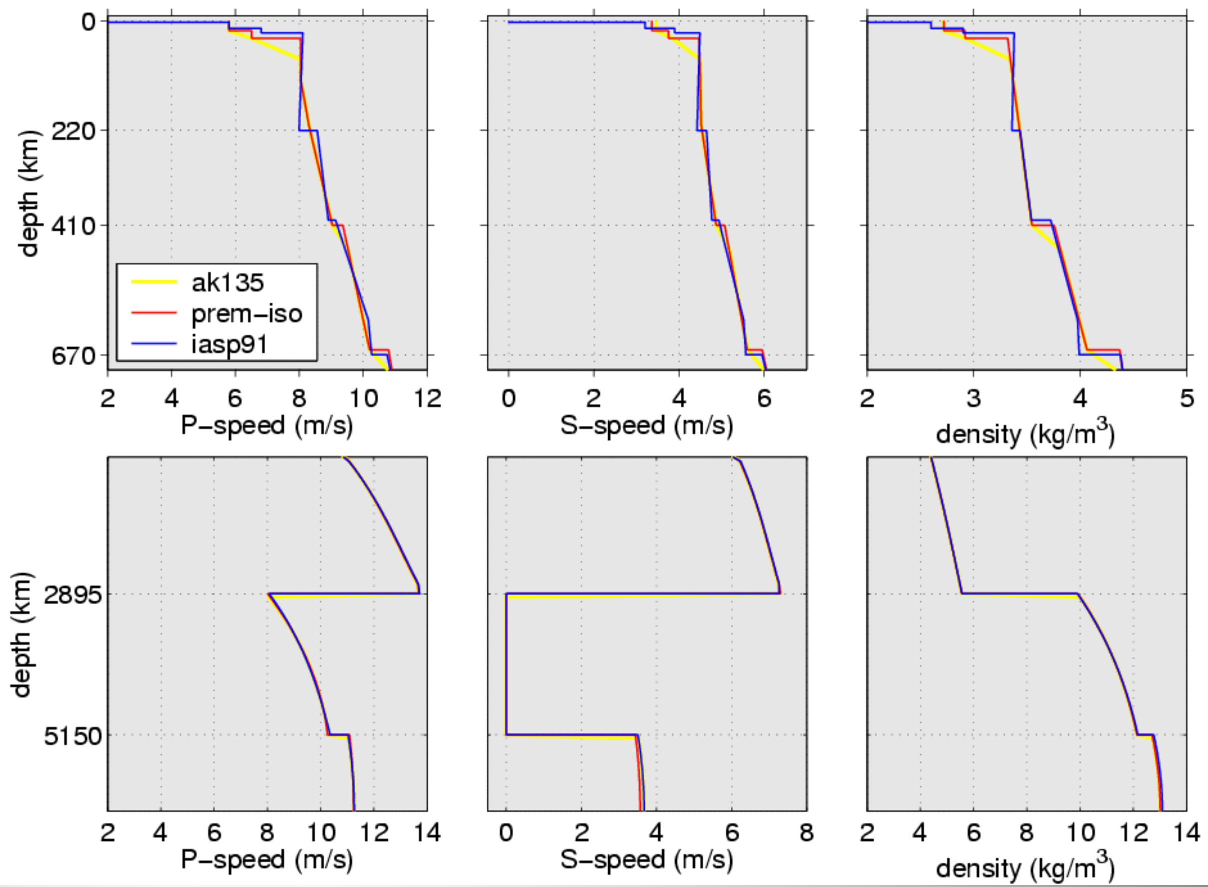
EXAMPLES OF REFERENCE EARTH MODELS

HERE ARE THREE STANDARD REFERENCE EARTH MODELS (ONE-DIMENSIONAL, RADIALLY SYMMETRIC EARTH). THE ONES WE KNOW BEST ARE CALLED AK135, iasp91 AND PREM. THEY ARE ALL VERY SIMILAR, ESPECIALLY AT DEPTH, BUT THEY HAVE SOME VARIATIONS AT SHALLOWER LEVELS.

ALL THREE REFERENCE MODELS ARE VERY GOOD MODELS OF AVERAGE SEISMIC WAVE SPEED FOR THE WHOLE EARTH.

NOT ONE OF THESE MODELS IS A VERY GOOD REPRESENTATION OF THE EARTH IN ANY PARTICULAR PLACE.

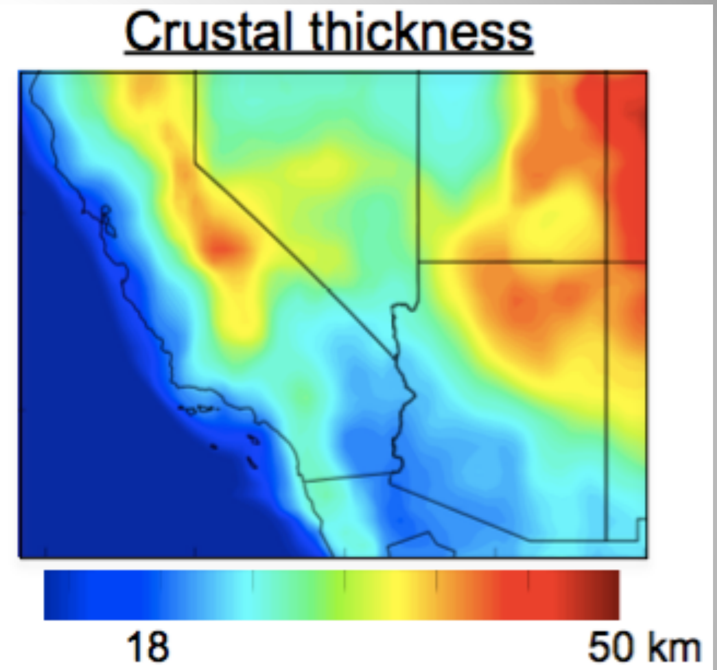
SO FOR PREDICTING THE TIME IT TAKES A SEISMIC WAVE TO TRAVEL OVER A GREAT DISTANCE, THEY ARE OKAY.



FOR SMALL REGIONAL OR LOCAL STUDIES THEY ARE TERRIBLE.

AS WE WORK AT SMALLER SCALES, THE EARTH BECOMES MORE COMPLICATED.

INSTEAD OF GLOBALLY UNIFORM MANTLE DEPTH, WE BEGIN TO SEE DIFFERENCES IN CRUSTAL THICKNESS AT REGIONAL AND LOCAL SCALES.



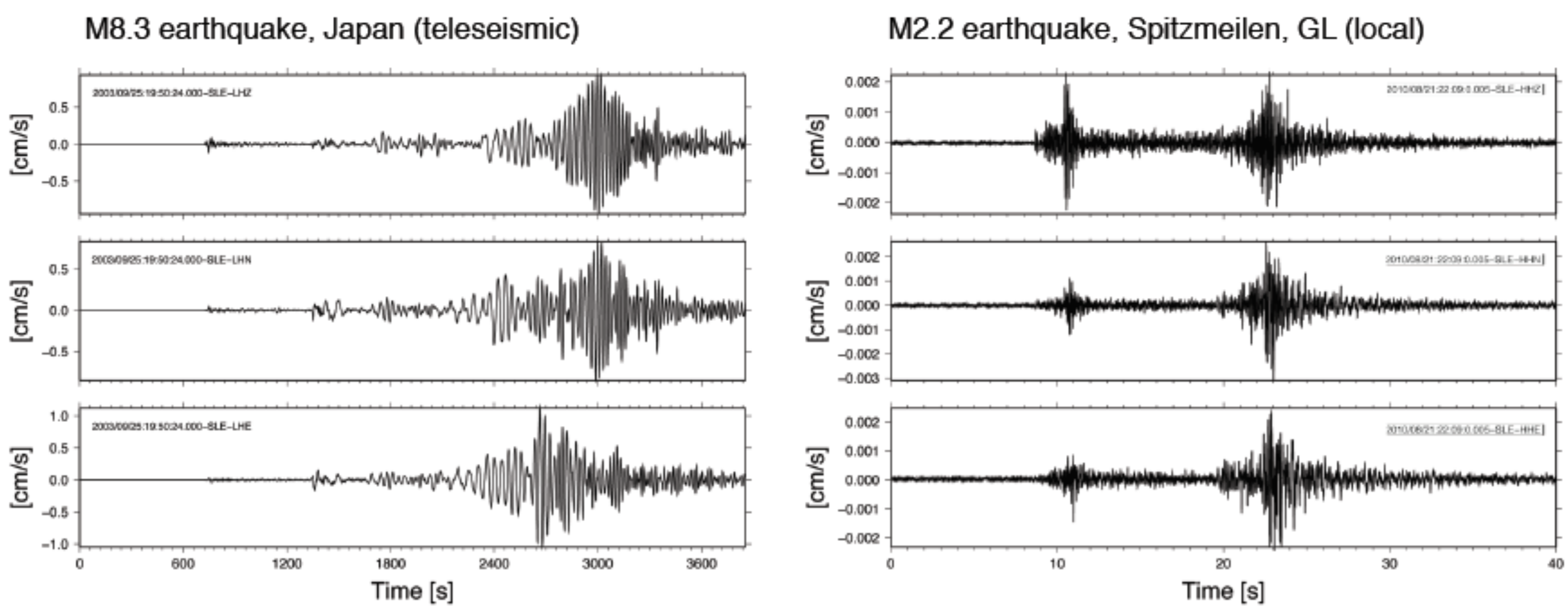
INSTEAD OF LATERALLY HETEROGENEOUS AND UNIFORM LAYERS OF “CRUST” AND “MANTLE” AND “CORE,” WE ARE DEALING WITH MANY GEOLOGIC VARIATIONS IN THE FABRIC, LITHOLOGY, STRENGTH AND CON-TINUITY OF ROCKS.

THERE ARE FAULTS AND BASINS AND INTRUSIONS. ALL OF THESE THINGS AFFECT THE SEISMIC WAVE SPEEDS AND MUST BE ACCOUNTED FOR IN OUR MODELS USED FOR EARTHQUAKE LOCATION.

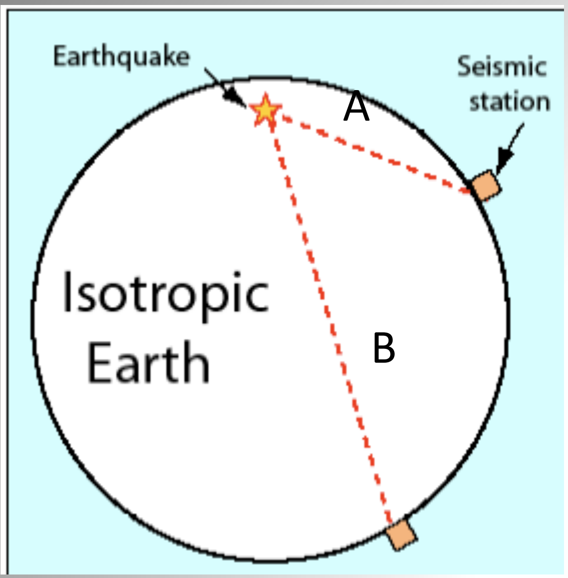
TO BEGIN WITH, WE NEED DATA FROM EARTHQUAKES. WE MUST HAVE HIGH QUALITY *PICKS* OF P OR P AND S WAVES, AND REASONABLE ESTIMATES OF EARTHQUAKE *LOCATIONS* SO THAT WE CAN FIND THE *TRAVEL TIME* OF THE P AND S PHASES FROM THE SOURCE TO THE STATION.

Seismograms in seismic tomography

Seismometers record ground velocity excited by an earthquake



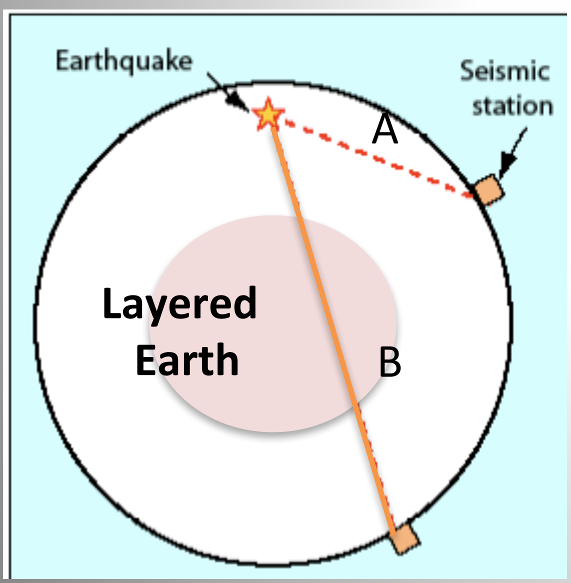
SO WE JUST TRACE THE WAVES THROUGH THE ROCKS AND WE CAN GET THE VELOCITIES, RIGHT?



DISTANCE TO STATION DIVIDED BY TRAVEL TIME IS THE VELOCITY IN KM PER SECOND.

So V(A) = length(A) / traveltime(A)
And V(B) = length(B) / traveltime(B)

BUT WHAT ABOUT A LAYERED EARTH?



V(A) = length(A) / traveltime(A)
For B we can estimate the average velocity:

V(B) = [length(pink) + length(white)] / (total traveltime)

V(B) will not be the same as V(A).

V(Bw) = V(A)
V(Bp) = length(pink) / traveltime(pink)

How can we determine this if we don't know length(pink)?

HOW DO WE DETERMINE LENGTH(PINK)?

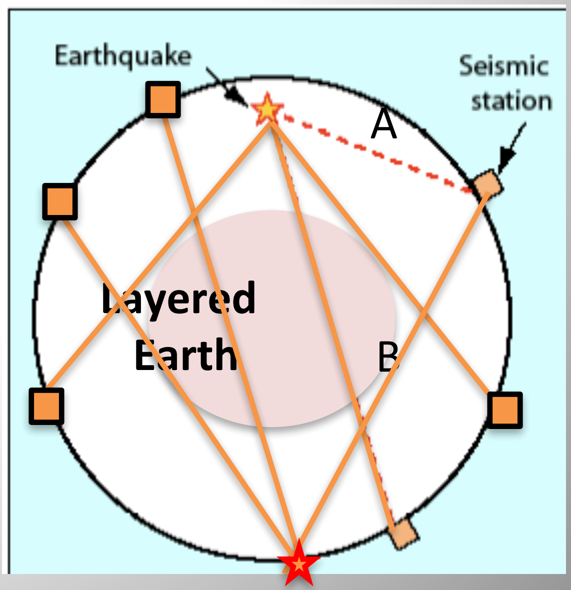
WE CAN TRY A FORWARD MODEL.

GUESS AT THE LENGTH. CALCULATE THE EXPECTED TRAVEL TIME IF WE ASSIGN A VELOCITY TO PINK. ADJUST VELOCITY AND LENGTH OF PINK UNTIL WE GET AN ANSWER THAT FITS THE OBSERVATIONS.

IS THIS THE UNIQUE, CORRECT ANSWER? NO, OF COURSE NOT.

IF WE ASSUME A DIFFERENT VELOCITY FOR PINK, THEN TO FIT THE TRAVEL TIME, WE WOULD NEED A DIFFERENT SIZE FOR PINK. ALTHOUGH WE KNOW WHAT V(Bw) IS, CHANGING V(Bp) WILL REQUIRE A CHANGE OF length(W) AS WELL AS length(P) TO FIT THE OBSERVED TRAVEL TIME

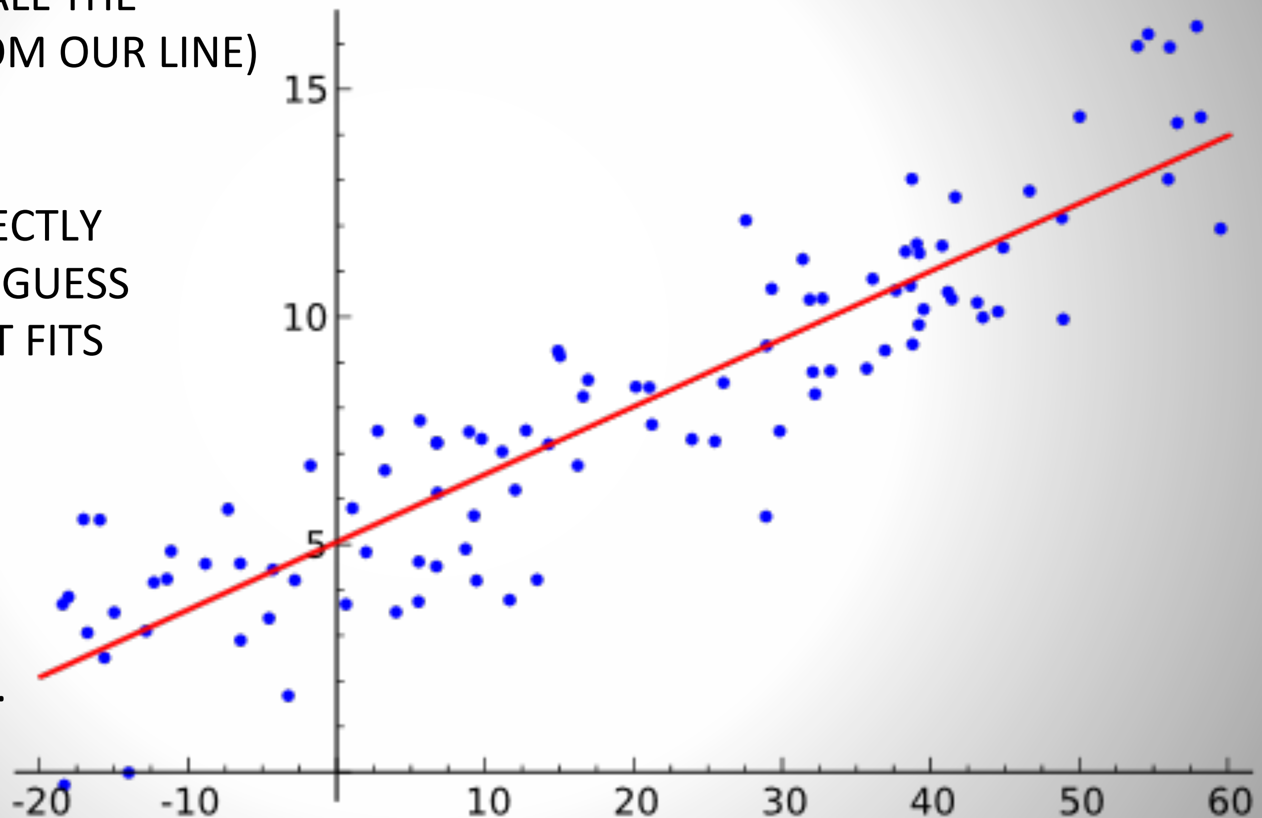
THE ANSWER IS THAT WE CLEARLY NEED MORE RAYS . WE NEED ENOUGH SOURCES AND RECEIVERS (EARTHQUAKES AND SEISMIC STATIONS), IN THE CORRECT POSITIONS, SO THAT WE CAN *CONSTRAIN* THE SIZE OF THE PINK LAYER BY ADJUSTING ITS SIZE AND VELOCITY UNTIL WE FIT ALL THE KNOWN TRAVEL TIMES.



WE WILL NEVER FIT THEM ALL PERFECTLY. WE SEEK TO MINIMIZE THE *MISFIT.*

RESOLVING THE SIZE AND VELOCITY OF THE PINK LAYER IS AN EXERCISE IN ***REGRESSION***. A SIMPLE EXAMPLE OF REGRESSION TO MINIMIZE A MISFIT FOR MANY DATA POINTS IS THE FITTING OF A STRAIGHT LINE THROUGH DATA POINTS.

TO BEST FIT THE DATA WE WANT TO FIND THE SLOPE AND INTERCEPT DEFINING A LINE THAT MINIMIZES ALL THE MISFITS (DISTANCE FROM OUR LINE) FOR ALL DATA POINTS.



NO DATA ARE FIT PERFECTLY BUT WE HAVE A GOOD GUESS AT THE FUNCTION THAT FITS THE DATA.

THE REMAINING MISFIT MAY COME FROM ERRORS IN THE DATA MEASUREMENTS. IT MAY MEAN THAT A STRAIGHT LINE IS NOT THE CORRECT FUNCTION (MODEL) TO USE.

COULD WE FIT ALL THE DATA PERFECTLY?
SURE. LOOK AT THE YELLOW FUNCTION. THIS FITS THE DATA PERFECTLY.

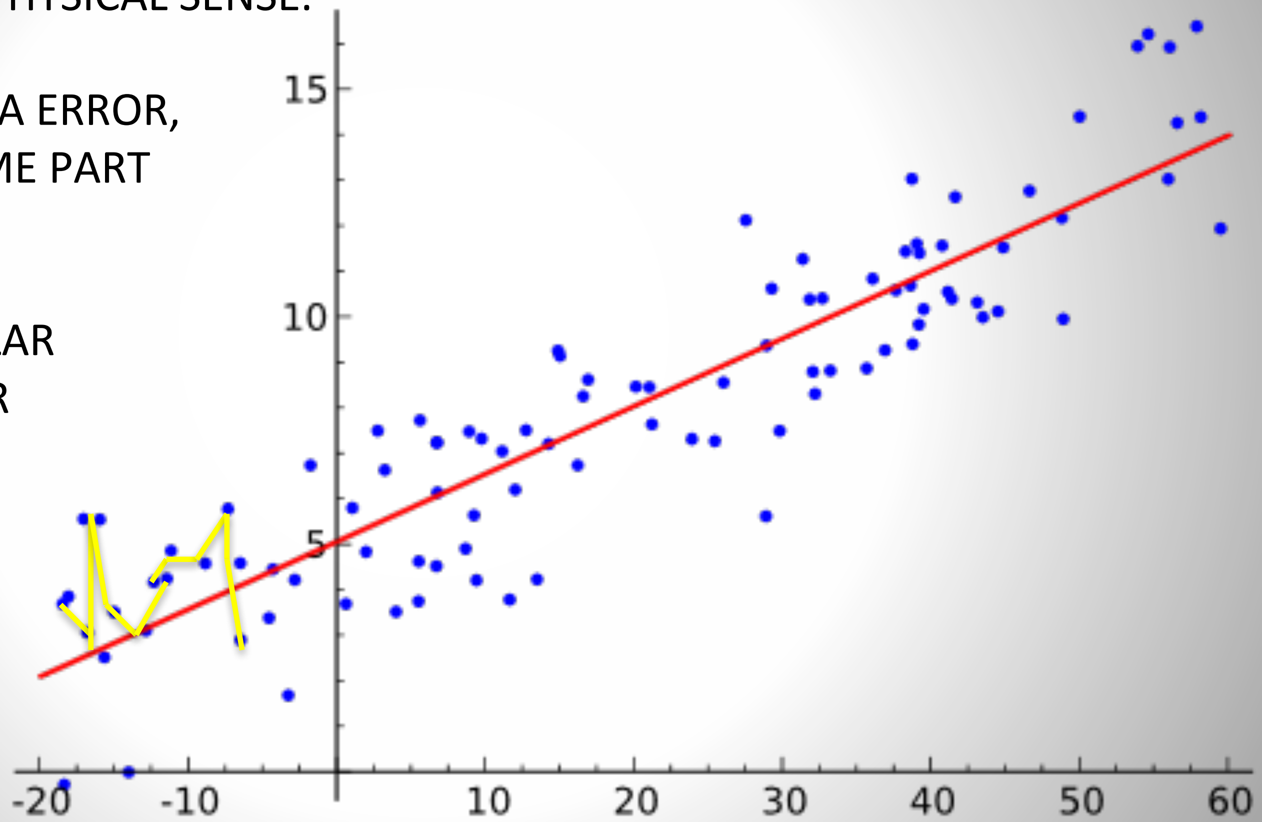
WHY IS THIS YELLOW SOLUTION PROBABLY INCORRECT?

IT PROBABLY MAKES NO PHYSICAL SENSE.

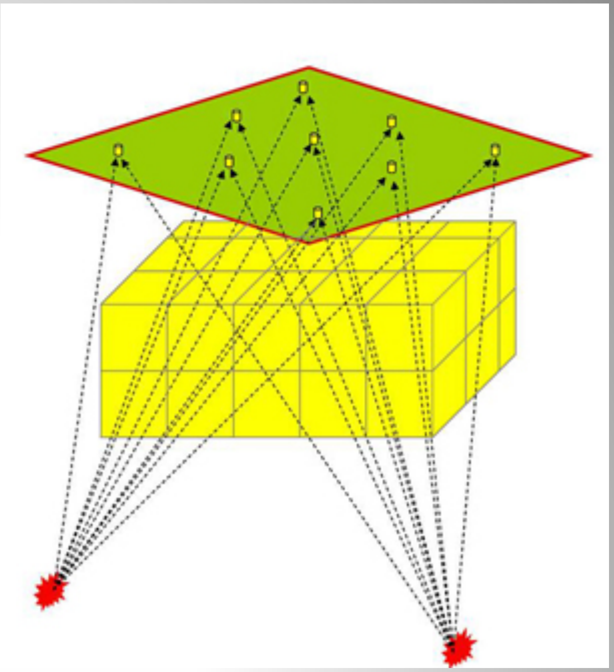
IT COULD BE FITTING DATA ERROR, FORCING THAT TO BECOME PART OF THE MODEL.

WE HAVE TO BRING SIMILAR CONSIDERATIONS TO OUR TOMOGRAPHY PROBLEM.

IN THE END WE HAVE TO BALANCE FITTING THE DATA AGAINST FINDING A SENSIBLE MODEL.



PARAMETERIZING OUR MODEL



HERE WE SHOW TWO SOURCES AND A NETWORK OF STATIONS ON THE SURFACE. THE EARTH WE ARE MODELING HAS BEEN DIVIDED INTO SEVERAL BOXES, EACH OF WHICH WE COULD ASSIGN A SEISMIC VELOCITY. WE SAY THAT THE MODEL HAS BEEN *PARAMETERIZED* AS A *VOLUME OF DISCRETE CELLS* OR ELEMENTS.

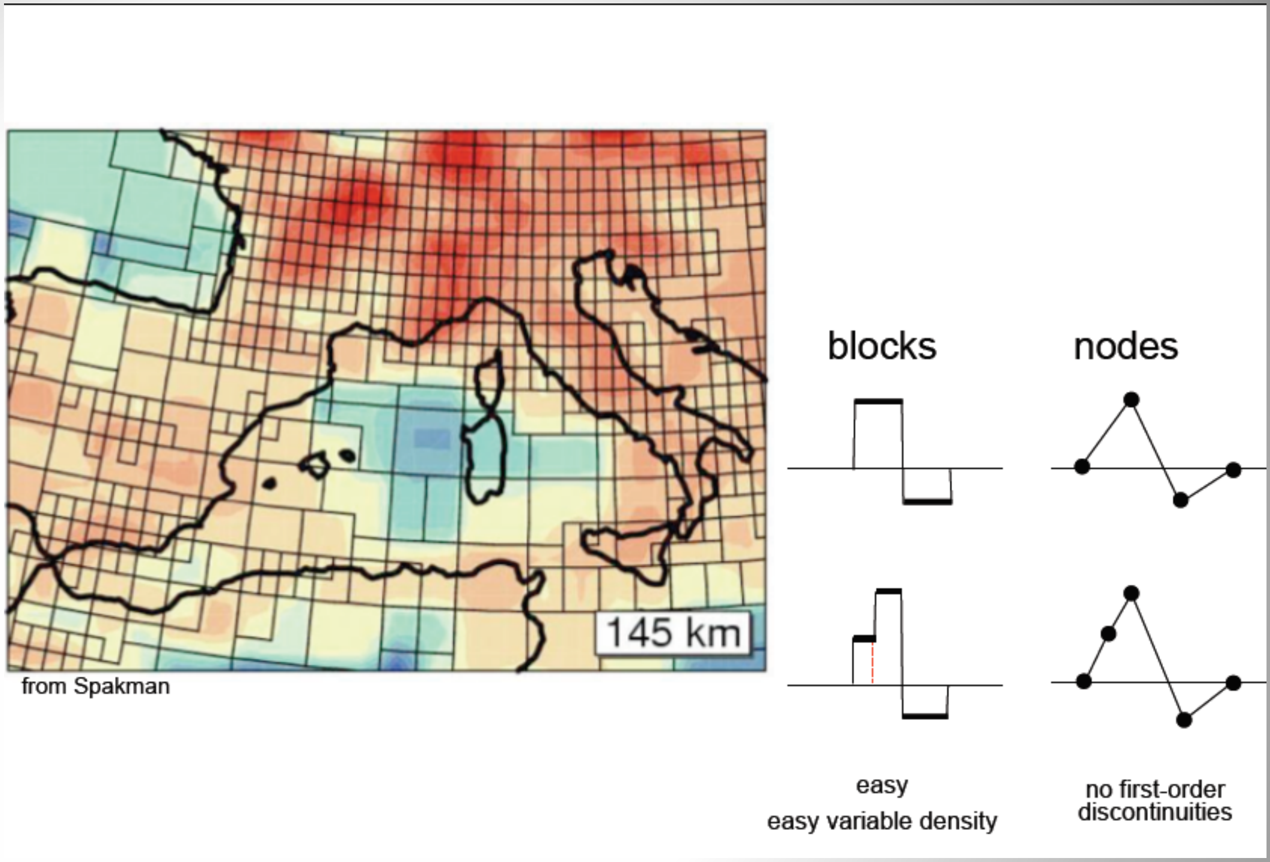
EACH ELEMENT THAT HAS *MULTIPLE RAYS CROSSING* IT CAN PROBABLY BE RESOLVED AND A VELOCITY FOR THAT CELL CAN BE FOUND.

IF OUR CELL SIZES ARE TOO SMALL ,THEN MANY WILL NOT BE SAMPLED AND CANNOT BE RESOLVED.

IF OUR CELL SIZES ARE TOO LARGE, THEN WE WILL MISS OUT ON SMALL VELOCITY CHANGES; THEY WILL BE AVERAGED INTO A LARGER BOX.

SOME OTHER CONSIDERATIONS

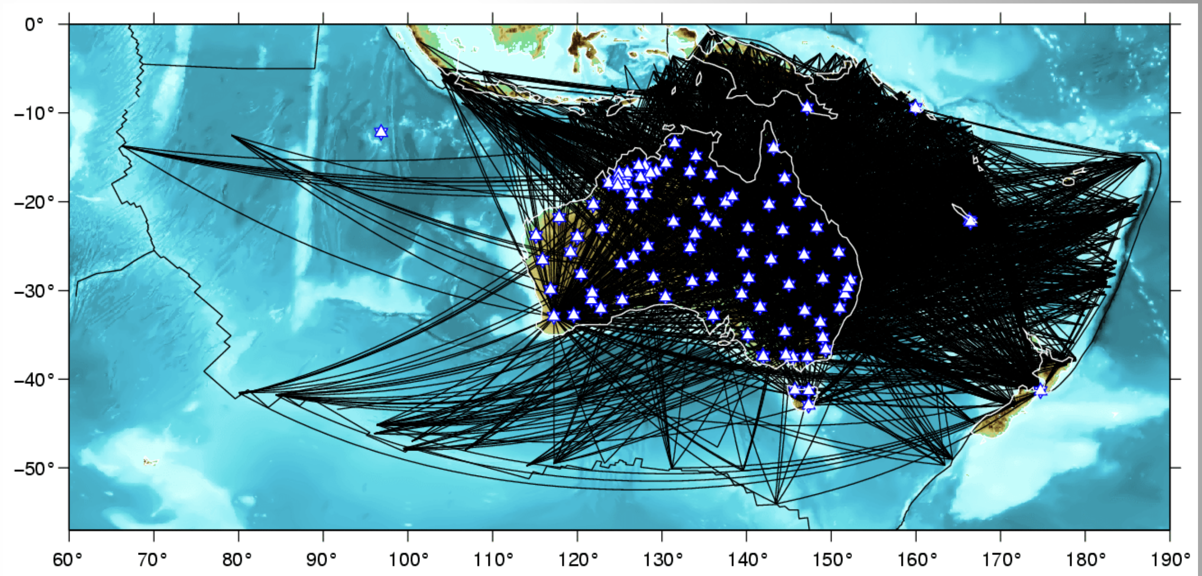
WE MAY CHOOSE TO *PARAMETERIZE* OUR 3D MODEL AS A **GRID** OF NODES, OR POINTS, EACH OF WHICH DEFINES VELOCITY AT A POINT, INSTEAD OF AS A VOLUME OF BOXES HAVING DISCRETE VELOCITIES. THIS APPROACH THEN ASSUMES THAT THE VELOCITY FROM ONE NODE TO THE NEXT VARIES LINEARLY.



WE MAY CHOOSE TO PARAMETERIZE OUR MODEL WITH *VARIABLE NODE DENSITY* (OR BOX SIZES), SO IN PLACES WHERE WE EXPECT TO HAVE MANY CROSSING RAYS, WE CAN HAVE A MODEL WITH MORE DETAIL.

WE WORRY A LOT ABOUT RAY COVERAGE

HERE WE SEE A RAY DIAGRAM FOR A TOMOGRAPHIC EXPERIMENT IN AUSTRALIA. PURPLE DOTS SHOW THE SEISMIC STATIONS USED, AND THE BLACK LINES ARE RAYS FOR THE EARTHQUAKES USED IN THE STUDY.



THE CONTINENT AND AREA JUST
EAST OF IT MAY BE WELL-RESOLVED, BUT WE CAN SEE THAT THERE ARE VERY FEW CROSSING RAYS IN THE OCEAN, ESPECIALLY TO THE SOUTH AND WEST. FOR THIS PART OF THE EARTH IT WILL NOT BE POSSIBLE TO OBTAIN A RELIABLE VELOCITY MODEL USING THESE DATA.

ANOTHER COMPLICATION….

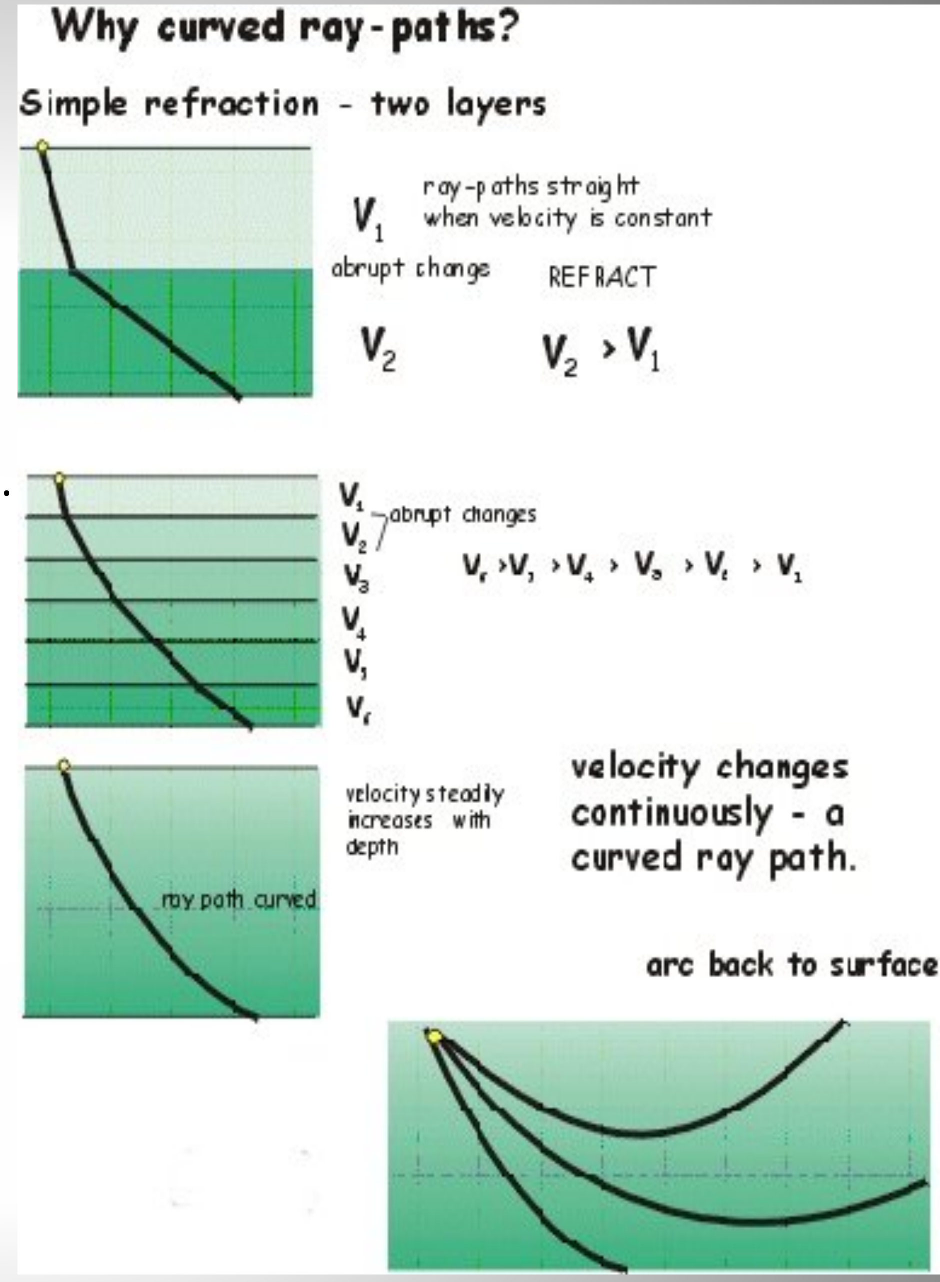
SEISMIC WAVES ARE AFFECTED BY VELOCITY CHANGES THROUGH WHICH THEY TRAVEL.

THEY DO NOT KEEP TRAVELING IN THE SAME DIRECTION. YES – THEY CHANGE DIRECTION WHEN THEY ENCOUNTER A CHANGE IN VELOCITY.

SEISMIC RAYS BEND WHEN THEY MOVE FROM ONE VELOCITY MEDIUM INTO ANOTHER. THE AMOUNT OF BENDING DEPENDS ON THE VELOCITY CONTRAST AND IS GOVERNED BY *SNELL'S LAW*, WHICH DEFINES A RELATIONSHIP

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$$

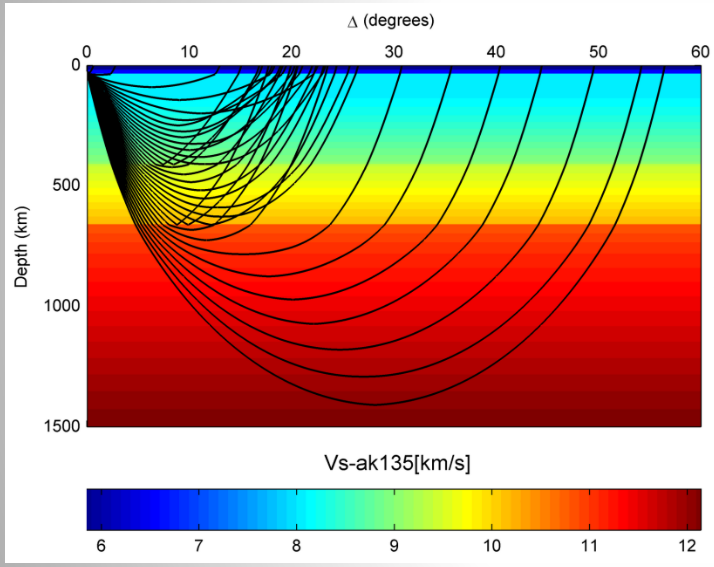
WHERE THETA(1) AND THETA(2) ARE INCIDENCE AND REFRACTED ANGLES AND v1 AND v2 ARE THE RESPECTIVE VELOCITIES.

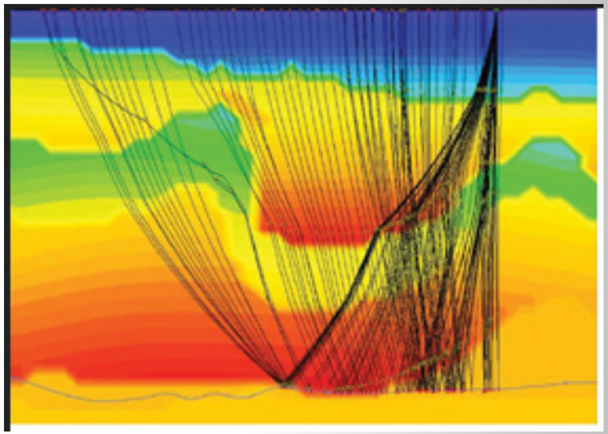


ANOTHER COMPLICATION….

NOT ONLY MUST WE WORRY ABOUT OUR RAY *COVERAGE* WHEN WE WANT TO SOLVE A TOMOGRAPHIC PROBLEM, BUT WE HAVE TO KNOW THAT THE RAY PATHS ARE NOT STRAIGHT.

WHEN WE PERFORM OUR TOMOGRAPHY AND WE CHANGE THE MODEL, THEN OUR RAYS WILL ALSO CHANGE.





SO WE ONLY ALLOW THE MODEL TO CHANGE A LITTLE, THEN WE TRACE THE NEW RAYS THROUGH THE NEW MODEL AND ADJUST THE MODEL AGAIN, THEN WE TRACE NEW RAYS. AND THEN WE DO IT AGAIN. AND AGAIN….. THIS *ITERATIVE* PROCESS DEPENDS ON CAREFUL CHOICE OF MODEL STABILITY (*DAMPING)* AND REQUIRING THE MODEL TO BE PHYSICALLY SENSIBLE (*SMOOTHING*). IT IS AN ART, AND REQUIRES UNDERSTANDING THE GEOLOGY, THE DATA AND THE BASIC MATHEMATICS OF THE PROCESS.

OH, AND ANOTHER THING….

IF WE ARE USING LOCAL EARTHQUAKES AND STATIONS TO SOLVE FOR A LOCAL VELOCITY MODEL, WE HAVE TO UNDERSTAND THAT ONCE WE HAVE CHANGED THE VELOCITY MODEL, THEN THE TRAVEL TIMES WE HAVE USED, BASED ON OUR INITIAL EARTHQUAKE HYPOCENTER LOCATIONS, WILL HAVE CHANGED.

IF THE TRAVEL TIME FOR THESE HYPOCENTERS CHANGE, THEN THE LOCATION ESTIMATES NEED TO CHANGE.

SO AN IMPORTANT STEP IS TO RE-LOCATE ALL THE EARTHQUAKES USED IN THE TOMOGRAPHIC MODEL, USING THE NEW MODEL.

ONCE WE HAVE RE-LOCATED THE EARTHQUAKES, THEN WE OBTAIN NEW HYPOCENTERS, NEW TRAVEL TIMES (IN THE NEW MODEL) AND WE MUST PERFORM THE TOMOGRAPHY AGAIN TO UPDATE THE MODEL BASED ON OUR NEW EARTHQUAKE LOCATIONS.

REPEAT UNTIL THE MODEL STOPS CHANGING AND THE HYPOCENTERS DO NOT MOVE ANY MORE.

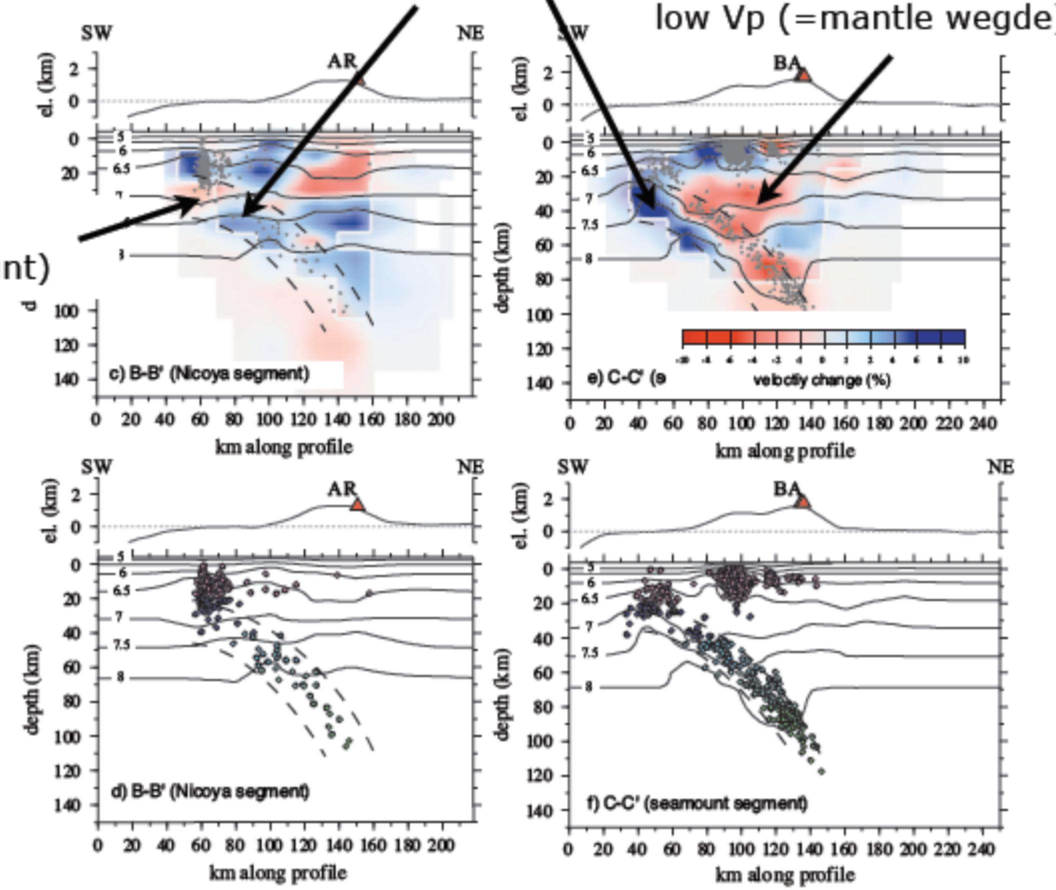
THINGS TO CONSIDER FOR 3D SEISMIC TOMOGRAPHY

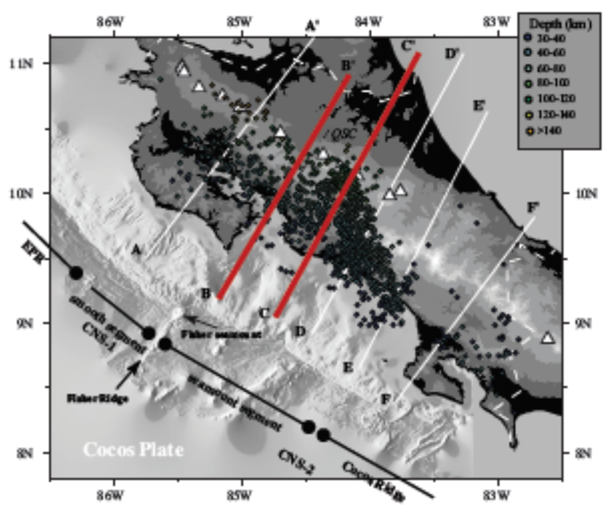
- DECIDE WHAT YOUR TARGET IS
- ASSESS YOUR SOURCES AND RECEIVERS AND THE GEOMETRY.
- DO YOU HAVE ENOUGH DATA? DO YOU HAVE THE RIGHT DATA? CAN YOU GET MORE DATA?
- YOU NEED TO PARAMETERIZE YOUR MODEL AREA. GRID? CELLS? WHAT SIZE?
- YOU NEED A STARTING MODEL. PROBABLY A SIMPLE 1-D LAYERED MODEL WILL DO, UNLESS YOU KNOW MANY DETAILS ABOUT YOUR AREA ALREADY. THE STARTING MODEL SHOULD BE AS CLOSE TO CORRECT AS POSSIBLE. REMEMBER, TINY CHANGES.
- DECIDE WHAT TOMOGRAPHY CODE IS APPROPRIATE FOR YOUR NEEDS.
- PERFORM DATA QUALITY CONTROL. IF YOU START OUT WITH POOR EARTHQUAKE LOCATIONS AND BAD PICKS, YOUR INVERSION WILL FAIL OR YOUR RESULTING MODEL WILL BE NONSENSE.
- COMPARE YOUR RESULTS WITH OTHER STUDIES IN THE TARGET AREA. COMPARE TO KNOWN GEOLOGIC AND TECTONIC FEATURES. IS IT CONSISTENT WITH GRAVITY , MT, AND OTHER INDEPENDENT ANALYSES? HOW DOES IT DIFFER FROM OTHER SEISMIC MODELS?

Applications of Local Earthquake Tomography

With local earthquake tomography we can image the 3-D seismic structure:

- in subduction zones (e.g. Costa Rica):



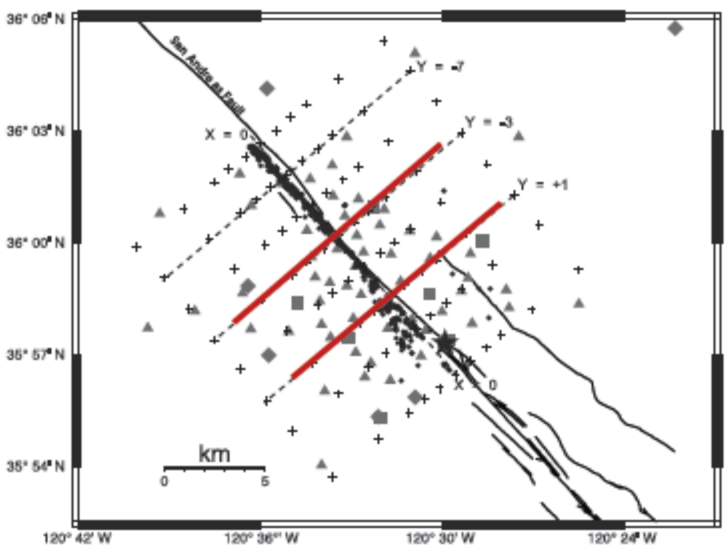


(Husen et al. 2003)

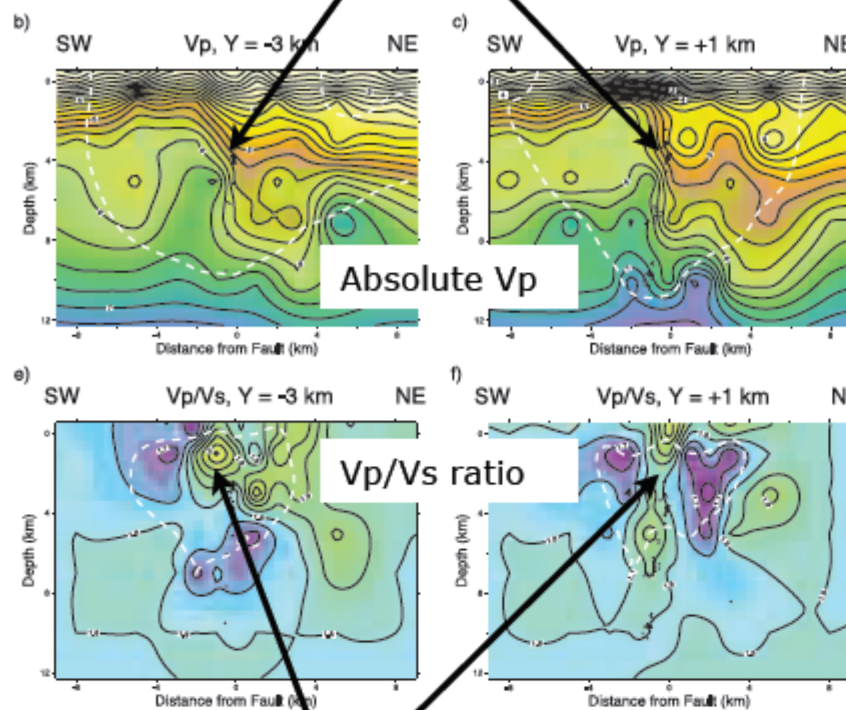
Applications of Local Earthquake Tomography

With local earthquake tomography we can image the 3-D seismic structure:

- in fault zones (e.g. San Andreas Fault SAF):



high/low Vp contrast across SAF



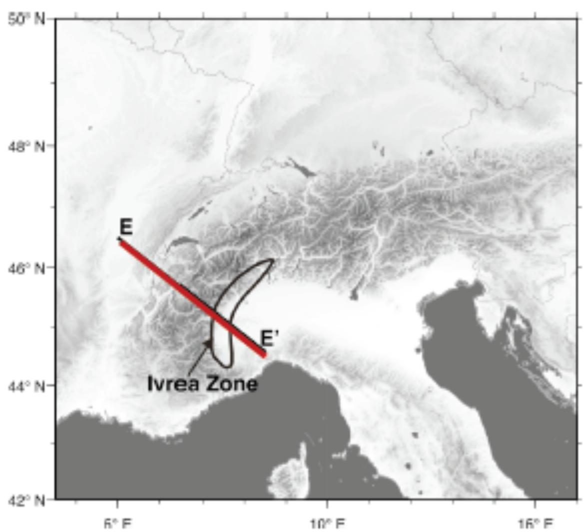
high Vp/Vs

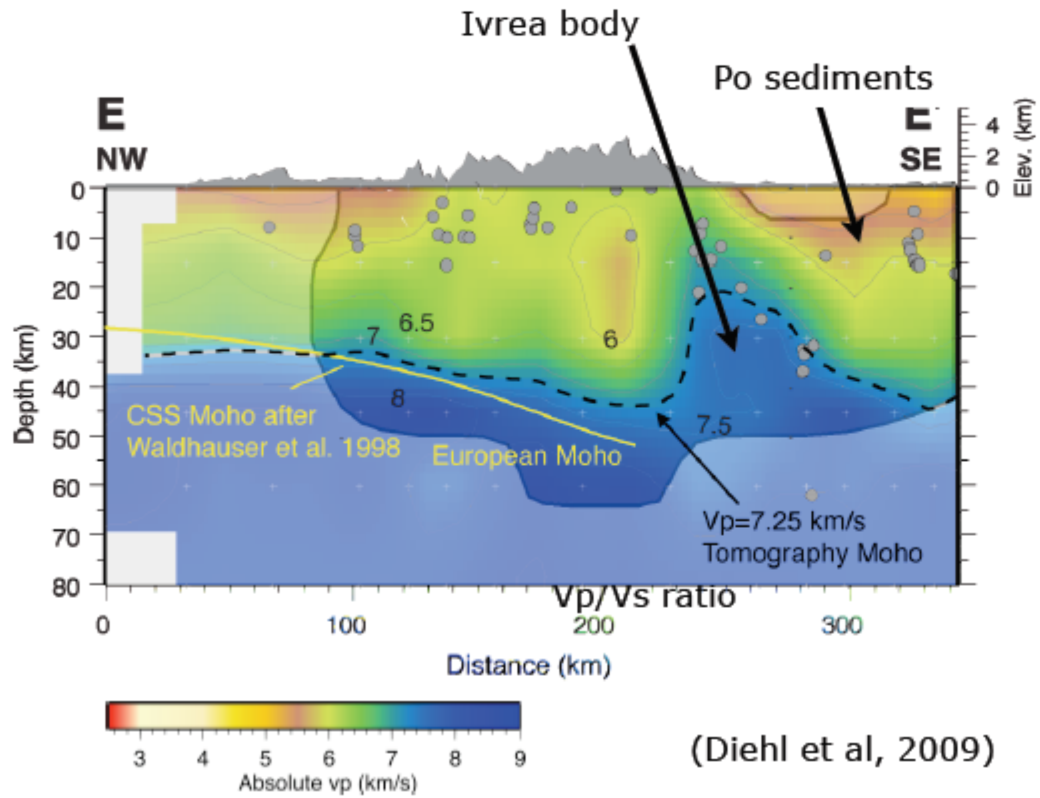
(Thurber et al, 2003)

Applications of Local Earthquake Tomography

With local earthquake tomography we can image the 3-D seismic structure:

- in collision zones (e.g. Alpine region):



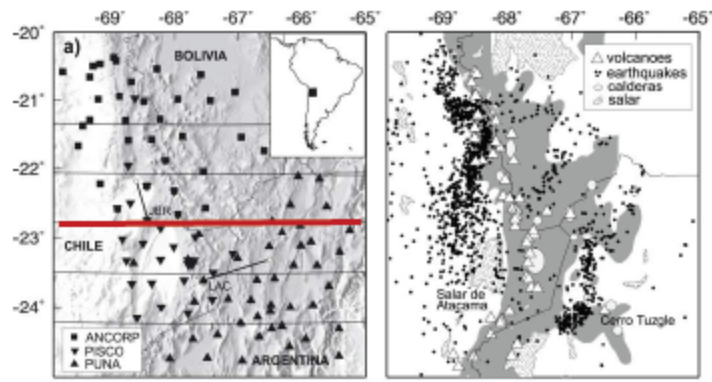


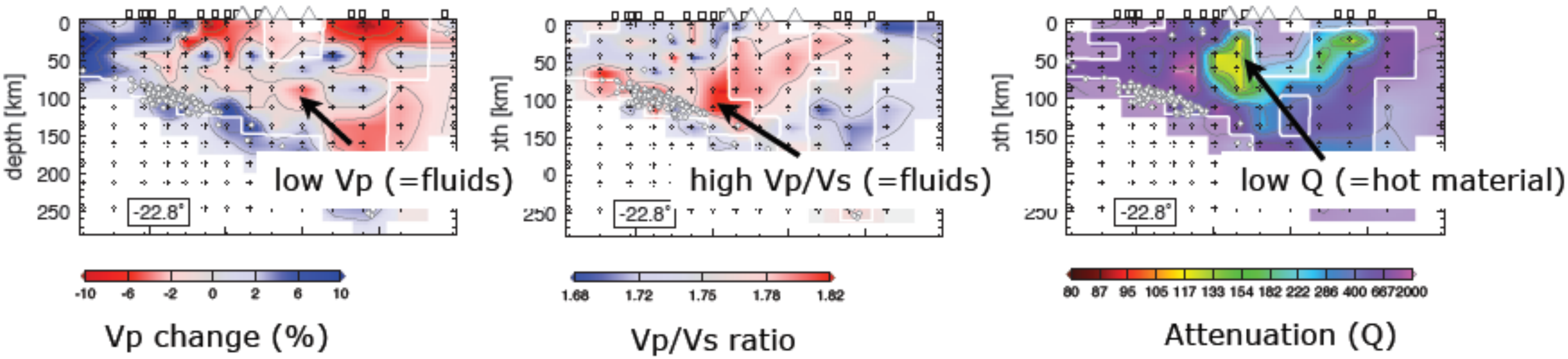
(Diehl et al, 2009)

Applications of Local Earthquake Tomography

but also geodynamical processes, such as

- ascent of magmatic fluids (e.g. in the Andes):





(Schurr, 2000)

THANK YOU