INTERPRETATION OF SEISMOGRAMS

Suggested literature:

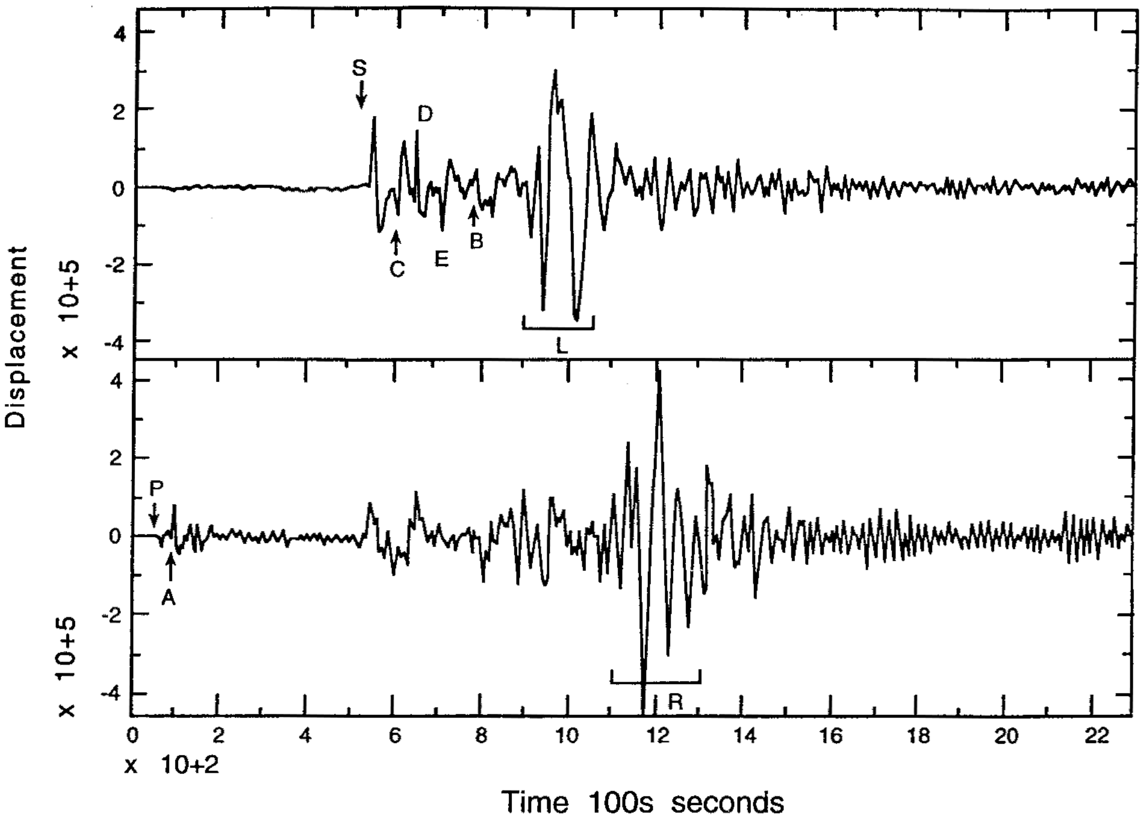
Lay, T. & Wallace, T.C. 1995. Modern Global Seismology. Academic Press, Inc.

Scherbaum, F. 1996. Of Zeros and Poles. Fundamentals of Digital Seismology. In 'Modern Approaches in Geophysics', Kluwer Academic Publishers. 256 pages.

Thurber, C.H. & Rabinowitz, N. (eds.) 2000. Advances in Seismic Event Location. Kluwer Academic Publishers, Dordrecht.

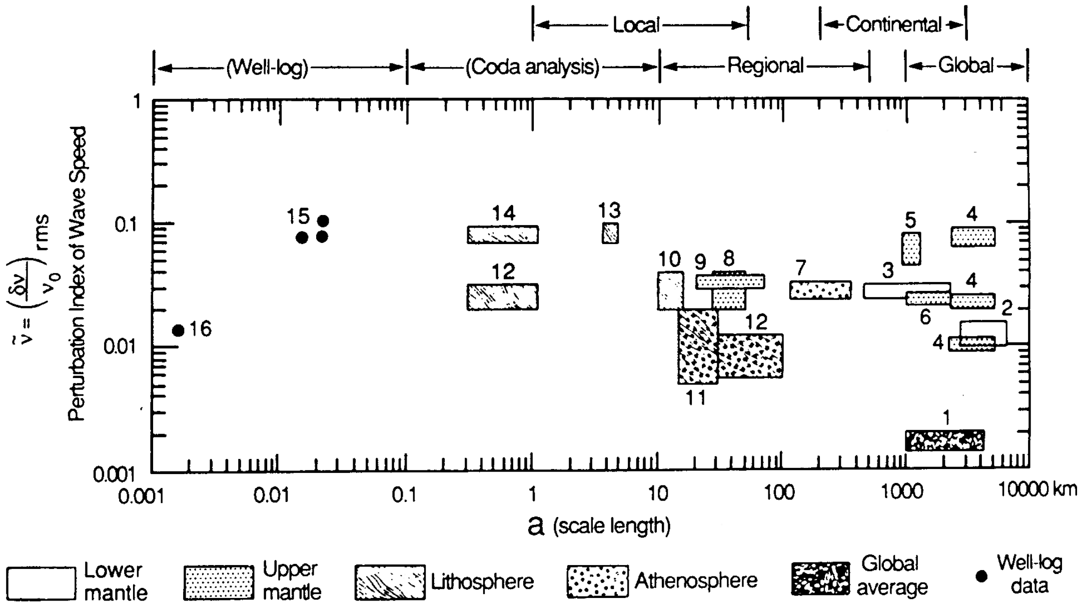
INTRODUCTION

Keywords: Source & Path



lw0601

Broadband seismic recording (top = horizontal, bottom = vertical component) of a deep earthquake beneath Peru (May 24, 1991)



lw0707

Investigating the Earth's interior. The Perturbation Index reflects the degree of heterogeneity.

SEISMIC ONSETS

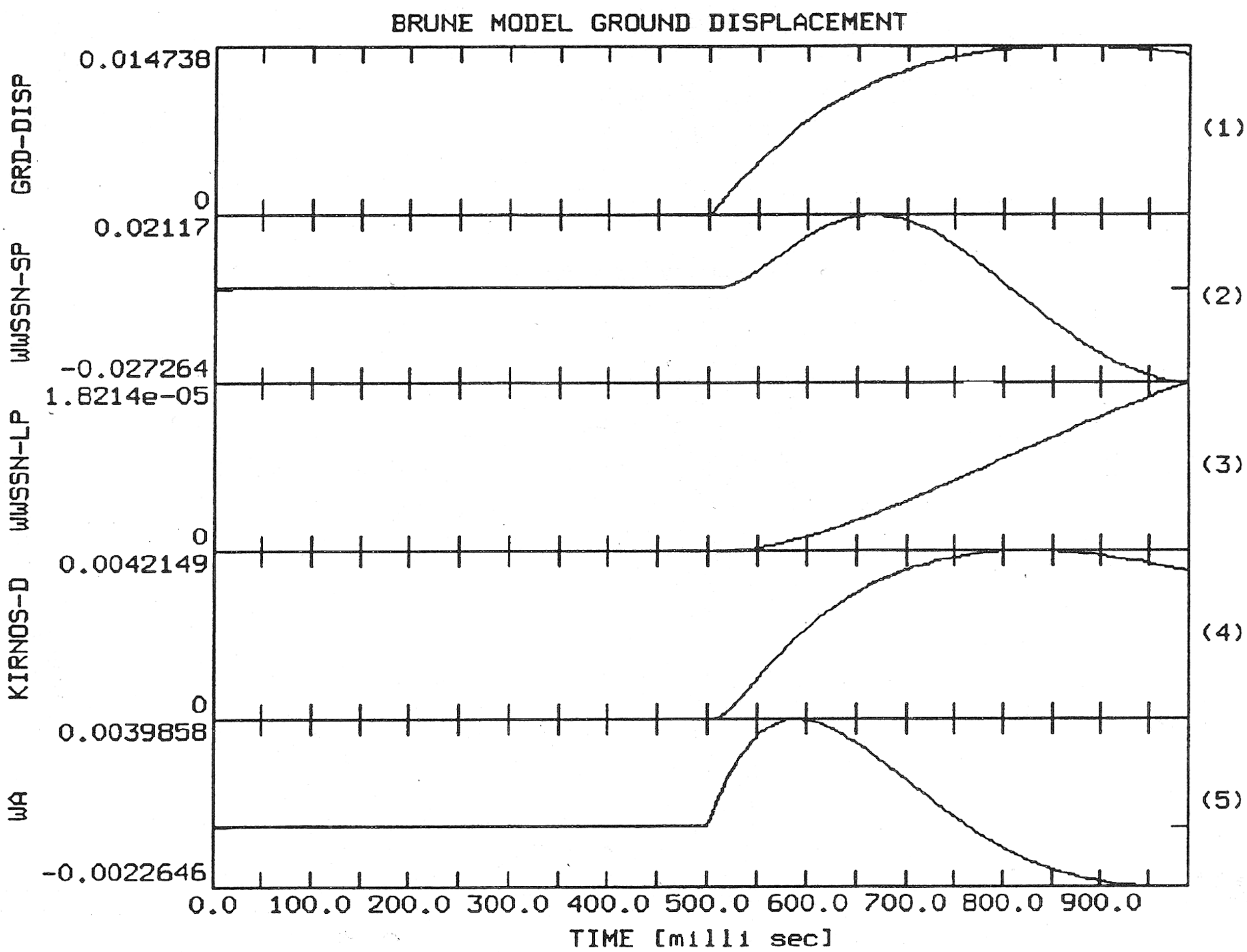
PROPERTIES

Definition:

(see Scherbaum, F. 1996, after Seidl & Stammler, 1984)

The discontinuity of the signal front at t = 0 is called an **onset of order** *p*, if $f^{(p)}$ (0+) is the first non-zero derivative.

1. **Time**
2. **Polarity**
3. **Amplitude**
4. **Onset order „p“**



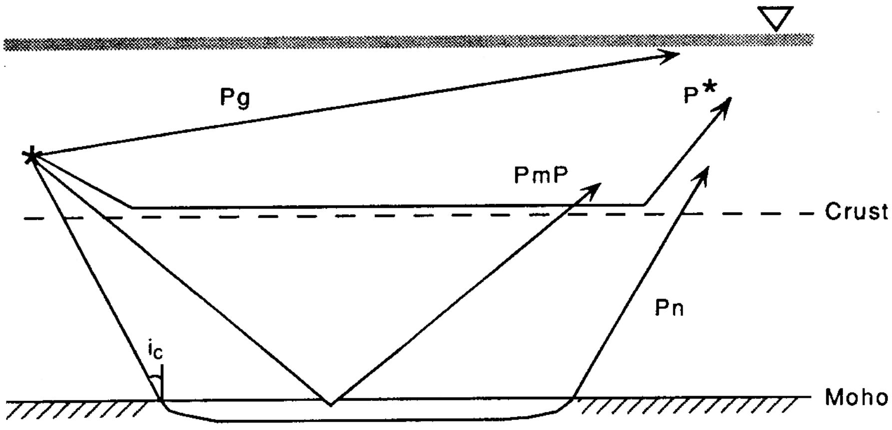
S1011

Onset distortion of a far field Brune model ground displacement pulse (top trace).
Bottom trace: simulated Wood-Anderson seismograph output).
Comment: A zero order onset (p = 0) would be a step-function (= no return to DC).

NOMENCLATURE

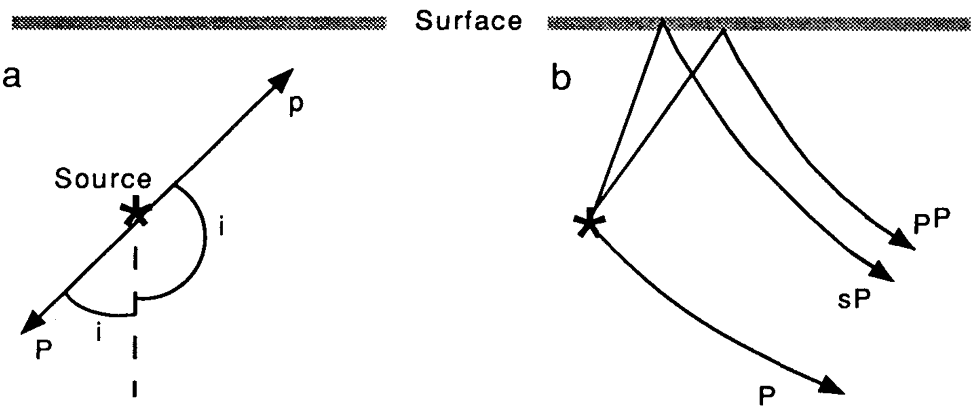
BODY WAVES

CRUSTAL PHASES



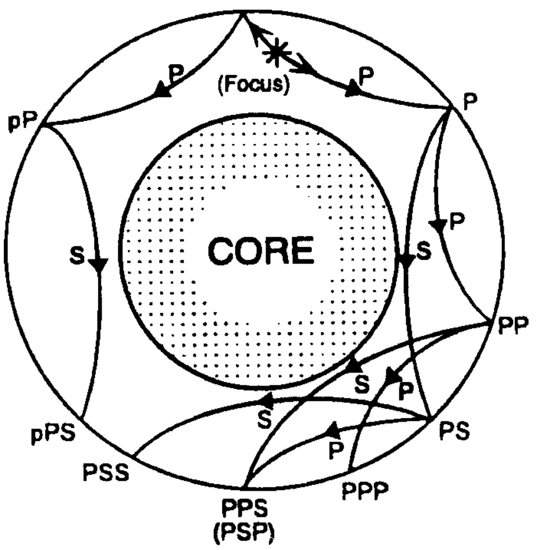
lw0605

DEPTH PHASES

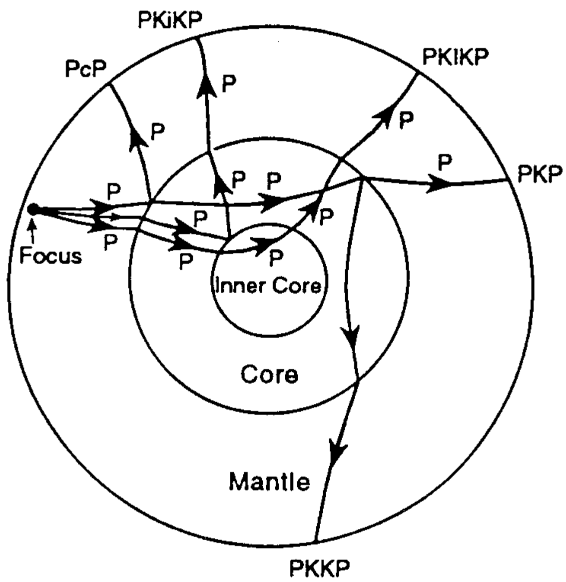


lw0603

CORE PHASES



lw0608a

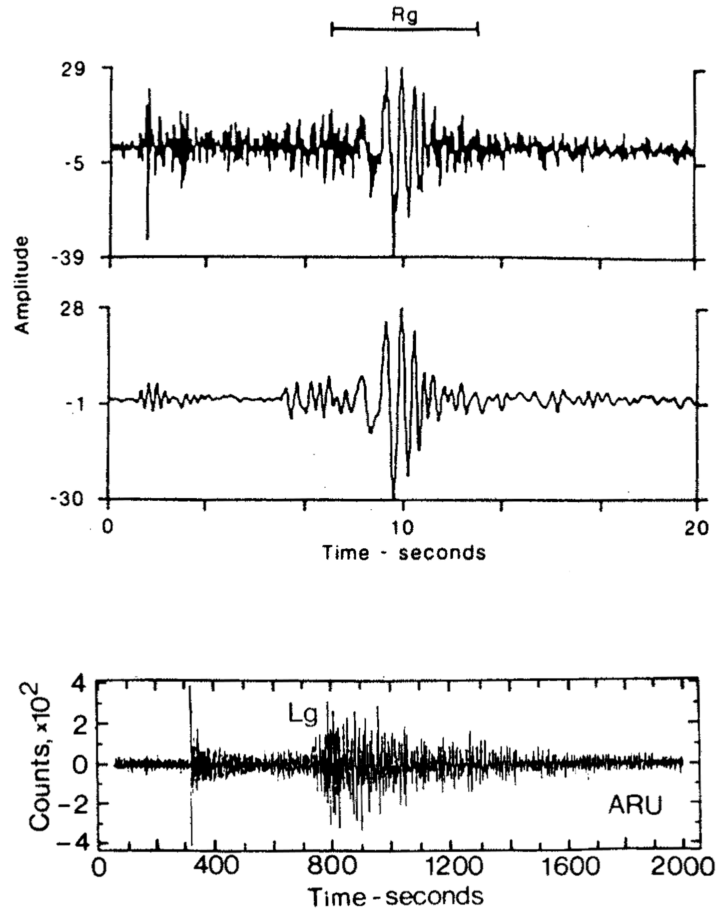


lw0608 b

NOMENCLATURE

SURFACE WAVES

Period < 3 seconds
Rg (fundamental Rayleigh wave, period < 3 seconds, group velocity 3 km/s, absent if focal depth exceeds 3 km) **Lg** (combination of Rayleigh and Love wave, group velocity 3.5 km /s, observed out to 1000 km)



lw0610

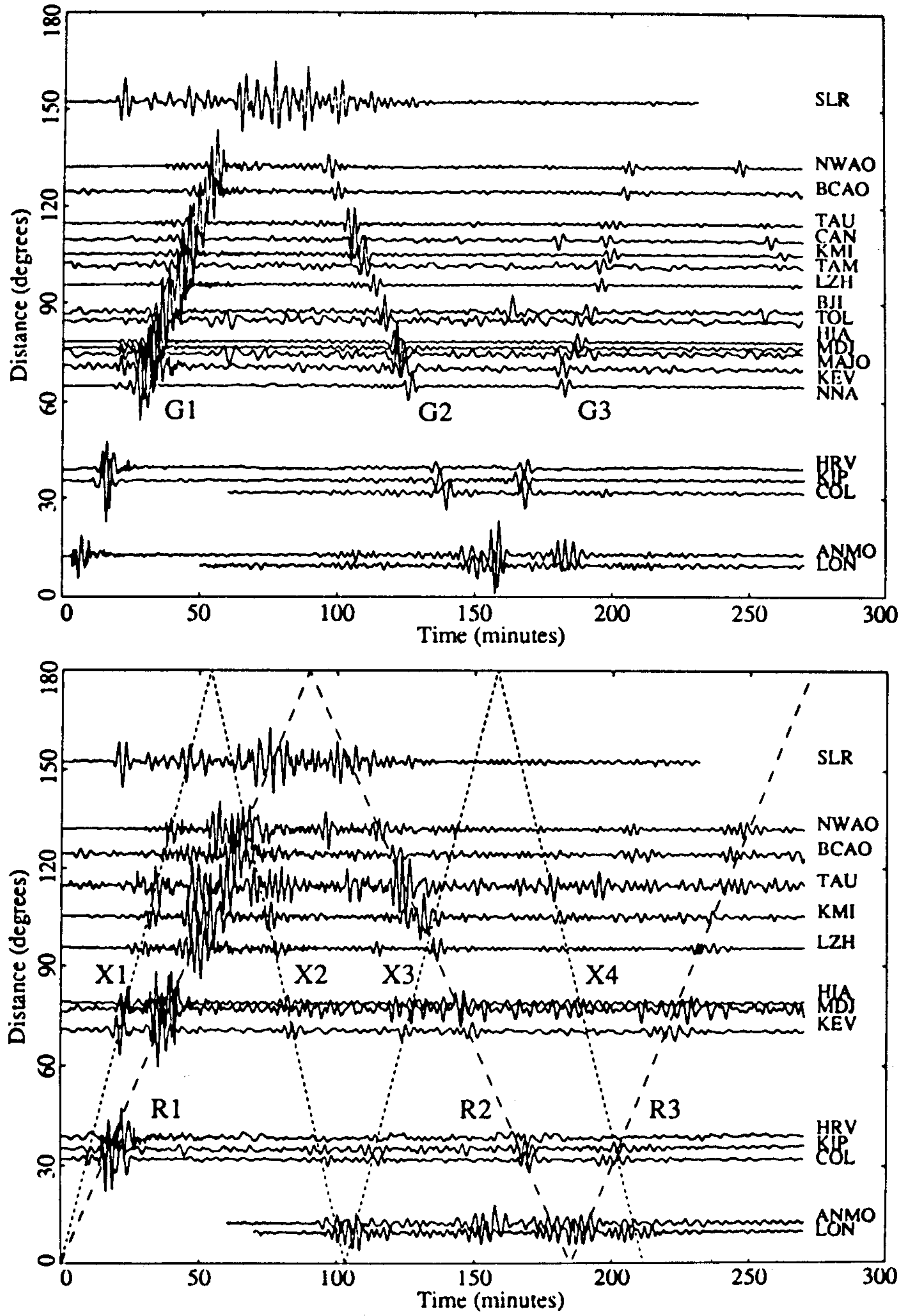
Examples of Rg and Lg waves
(top: record from shallow explosion, distance 39 km,
centre: same as top trace, but low-pass filtered,
bottom: vertical component of nuclear explosion, distance 24°)

Period 3 - 60 seconds
R or LR (Rayleigh waves) **L or LQ** (Love waves, 'Q' = Querwellen)

NOMENCLATURE

SURFACE WAVE RECURRENCE

G... great-circle long-period Love waves (named after Gutenberg)
R... Rayleigh waves
X... Rayleigh-wave overtones

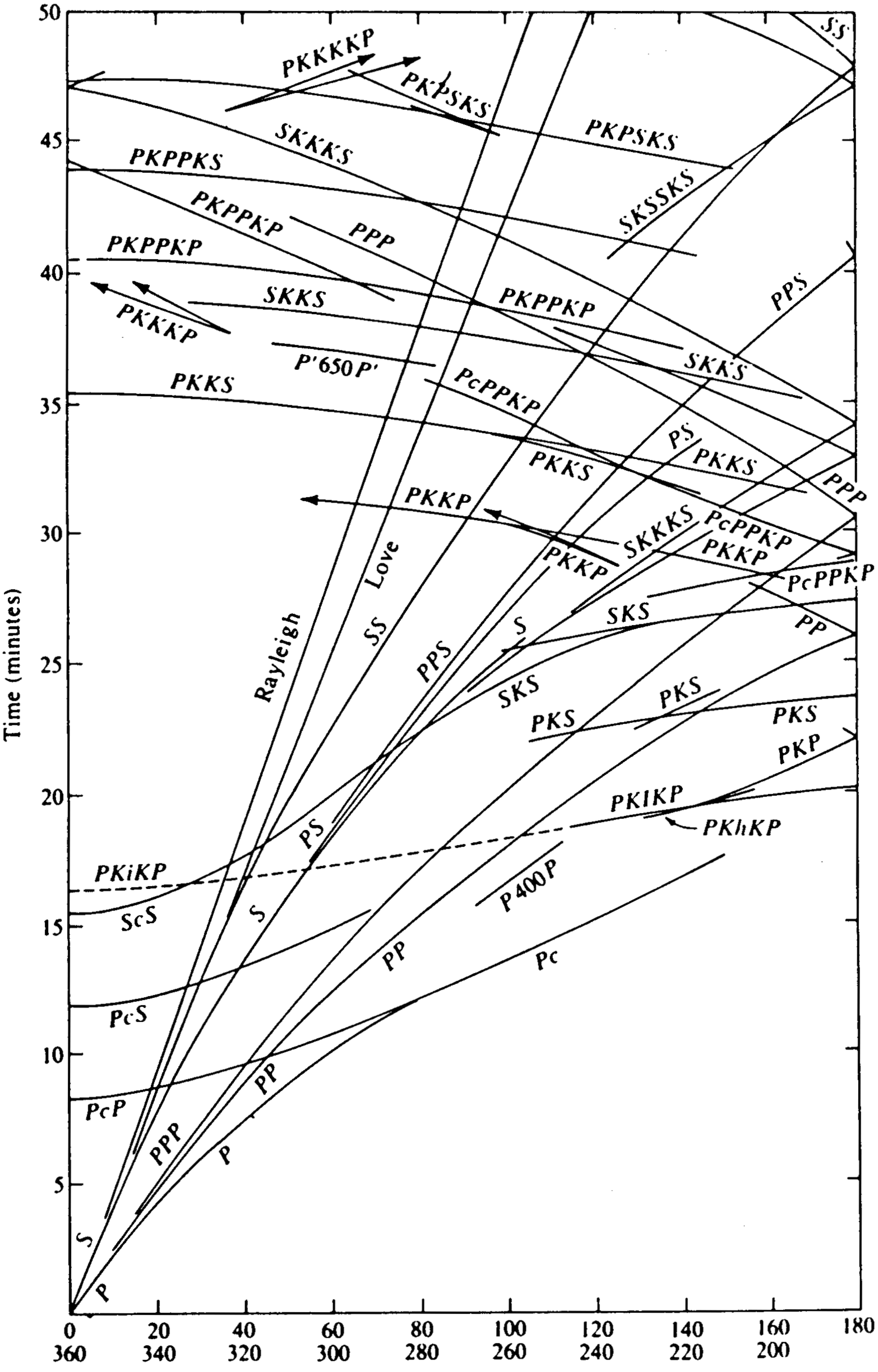


lw0611

1989 Loma Prieta earthquake
(top: transverse component, bottom: longitudinal component)

TRAVEL TIME CURVES

(surface source, after Bolt, 1982)



lw0119

DETERMINATION OF SEISMIC SOURCE PARAMETERS

LOCATING SEISMIC EVENTS

General: Best solution is given by the global minimum of residuals.

(see also Gibowicz, S.J. & Kijko, A. (1994): An Introduction to Mining Seismology, Academic Press)

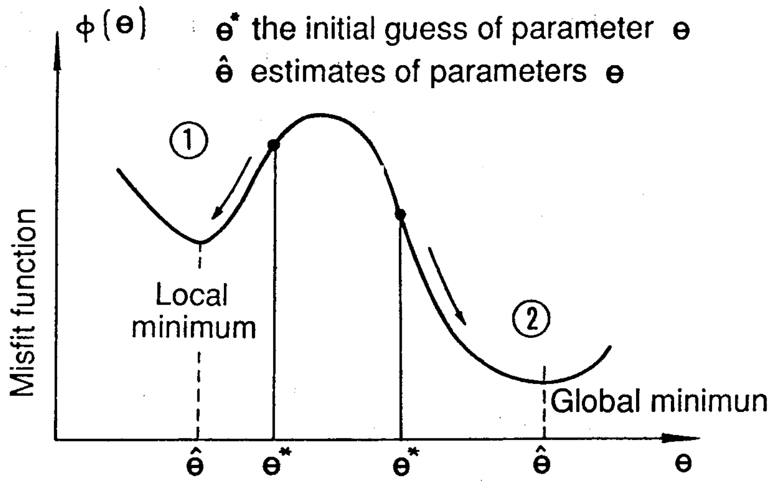
1. GEIGER - METHOD (1912)

Classic approach. Sum of squared time-residuals **r** ('misfit function')

$$\Phi\ (t_0, x_0, y_0, z_0) = \Sigma\, r_i^2$$
$$r_i = t_i - t_0 - T_i\ (x_0, y_0, z_0)$$

t_0... focal time
t_i... observed travel time
T_i... calculated travel time

has to become a minimum.



g0401
Effect of θ^* on the final solution. To find the global minimum is the objective.

Procedure of iteration process

1. Guess trial origin time t_0^* and hypocenter $(x_0^*, y_0^*, z_0^*) = \boldsymbol{\theta}^*$.
2. Compute time residuals r_i and derivatives at point $\boldsymbol{\theta}^*$ $(t_0^*, x_0^*, y_0^*, z_0^*)$
3. Solve system of four linear equations $d\boldsymbol{\theta} = \mathbf{B}^{-1}\,\mathbf{b}$ with $\mathbf{B} = \mathbf{A}^T\mathbf{A}$ and $\mathbf{b} = \mathbf{A}^T\mathbf{r}$.
   $d\boldsymbol{\theta}$ represents the adjustment-vector for the origin time and hypocenter coordinates with error **r**.

$$\boldsymbol{\theta}_{new} = \boldsymbol{\theta}^* + d\boldsymbol{\theta}$$
$$\boldsymbol{\theta}^* = \boldsymbol{\theta}_{new}$$

4. Repeat from point 2 until a termination criteria is met.

Based on the *Singular Value Decomposition* (SVD), the condition number ($\lambda^2_{max}/\lambda^2_{min}$, with λ being the eigenvalues of the matrix $\mathbf{\Lambda}$ given by $\mathbf{A} = \mathbf{U}\,\mathbf{\Lambda}\,\mathbf{V}^T$), represents the quality of the matrix **B**.

Problems:

1. matrix **A** ill defined (near singular): leads to oscillation of $d\boldsymbol{\theta}$
2. and/or poor choice of $\boldsymbol{\theta}^*$: leads to convergence at local - and not global - minimum

Solution:

1. Centring: Travel times are similar (hypocentre outside of network).
   Mean values are used for initial estimate $\boldsymbol{\theta}^*$, except for t_0^*.
2. Scaling: network and hypocentre are at the same mining level.

Used in South Africa and Poland.

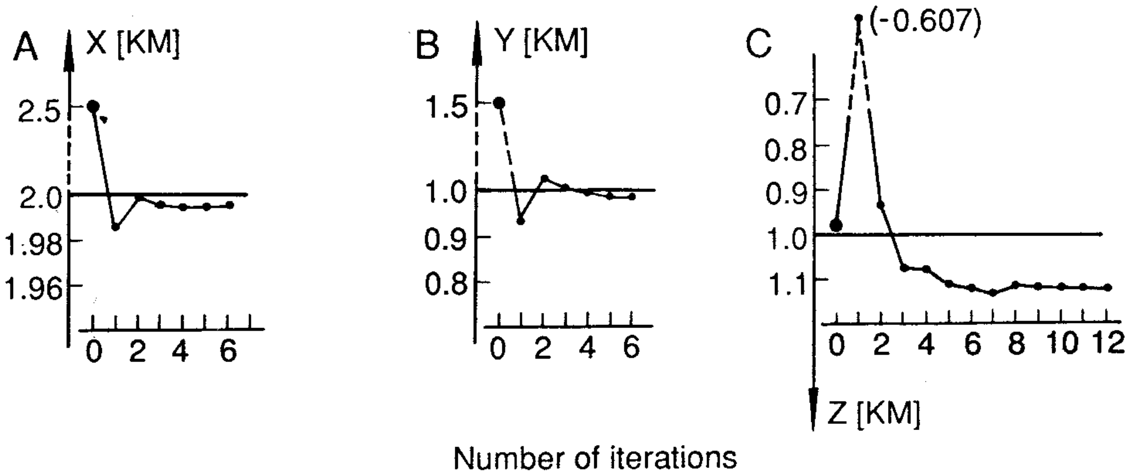
2. BAYESIAN APPROACH

Location algorithm is extremely efficient.
Input: Arrival times $\mathbf{t} = (t_1,....,t_n)^T$ and a priori location of seismic event $\mathbf{h} = x_0,y_0,z_0)^T$
Assumption: Time residuals are Gaussian distributed. Hypocentre must be close to mine workings.

Problem: Wrong a priori location

Solution: If depth can be fixed, the location accuracy becomes very good.

Used in 30 mines in Poland. Tests were performed in South Africa and China.



g0402

Hypocentre location without a priori information. The depth is badly resolved due the dominating horizontal spread of the network

3. LOCATION WITH APPROXIMATE VELOCITY MODELS

Generalization of the Least-Square Procedure.
Assumption: Velocity model consists of random variables. Their deviations from an average model are Gaussian distributed.

Problem: Layered structure (e.g. lava and quartzite)

Solution: Selection of sensors within strata of interest, after first location estimate has been made.

Used in Poland and China.

4. RELATIVE LOCATION TECHNIQUE

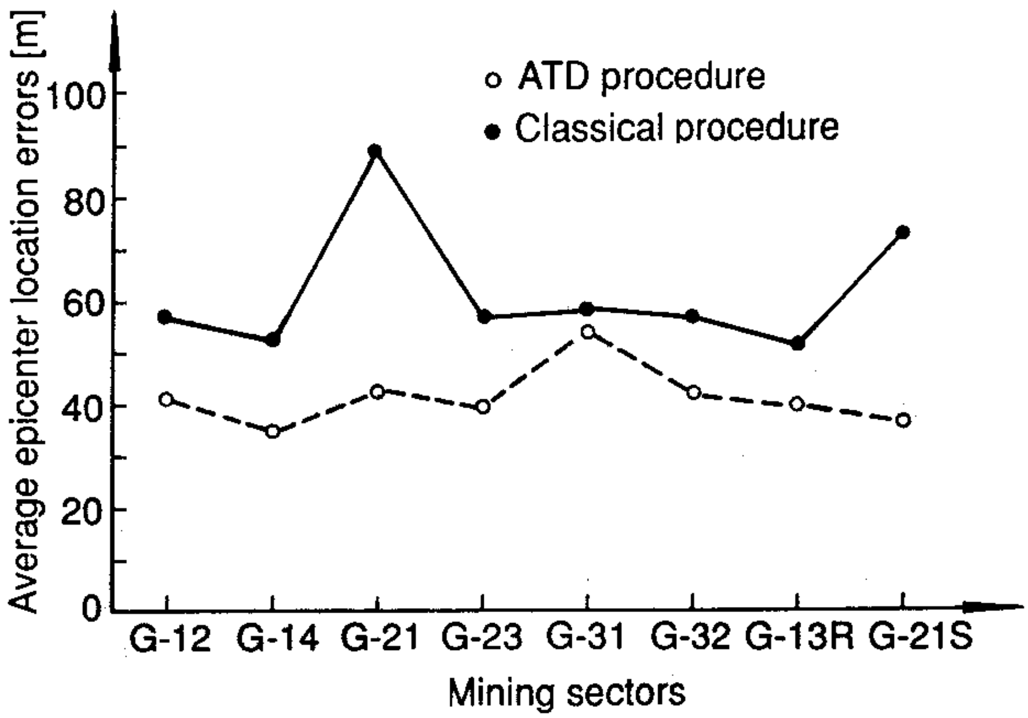
(ATD = arrival time difference)

30% more accurate than the classic approach and fast algorithm (no iterations necessary).
All P-wave-arrivals of particular event are related to a reference event. The difference of arrival-times is minimized by adjusting the coordinates and focal time of the master event.

Problems: Wrong reference event - or unknown focal time.

Solution: Careful selection of reference event according to first arrival, etc. Focal time of reference event can be estimated from first arrival.
Does not work in a layered structure, where wave paths cross different geology.

Used in Germany and Poland.



g0405

Average errors of epicentre locations of 354 dynamite blasts. ATD improves locations by 30 %.

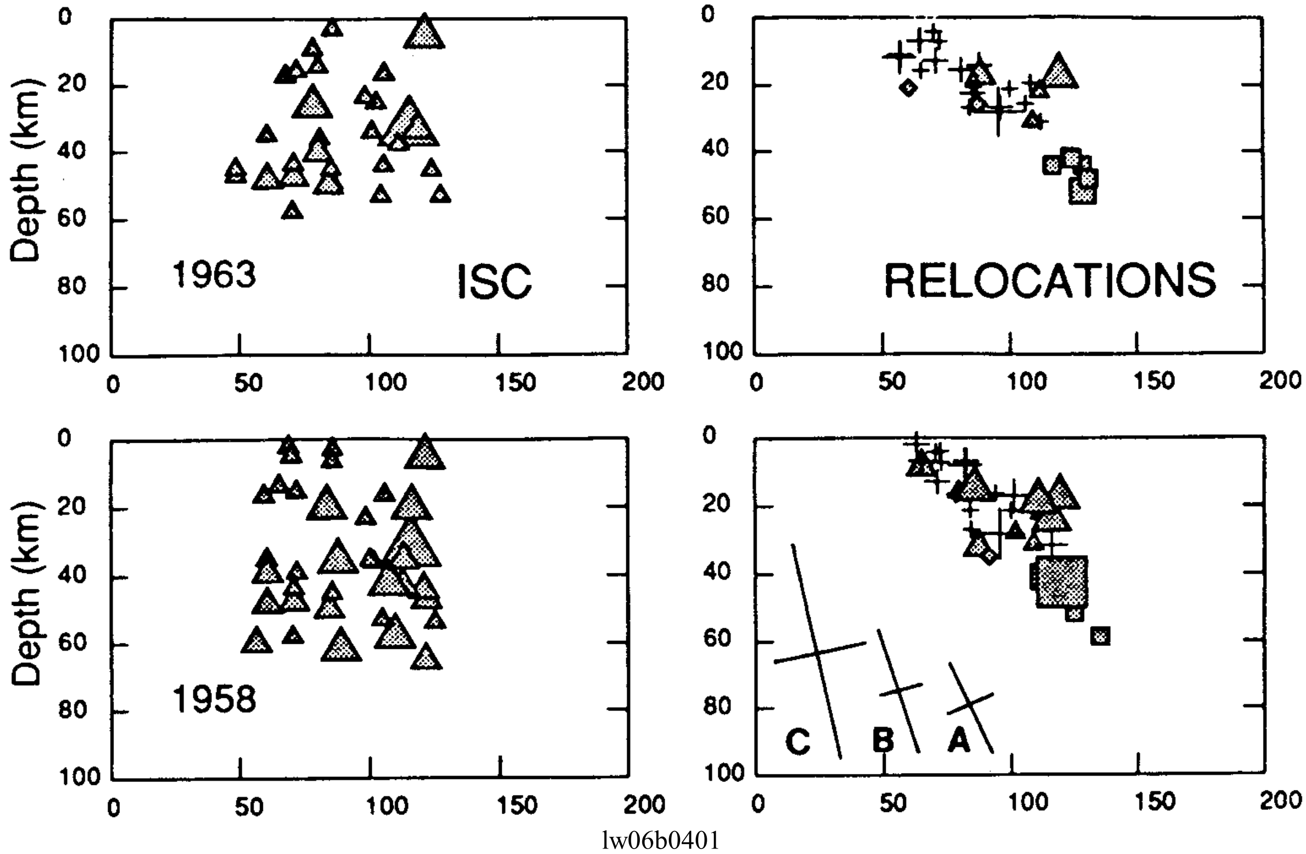
5. SIMULTANEOUS HYPOCENTER AND VELOCITY DETERMINATION

Simultaneous location of a group of seismic events and the velocity model.
Follows ATD-technique. Known as *Simultaneous structure and hypocenter* (SSH) determination or *Joint determination of hypocentres* (JHD). The method does not require calibration blasts, is fast and can be run on small computers.

Problem: No correlations between arrival-time errors are allowed. Highly unstable method.

Solution: Automatic phase picker. Some a priori assumption necessary to stabilize iteration process.

Used in Czech Republic and South Africa.



Conventional and JHD-relocations from events located near the Kurile subduction zone.

6. OTHER LOCATION METHODS

Linear Methods
Fast and free from iterative problems. Requires constant velocity-model.

$$\mathbf{A}\,\boldsymbol{\theta} = \mathbf{r}$$

$$\{A\}_{ij} = \begin{Bmatrix} 2(t_{i+1} - t_i)V \\ 2(x_{i+1} - x_i) \\ 2(y_{i+1} - y_i) \\ 2(z_{i+1} - z_i) \end{Bmatrix} \begin{matrix} \text{for } j = 1 \\ \text{for } j = 2 \\ \text{for } j = 3 \\ \text{for } j = 4 \end{matrix}$$

$$\{\mathbf{r}_i\} = (x^2_{i+1} - x^2_i) + (y^2_{i+1} - y^2_i) + (z^2_{i+1} - z^2_i) + (t^2_{i+1} - t^2_i)\, V^2$$

with 'i' being the station number.

Often used to find first location-estimate for iterative procedures.

Large Time Residuals and L1 Norm
Takes account of arrival time-residuals, which are not Gaussian distributed.
The misfit-function

$$\Phi\,(t_0, x_0, y_0, z_0) = \Sigma\, |r_i|$$

decreases effects of few large time residuals.

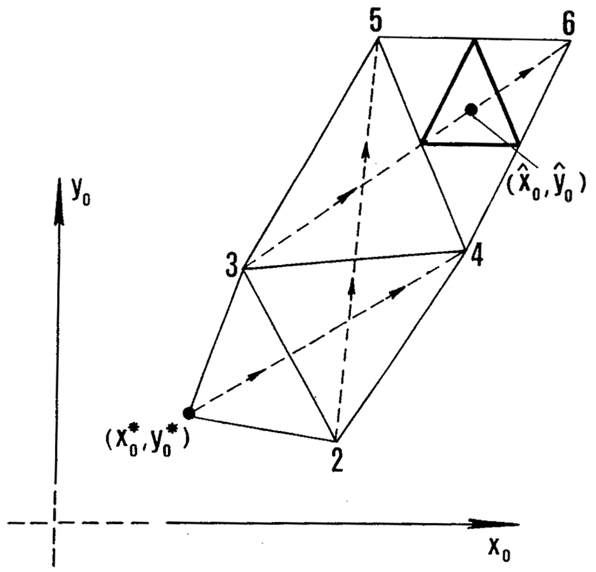
Problem: Difficult to formulate matrix and inversion

Solution: Minimization procedure (simplex subroutine)

Used in USA and South Africa.

Nelder-Mead Simplex Procedure
Relatively slow, but avoids calculation of derivatives (which can be very small, thus leading to ill-conditioned matrices). Constructs simplex structures, where the number of vertices = 1 + number of unknowns. Searches for best solution by changing and moving the simplex-structure through the space of unknowns. Solution is found when the simplex structure collapses in itself.

Relatively new.



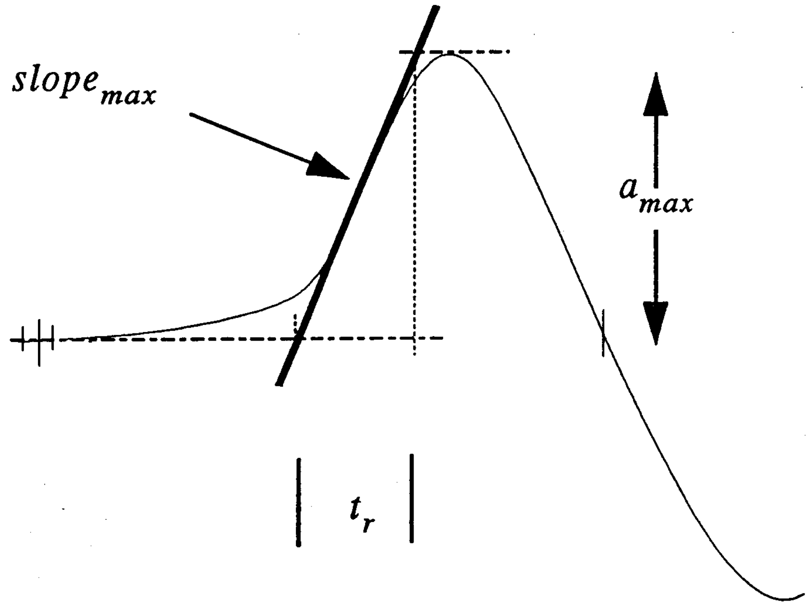
Principle of simplex algorithm

SOURCE PARAMETERS
(TIME DOMAIN)

RISE TIME

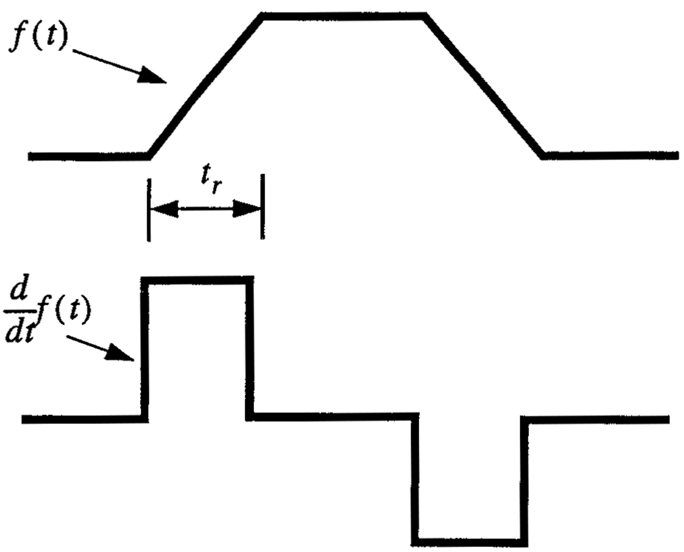
The ‘rise time’ can be determined from the displacement record (a_{max} = max. amplitude of recorded ground displacement):

$$t_r = a_{max}/slope_{max}$$



s1017

Alternatively, one can measure the length of the pulse duration from the velocity record (time between zero-crossings, bottom trace):



s1018

SOURCE PARAMETERS
(FREQUENCY DOMAIN)

SIGNAL MOMENT

$$M_0 = G\,A\,D$$

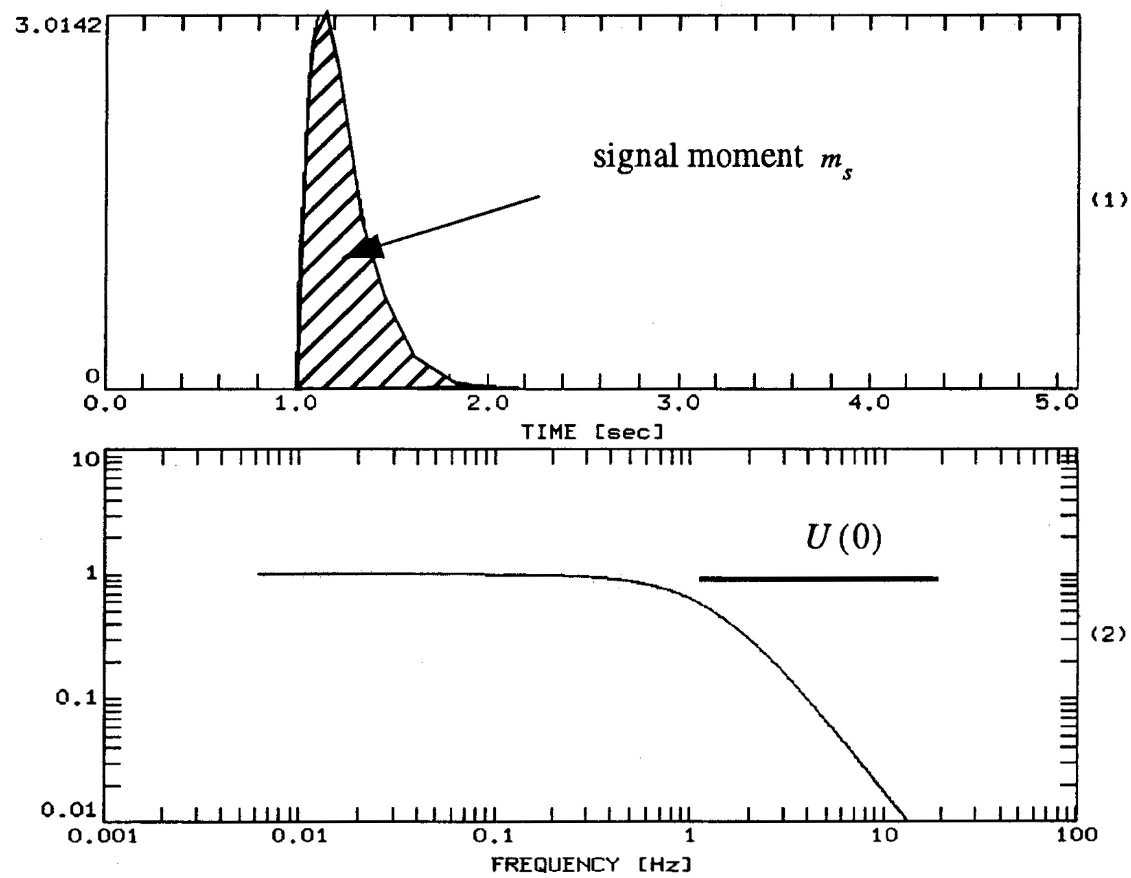
with G... modulus of rigidity, D... average displacement (slip) = U(0), A... area of slip

$$M_0 = CU(0)$$

$$U(0) = \int_{-\infty}^{\infty} u(t)e^{-j2\pi ft}dt = \int_{-\infty}^{\infty} u(t)e^{-j2\pi 0t}dt = \int_{-\infty}^{\infty} u(t)dt = m_s$$

with C... constant (= GA)

The pulse area of the displacement in the time domain (m_S = signal moment) equals the spectral level at U(0) in the frequency domain.

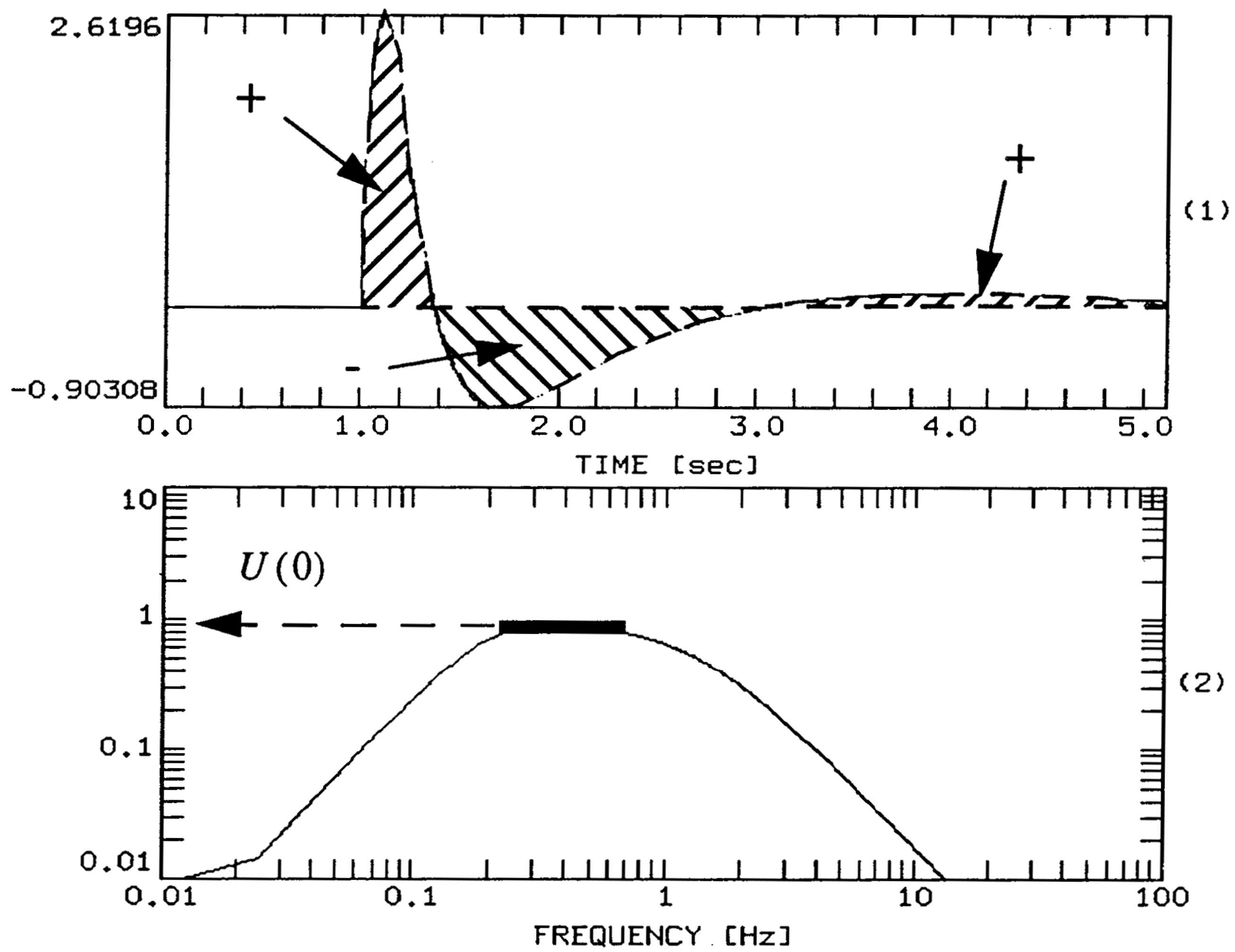


s1022

The seismometer affects the shape of the recorded displacement pulse u(t):

$$S(j\omega) = U(j\omega)T(j\omega)$$

The seismometer acts as a high pass filter. The frequency response function 'T(jω) = 0' at 'ω = 0'. The displacement pulse becomes two-sided, the area between the first arrival (onset) and the first zero-crossing underestimates the signal moment.



s1023

Signal moment and spectral level U(0) as if recorded by a 5-second displacement seismometer with damping factor of 0.707.

OTHER SOURCE PARAMETERS

The seismic moment, seismic energy, corner frequency, source radius, stress drop can be estimated by comparing power spectra of velocities and displacements:

$$S_{V2} = 2\int_0^\infty V^2(f)df; \longleftrightarrow S_{D2} = 2\int_0^\infty D^2(f)df$$

$$\Omega_0 = 2S_{V2}^{-1/4}S_{D2}^{3/4}$$

$$M_0 = 4\pi\rho V_S^3 \Omega_0 R_c$$

$$with\ a\ radiation\ factor$$

$$R_c = 0.55\, for\ P-waves\ and\ R_c = 0.63\, for\ S-waves,$$

$$shear\ wave\ velocity\ V_S = 3400 m/s,\ density = 2700 kg/m^3$$

$$E_s = 4\pi\rho V_S S_{V2}$$

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{S_{V2}}{S_{D2}}}$$

$$r = \frac{kV_S}{2\pi f_0}$$

$$with\ a\ source\ shape\ factor\ 'k'\ of = e.g.\ 2.34\ (Brune)$$

$$\sigma = \frac{7M_0}{16r^3}$$

Note: Effect of limited bandwidth!

See Di Bona, M. & Rovelli, A. 1988. Effects of the bandwidth limitation on stress drops estimated from integrals of the ground motion. Bull.Seism.Soc.Am., Vol.78, 1818 -1825.

FAR FIELD EFFECTS
PEAK GROUND VELOCITY

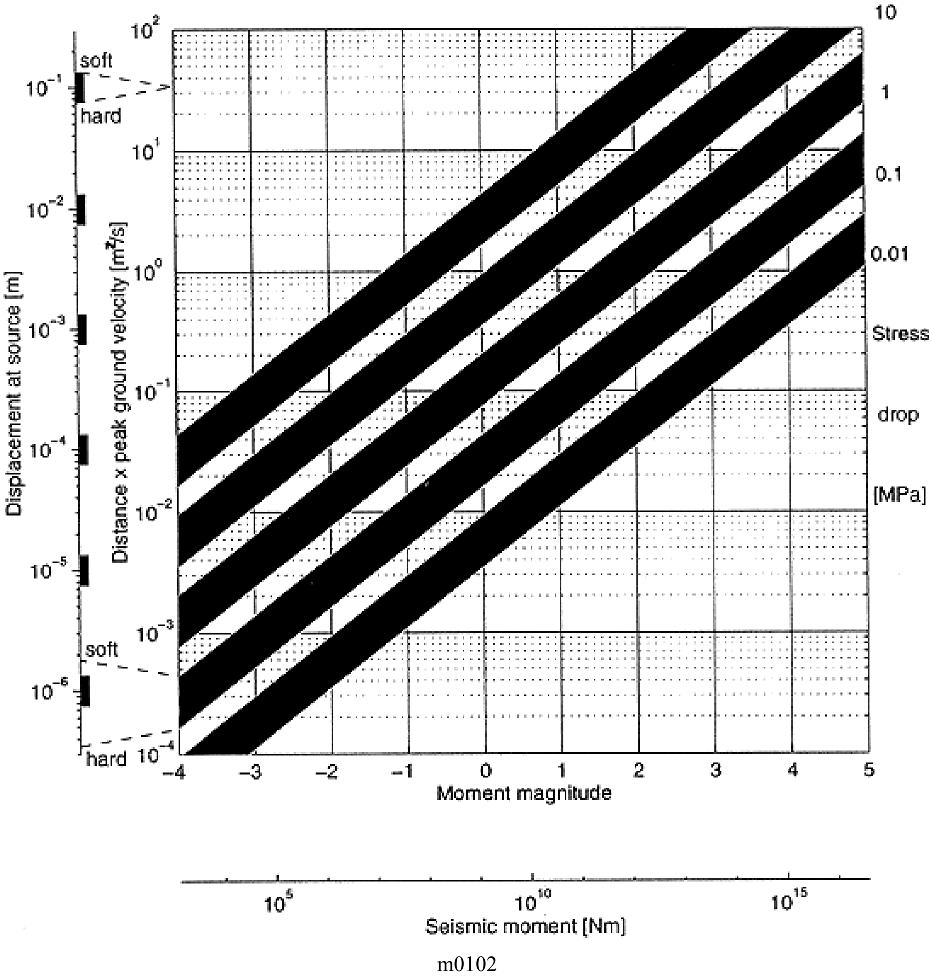
(see McGarr, 1991[1], and Mendecki, 1997)

$$f_0 = \frac{kV_S}{2\pi}\sqrt[3]{\frac{16\Delta\sigma}{7M_0}}$$

$$v_{peak} = \frac{R_S}{4\pi\rho R V_S^3} 2\pi f_0^2 M_0 \longleftarrow R_S = 0.57; k = 2.34$$

$$v_{peak} = \frac{0.0686}{\rho R V_S}\sqrt[3]{\Delta\sigma^2 M_0} \longleftarrow M_0 = GD\pi r^2$$

$$D_{peak} = \frac{8.1 R v_{peak}}{V_S}$$



m0102

Far field peak ground velocity and source displacement as a function of the stress drop and seismic moment.

[1]McGarr, A.(1991). Observations constraining near-source ground motions estimated from locally recorded seismograms. *J.Geophys.Res.*, 96, 16495-16508.