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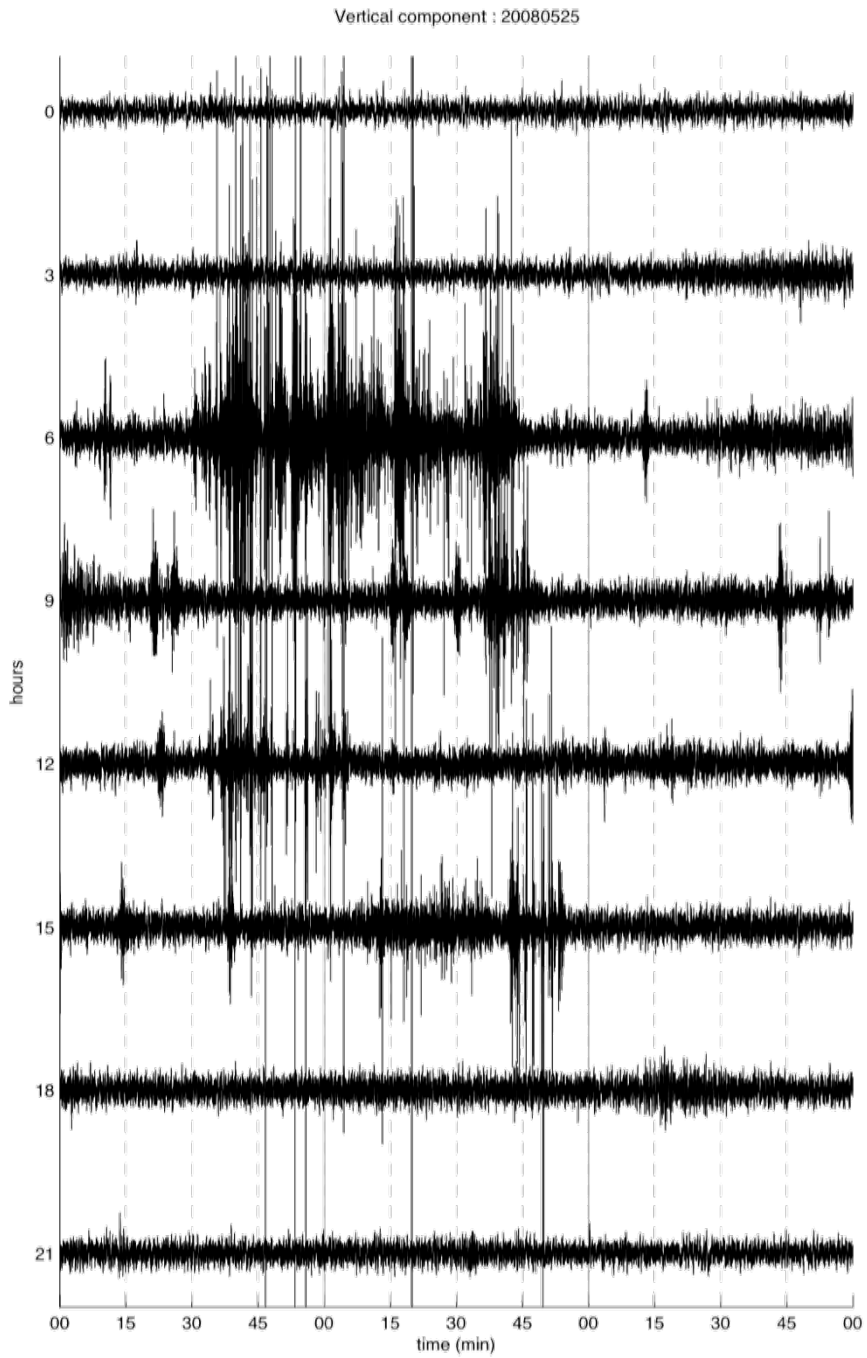
i. **Introduction: travel-time analyses**
ii. Tools for predicting travel time
iii. Travel-time analyses for array data
iv. Reference phases and statics corrections

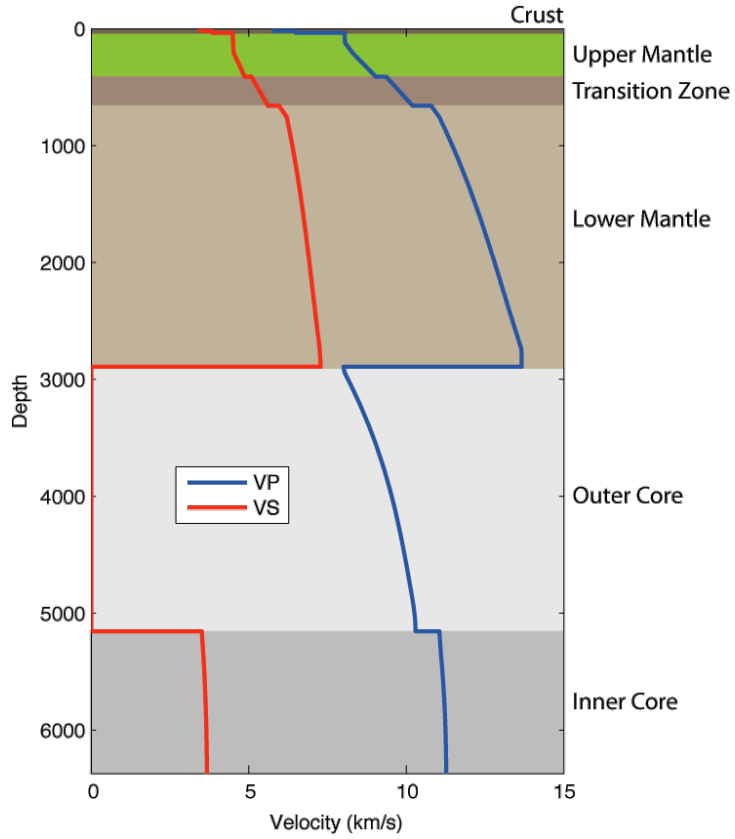
Travel time analyses

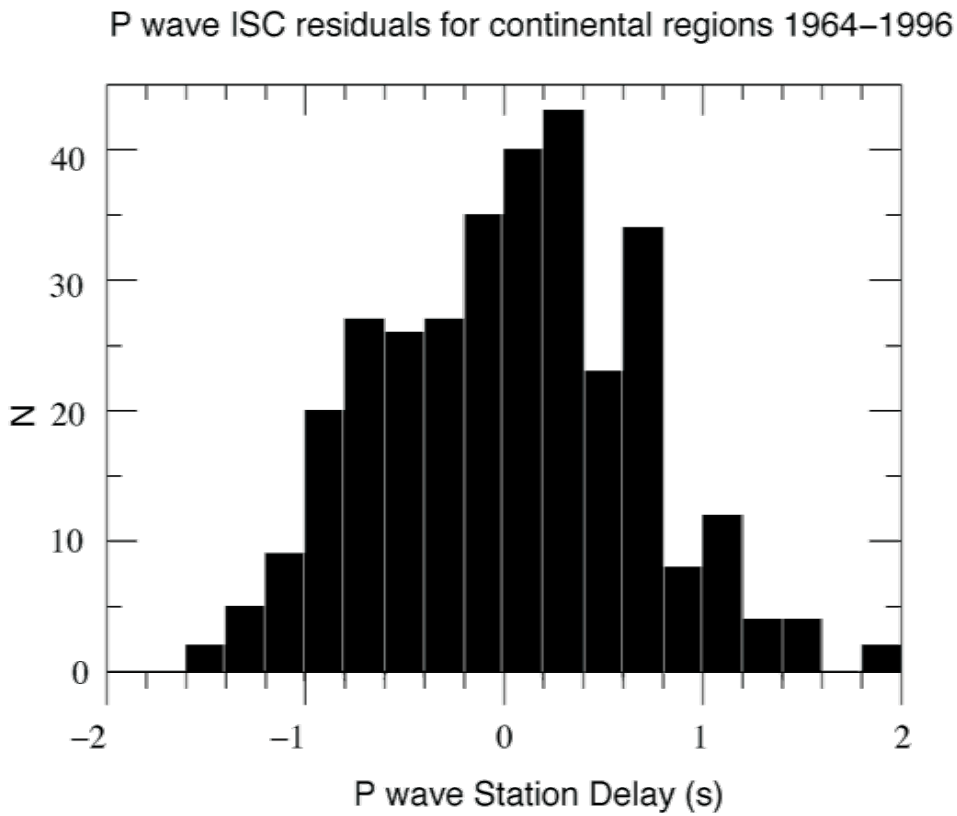
- Of all properties of a seismic phase, the most straight-forward to measure is the time at which it arrives
- It is this measurement which makes all more sophisticated processing possible
- The primary measurement of a seismic phase is the <u>absolute time</u>
- Modern seismic stations use GPS to provide an accurate, global common time base



Travel time analyses

- From the absolute time measurement of a network of stations the event origin time and hypocentre is determined
- By looking at large catalogues of recorded events all over the world, and comparing predicted pick times with actual phase arrivals build reference Earth models
- These are very accurate indeed – it appears that (at least on large scales) the Earth only deviates a few percent from these models:



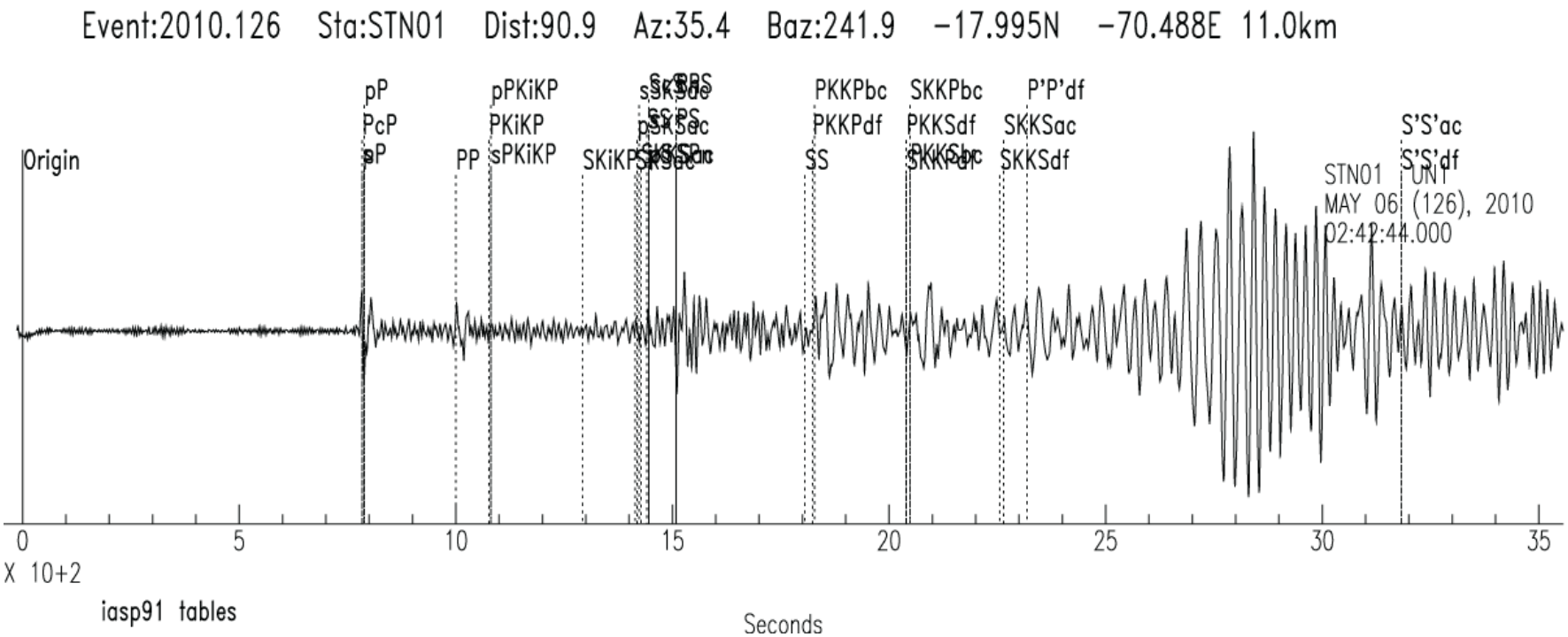


AK135 (Kennett et al, 1995)

Travel time analyses

- Thus, when looking at data from a located event (which covers most analyses which will be talked about in this section), we already have a pretty good idea what (major) phases we are looking at, and where they have been in the Earth

- We are usually interested in either the small deviations from the average travel-time (and hence variation in velocity), or other features of the waveform



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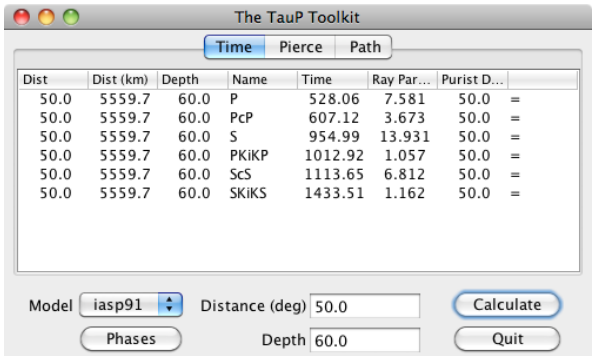
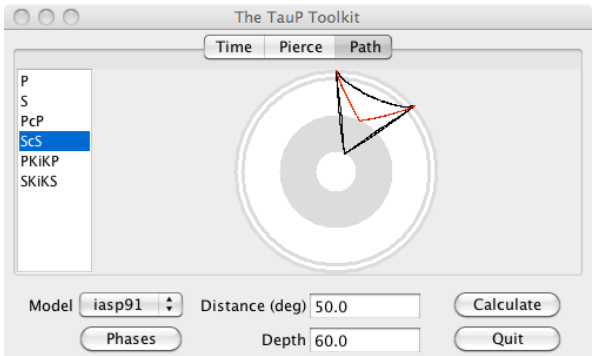
Predicting travel-times: Tau-P Toolkit

- The Tau-P Toolkit (Crotwell et al, 1999) provides a suite of tools for predicting travel-times and raypaths in 1D reference Earth models
- It is freely available (http://www.seis.sc.edu/TauP/), and implemented in Java for compatibility with a wide range of platforms
- It has a GUI, or can be run from the command line:






```
$ taup_time -mod ak135 -h 60 -deg 50 -ph ttall

Model: ak135
Distance   Depth   Phase        Travel    Ray Param   Purist
Purist
  (deg)     (km)   Name         Time (s)  p (s/deg)  Distance   Name
-----------------------------------------------------------------------
   50.00    60.0   P             528.17     7.576      50.00  = P
   50.00    60.0   pP            543.81     7.620      50.00  = pP
   50.00    60.0   sP            550.67     7.610      50.00  = sP
   50.00    60.0   PcP           607.39     3.669      50.00  = PcP
   50.00    60.0   PP            643.50     9.089      50.00  = PP
   50.00    60.0   PP            647.57    10.245      50.00  = PP
   50.00    60.0   PP            649.03     9.742      50.00  = PP
   50.00    60.0   ScP           837.87     4.286      50.00  = ScP
   50.00    60.0   PcS           844.39     4.288      50.00  = PcS
   50.00    60.0   S             954.50    13.923      50.00  = S
   50.00    60.0   SP            961.86    14.006      50.00  = SP
...
```

Predicting travel-times: ttimes

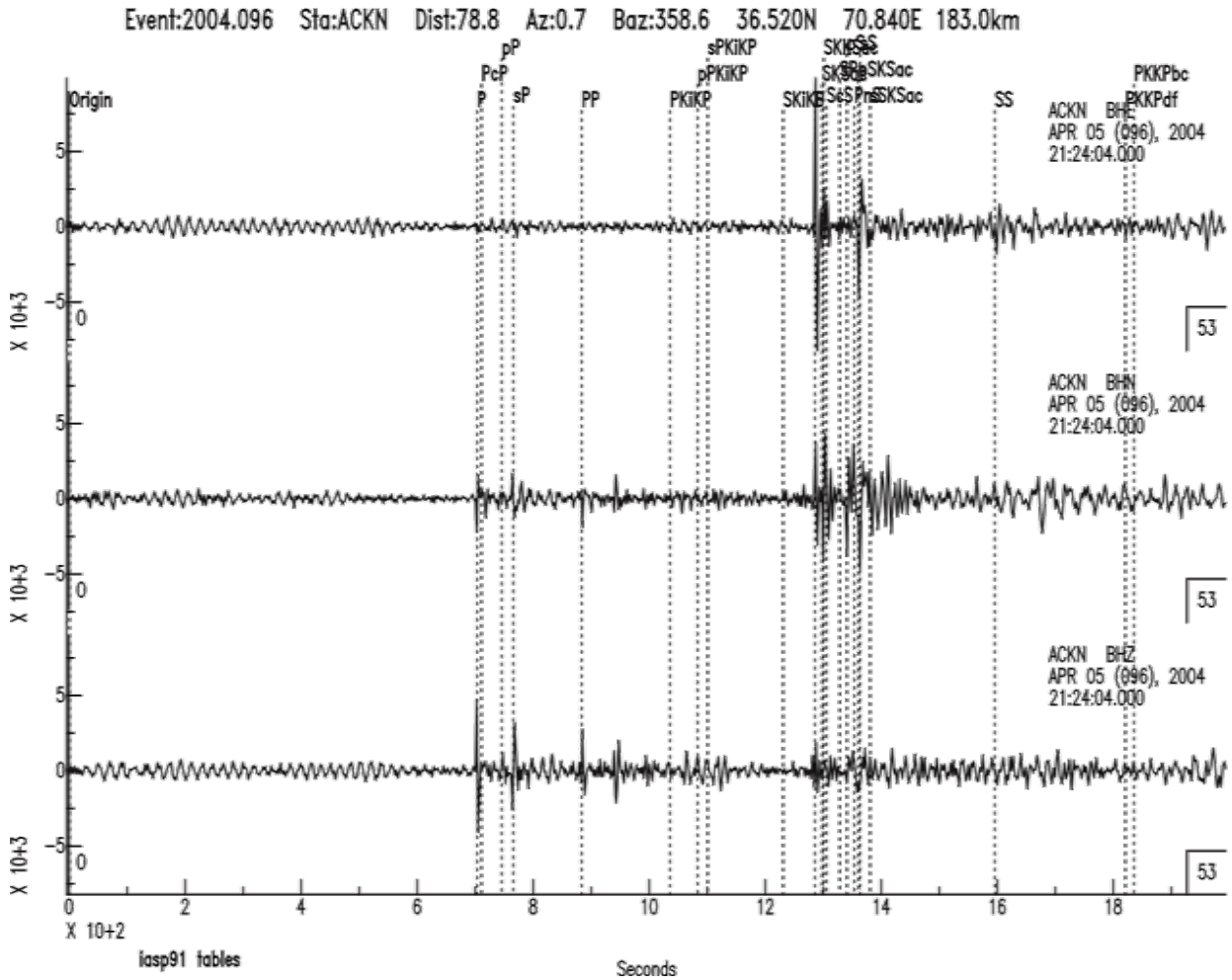
- ttimes in an older, interactive command line tool
- Compiled FORTRAN code – a bit faster than the Java
- Also now has tpttsub.o, a library for FORTRAN or C access to the calculation, (see, e.g., ak135picks.f90 in the tools subdirectory)

```
$ ttimes
 This routine for calculating travel times for
 specific distances uses a set of precalculated
 tau-p tables for the iasp91 model.

... snip ...

 Enter desired branch control list at the prompts:
*P
*
 Brnset:  the following phases have been selected -
              1  P
              2  PKP       P
              3  PKiKP
Source depth (km):  60

Enter delta:  50
   delta    # code       time(s)    (min s)    dT/dD     dT/dh      d2T/dD2

  50.00    1  P          528.07   8  48.07     7.5810  -1.04E-01  -4.19E-03
           2  PKiKP     1012.94  16  52.94     1.0575  -1.24E-01   1.62E-02...
```

Predicting travel-times: the ttsac macro

- The ttsac macro displays common phase times from within SAC for a single trace

```
SAC> r ACKN.BH?
SAC> m ttsac
```



- Calls ttimes for information. Station location, event location and origin time must be set. Only information from the first trace in memory is used.

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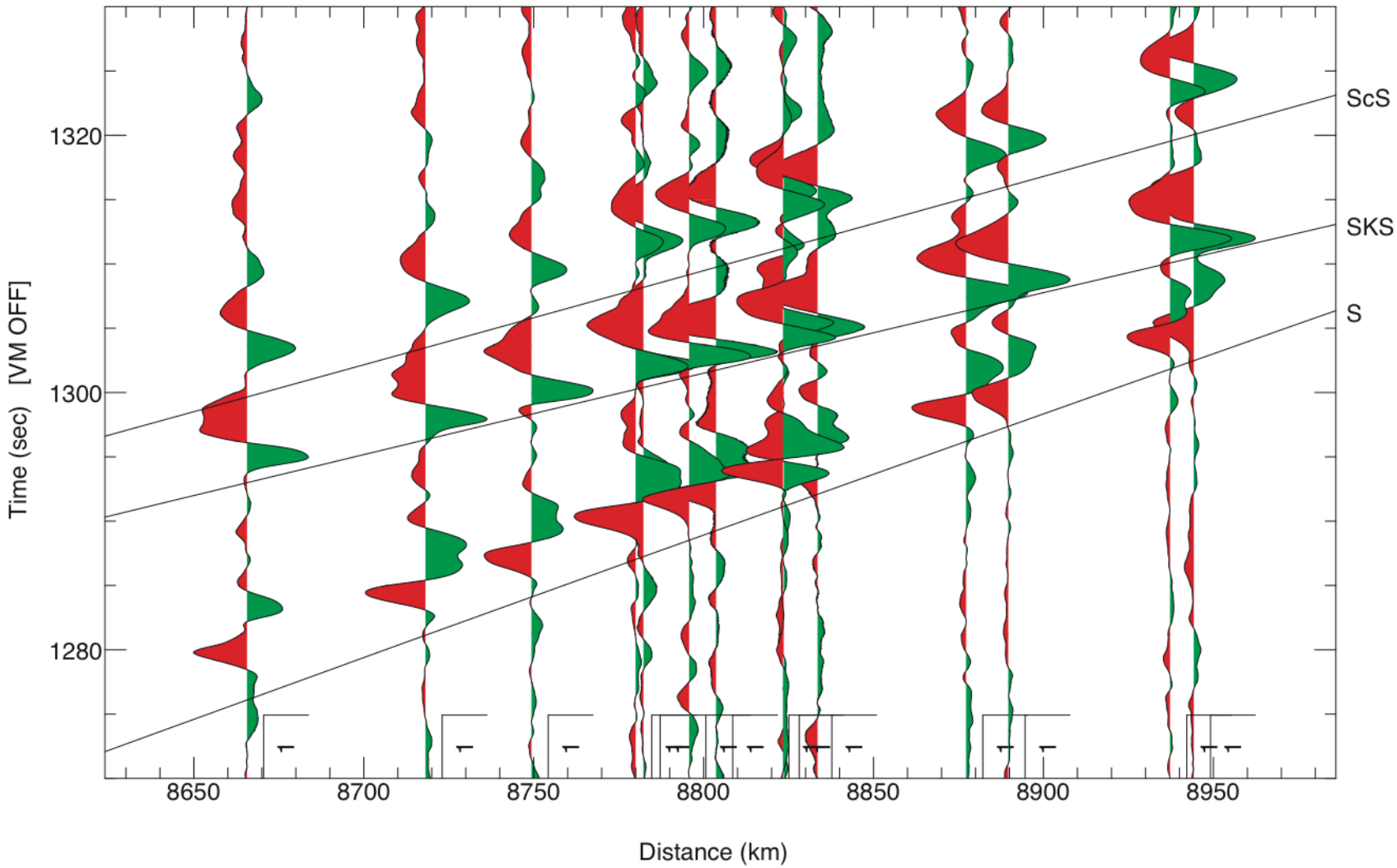
Plotting travel time curves on recordsections

- In SSS the traveltime command can be used to add travel-time curves to record section
- A convenient way of adding such curves is using the taup_curve utility which is distributed with the Tau-P toolkit:

```
SAC> r *.BHN
ACKN.BHN BOXN.BHN CAMN.BHN COWN.BHN DSMN.BHN DVKN.BHN EKTN.BHN
GBLN.BHN GLWN.BHN IHLN.BHN ILKN.BHN LDGN.BHN LGSN.BHN LUPN.BHN
SAC> sss
 Signal Stacking Subprocess.
SAC/SSS> tw 1270 1330
SAC/SSS> sc taup_curve -h 183 -ph S,ScS,SKS
SAC/SSS> traveltime taup taup_curve.gmt
SAC/SSS> line 1 fill red/green
SAC/SSS> prs ref off label off tt on
```

Plotting travel time curves on recordsections



Travel times for array data

- Travel-time analysis of array data can often improve resolution over single station
- For array data, we generally work with **pick files**
- These are preferable for several reasons
  - Saves header real estate
  - Amenable to external manipulation with scripts and programs
  - Can be used as control files for other programs (see slant stacking)

```
$ head -10 ak135picks-P.pik
109C.BHZ      544.6038        1.0000
112A.BHZ      531.7048        1.0000
113A.BHZ      528.9495        1.0000
115A.BHZ      521.7291        1.0000
117A.BHZ      514.5014        1.0000
118A.BHZ      511.3836        1.0000
119A.BHZ      509.0168        1.0000
214A.BHZ      521.2360        1.0000
216A.BHZ      515.2449        1.0000
217A.BHZ      511.3333        1.0000
218A.BHZ      508.7280        1.0000
219A.BHZ      505.3044        1.0000
318A.BHZ      506.0765        1.0000
319A.BHZ      502.5539        1.0000
A04A.BHZ      622.4898        1.0000
A05A.BHZ      621.5234        1.0000
A06A.BHZ      620.0289        1.0000
A07A.BHZ      616.5380        1.0000
A08A.BHZ      612.8518        1.0000
A09A.BHZ      610.8727        1.0000
A10A.BHZ      607.8396        1.0000
A11A.BHZ      604.2186        1.0000
A12A.BHZ      602.0397        1.0000
A13A.BHZ      598.4326        1.0000
B04A.BHZ      622.7854        1.0000
B05A.BHZ      619.0606        1.0000
B06A.BHZ      618.0369        1.0000
B07A.BHZ      613.6376        1.0000
B08A.BHZ      610.8574        1.0000
B09A.BHZ      607.4876        1.0000
B10A.BHZ      604.2220        1.0000
B11A.BHZ      602.1780        1.0000
B12A.BHZ      599.9900        1.0000
B13A.BHZ      596.2867        1.0000
C04A.BHZ      619.9797        1.0000
C05A.BHZ      615.8372        1.0000
C06A.BHZ      614.1290        1.0000
C07A.BHZ      610.6911        1.0000
C08A.BHZ      607.8622        1.0000
```

Creating pick files

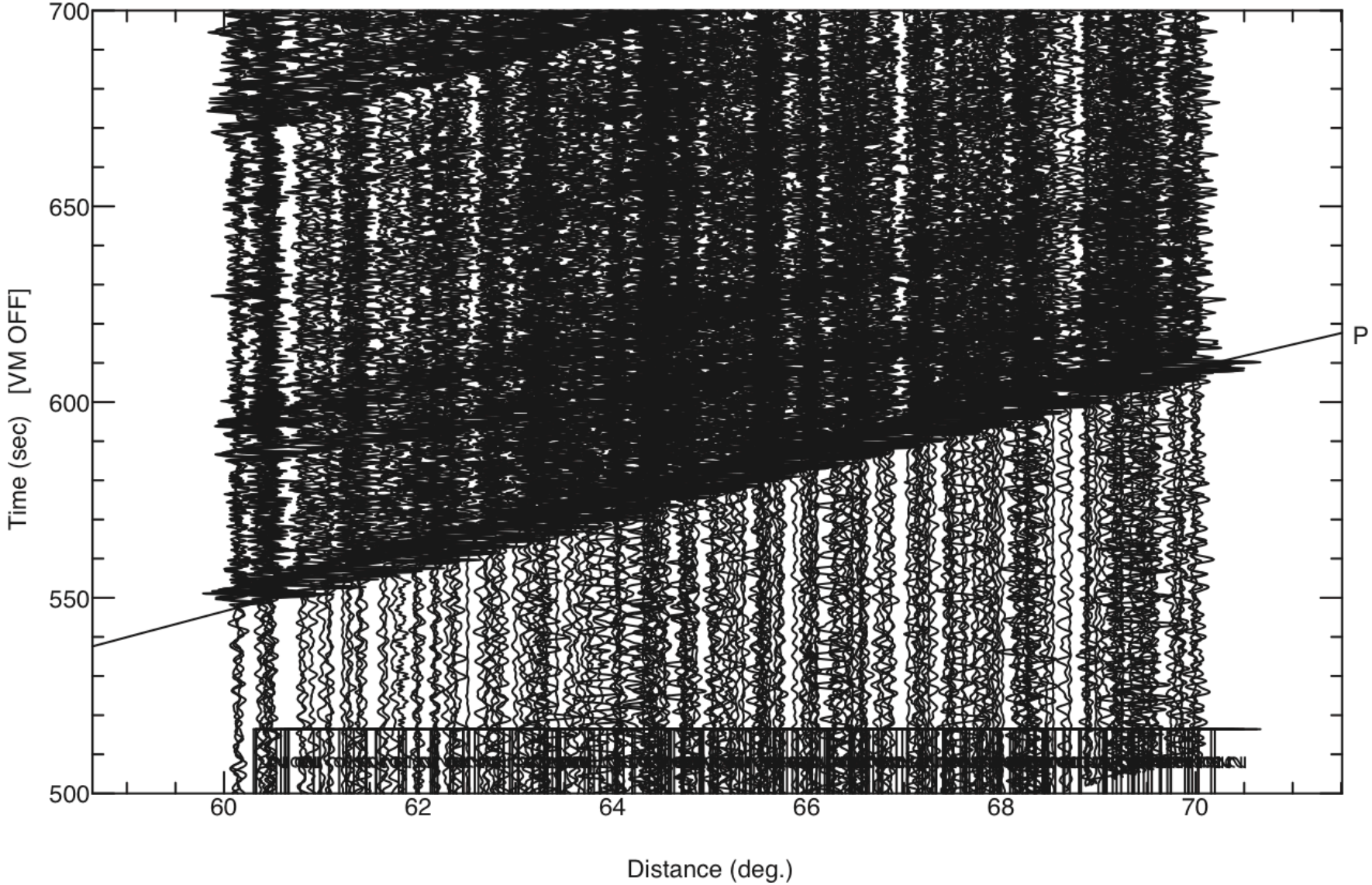
- ak135picks is a tool which generates pick files for a set of data:

```
$ ak135picks P *.BHZ
AK135PICKS
Processed   312 files
Phase                    # of picks:
 P                        312
$ head -10 ak135picks-P.pik
109C.BHZ      544.6038        1.0000
112A.BHZ      531.7048        1.0000
113A.BHZ      528.9495        1.0000
115A.BHZ      521.7291        1.0000
117A.BHZ      514.5014        1.0000
118A.BHZ      511.3836        1.0000
119A.BHZ      509.0168        1.0000
214A.BHZ      521.2360        1.0000
216A.BHZ      515.2449        1.0000
```

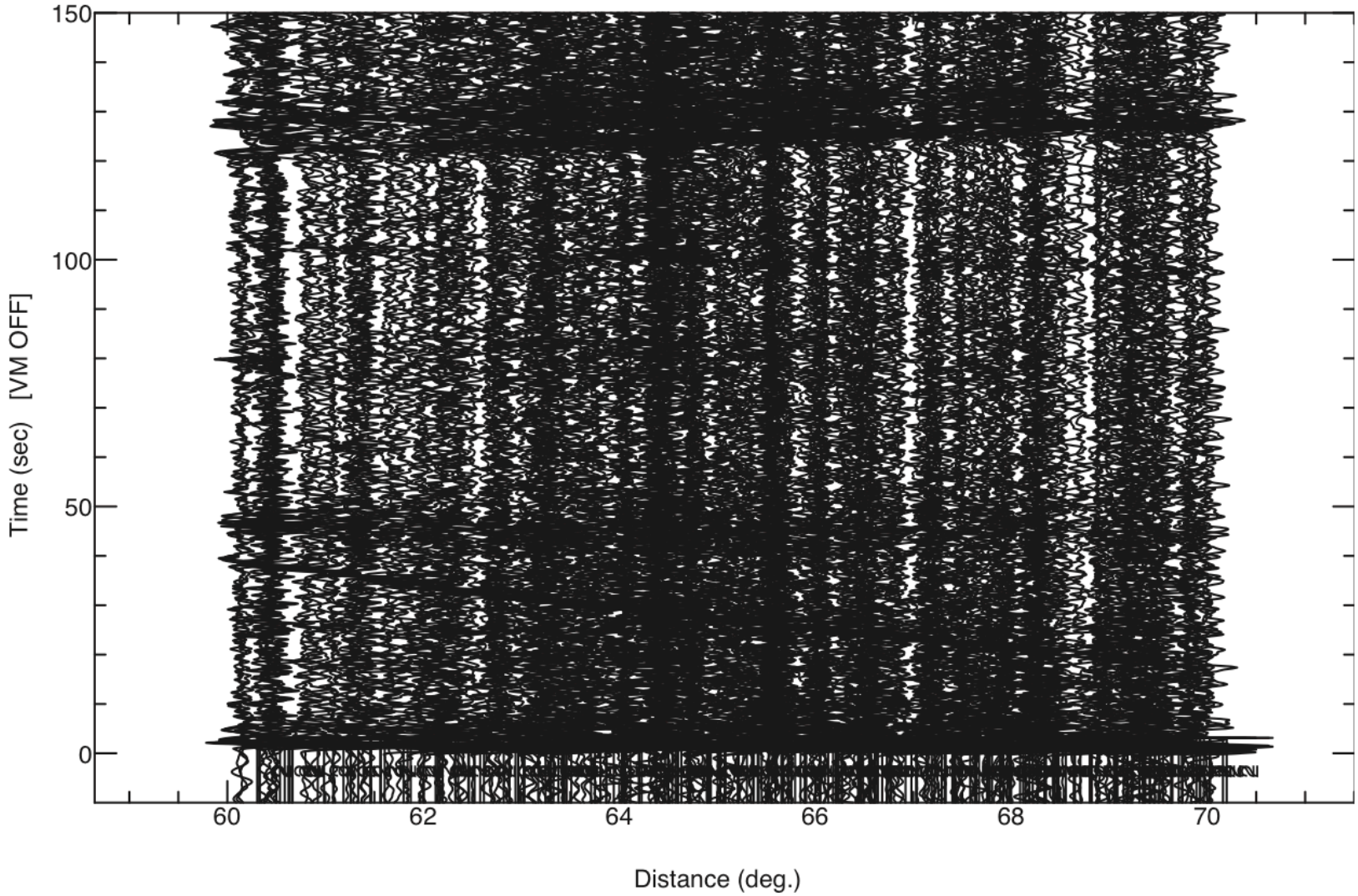
- This takes the event depth and epicentral distance from SAC files and calculates travel times using tpttsub.o

- These can then be used in SSS in SAC ...

Absolute time:



Relative (to P) time:



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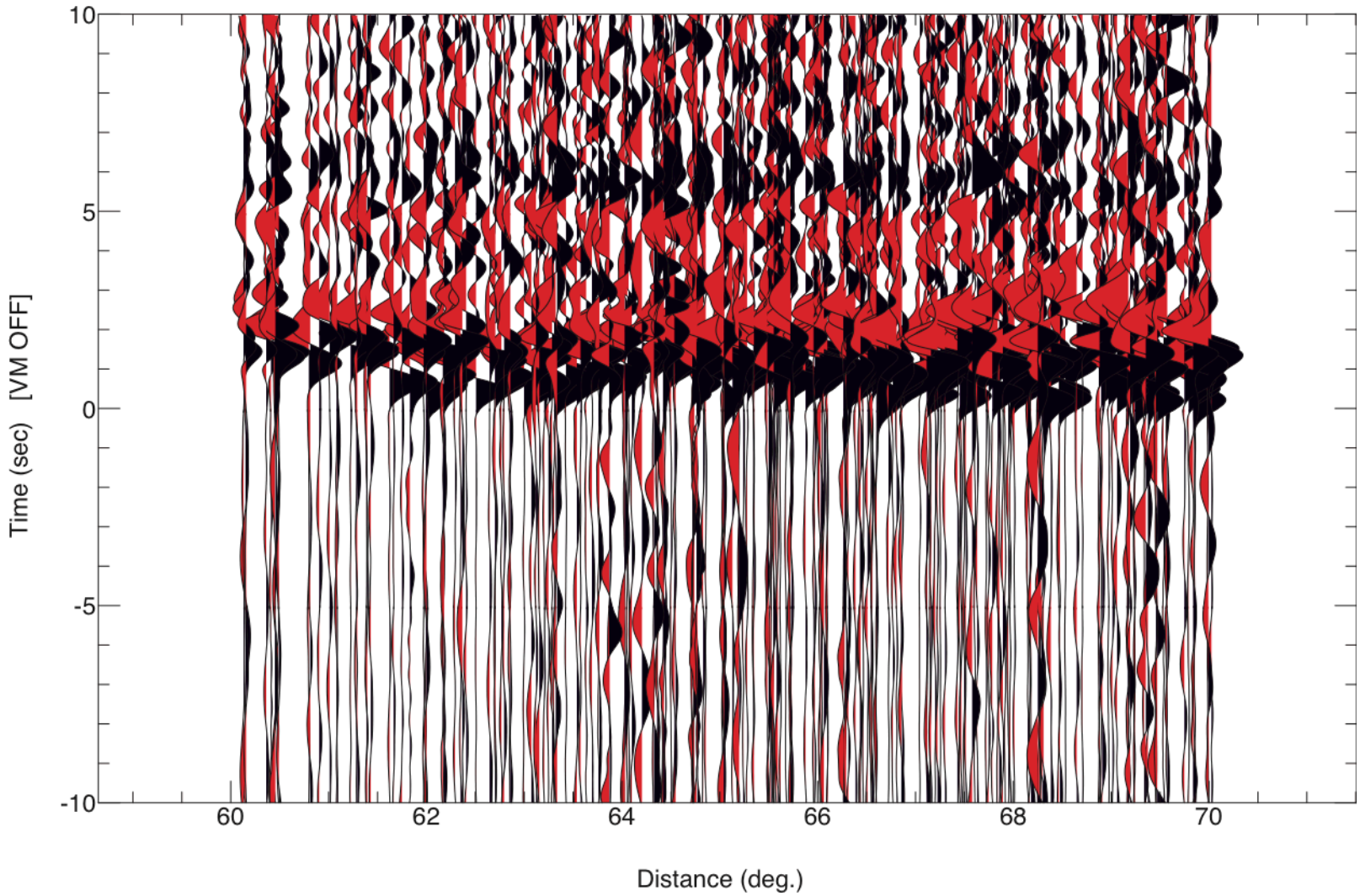
Statics

- Even though deviations are small, there are always some small perturbations from the predicted travel time



Statics

- These small, non-distance dependent time shifts (called 'statics' are generally the result of small-scale heterogeneity near the receivers
- These are not, generally speaking, the focus of the study and so are often removed
- This can be done by manual picking:
  - In standard SAC the PPK command can be used (as in lesson 2.1), though this rapidly becomes tedious for large numbers of traces
  - In MacSAC, the plotrecordsection command has some special array picking options which can make the process less painful

- Also, there are good methods of automating the picking (for example, the STA/LTA method from practical 3.2)

Statics correction with *tcas*

- Another methodology for removing statics is adaptive stacking (Rawlinson and Kennet, 2003)
- Program is sactcas

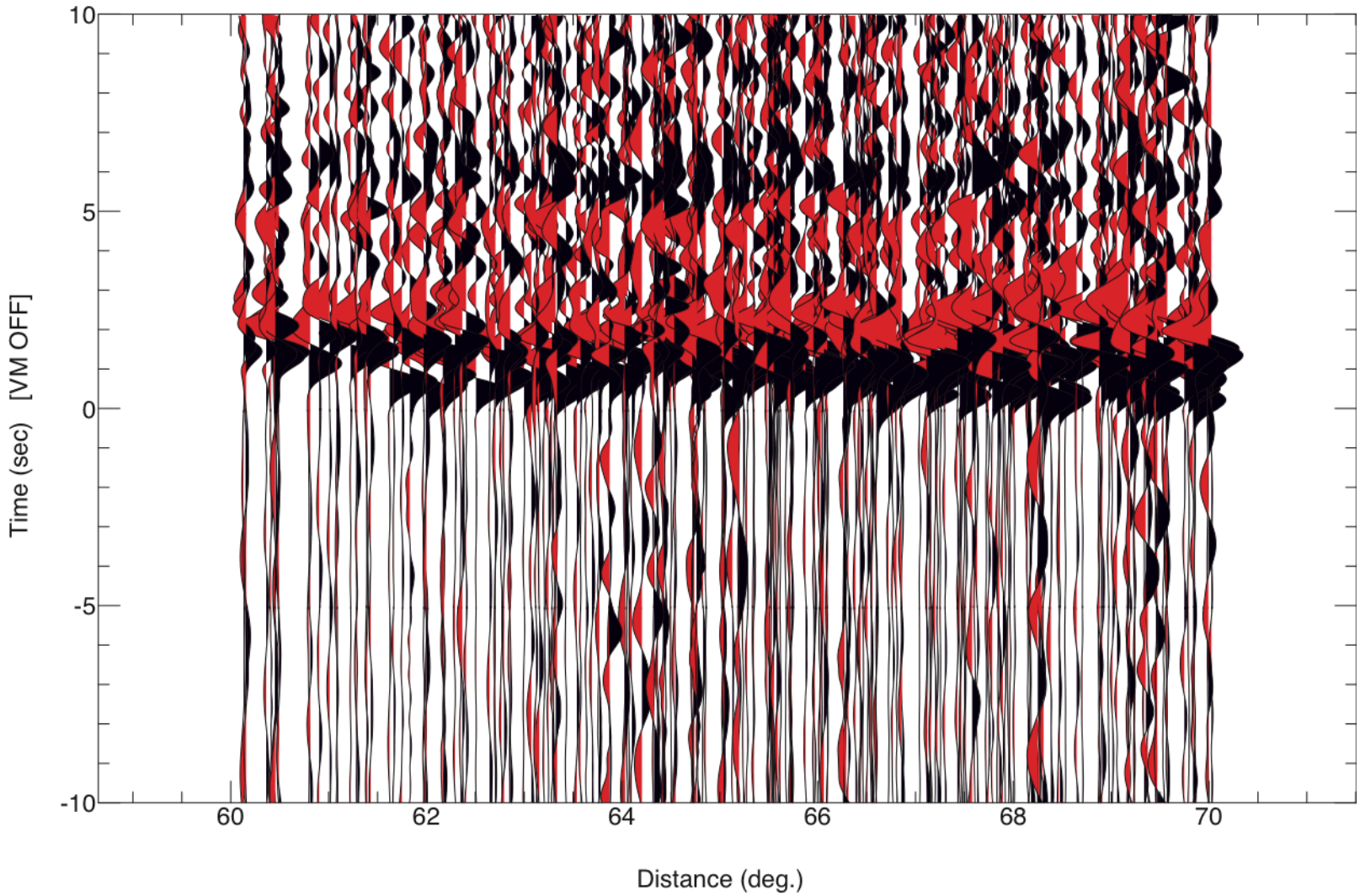
```
$ head -5 ak135picks-P.pik
60-70/A10A.BHZ      607.8396        1.0000
60-70/A11A.BHZ      604.2186        1.0000
60-70/A12A.BHZ      602.0397        1.0000
60-70/A13A.BHZ      598.4326        1.0000

$ sactcas -itmax 100 -win 0 5 -dtlim -2 2 < ak135picks-P.pik > ak135picks-P-tcas.pik
 pstakn =   3.36913228
 pstakn =   3.3638463
 pstakn =   3.36606288
 pstakn =   3.36585593
 pstakn =   3.36589861
 pstakn =   3.36589861
 pstakn =   3.36589861
 pstakn =   3.36589861
 pstakn =   3.36589861

$ head -5 ak135picks-P-tcas.pik
60-70/A10A.BHZ   606.8896  1.37315E+03
60-70/A11A.BHZ   603.9686  1.91132E+03
60-70/A12A.BHZ   601.8896  3.50417E+03
60-70/A13A.BHZ   598.1326  3.68030E+03
```

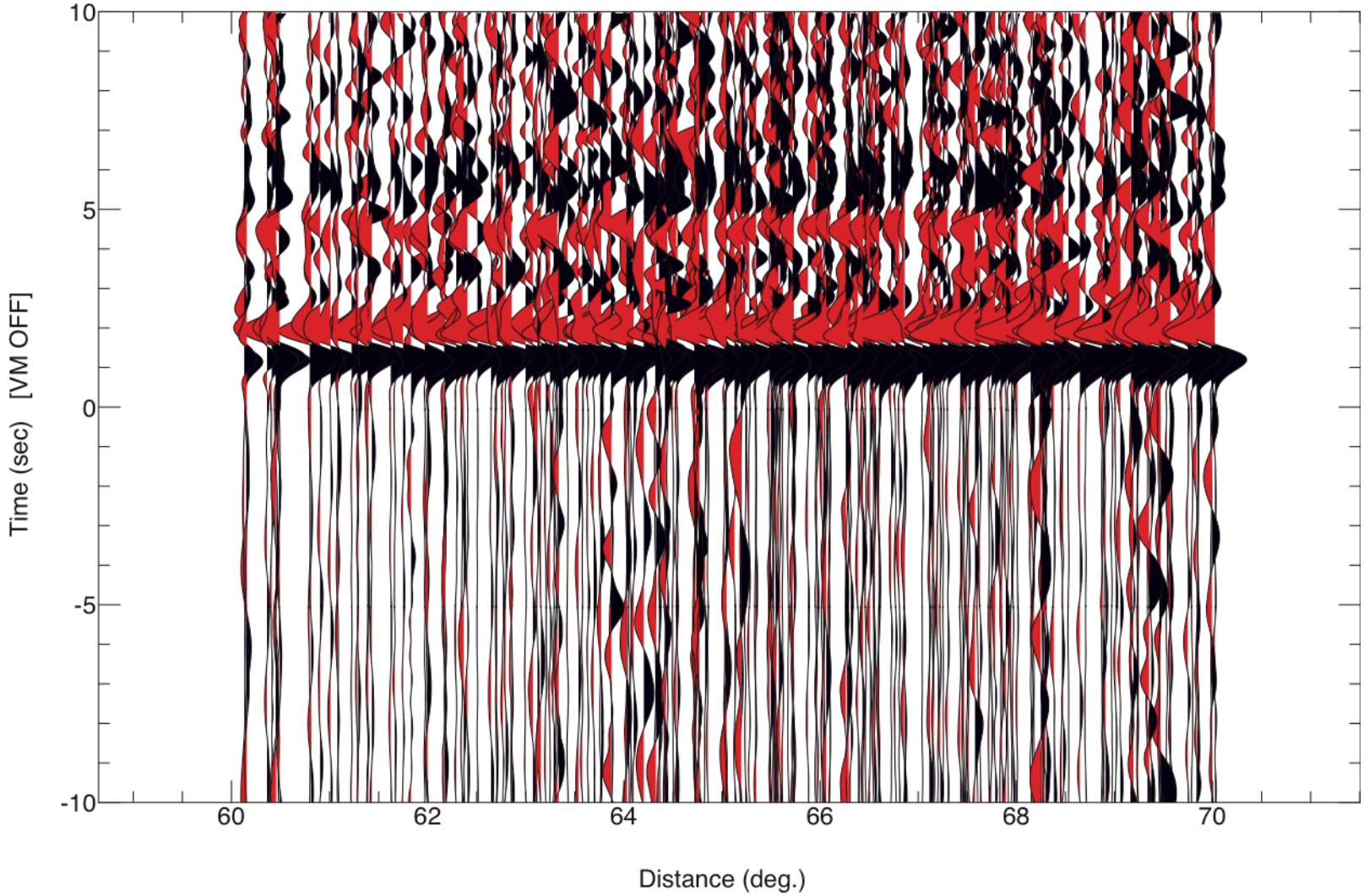
sactcas example

- Before adaptive stacking:



sactcas example

- After adaptive stacking:



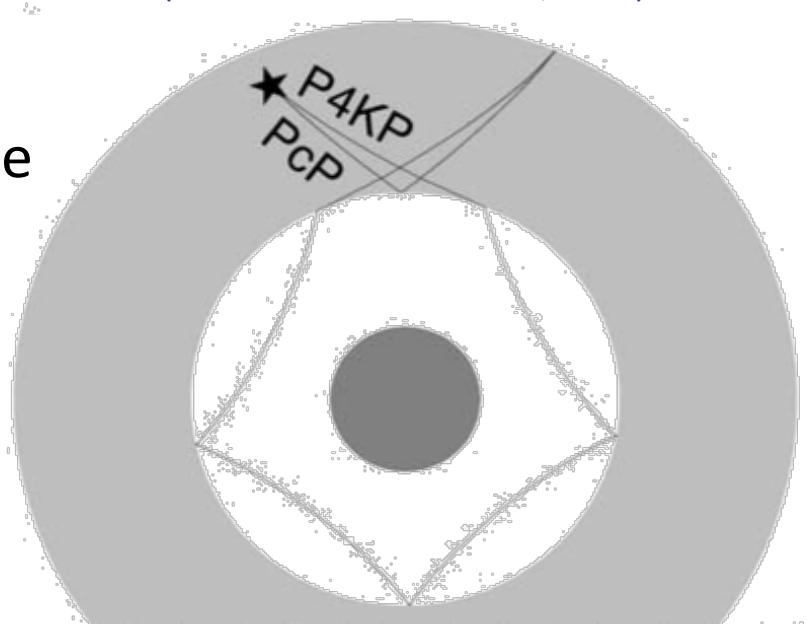
Reference phases

- This sort of approach leads to the concept of a *reference phase*

- A reference phase is, in general, a phase you can easily see (in individual traces) which is used to improve the coherency of ones you cannot

- This becomes even more useful when stacking methodologies are used (see 4.6)

(Helffrich and Kaneshima, 2003)



Reference Phase Example – PcP and ScP