Seismology - Seismogram Fornesic
Anatomy of Seismograms

Frequency of Earthquakes

<table>
<thead>
<tr>
<th>Type</th>
<th>M&lt;sub&gt;L&lt;/sub&gt;</th>
<th>Observation</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>&lt;2.0</td>
<td>not felt</td>
<td>&gt; 8,000 /day</td>
</tr>
<tr>
<td>very weak</td>
<td>2.0-2.9</td>
<td>felt</td>
<td>1,000 /day</td>
</tr>
<tr>
<td>weak</td>
<td>3.0-3.9</td>
<td>felt but no damage</td>
<td>49,000 /year</td>
</tr>
<tr>
<td>small</td>
<td>4.0-4.9</td>
<td>only small damage</td>
<td>6,200 /year</td>
</tr>
<tr>
<td>moderate</td>
<td>5.0-5.9</td>
<td>damage at certain buildings</td>
<td>800 /year</td>
</tr>
<tr>
<td>strong</td>
<td>6.0-6.9</td>
<td>damage in a radius of 100 km</td>
<td>120 /year</td>
</tr>
<tr>
<td>significant</td>
<td>7.0-7.9</td>
<td>sig. damage within a large area</td>
<td>18 /year</td>
</tr>
<tr>
<td>large</td>
<td>8.0-8.9</td>
<td>sig. damage within several 100s km</td>
<td>1 /year</td>
</tr>
<tr>
<td>very large</td>
<td>&gt; 9.0</td>
<td>radius of damage &gt; 1000km</td>
<td>within 20 years</td>
</tr>
</tbody>
</table>
Anatomy of Seismograms
Anatomy of Seismograms

local EQ < 10 km
Anatomy of Seismograms
Anatomy of Seismograms

local EQ < 100 km
Anatomy of Seismograms
Anatomy of Seismograms

local EQ < 300 km
Anatomy of Seismograms

\[\text{TIME [sec]}\]

Action: Menu  Mode: Normal  Hardcopy: OFF
Anatomy of Seismograms

local EQ < 50 km
Anatomy of Seismograms

local EQ < 50 km

Explosion!!

2004-12-02 15:17:29.8500

TIME [sec]

Action: Menu    Mode: Normal    Hardcopy: OFF
Anatomy of Seismograms

![Anatomy of Seismograms](image-url)
Anatomy of Seismograms

regional EQ < 2000 km
Anatomy of Seismograms

![Seismogram Graph](image)
Anatomy of Seismograms

teleseismic EQ > 12,000 km
Anatomy of Seismograms

Separation according to distance:
Anatomy of Seismograms

Separation according to distance:

- local events: $\Delta < 600$ km (150 km)
Anatomy of Seismograms

Separation according to distance:

- local events: $\Delta < 600$ km (150 km)
- regional events: $600$ km $< \Delta < 12,000$ km
Anatomy of Seismograms

Separation according to distance:

- local events: $\Delta < 600$ km (150 km)
- regional events: $600$ km $< \Delta < 12,000$ km
- teleseismic events: $\Delta > 12,000$ km
Anatomy of Seismograms

Separation according to distance:

- local events: $\Delta < 600 \text{ km (150 km)}$
- regional events: $600 \text{ km} < \Delta < 12,000 \text{ km}$
- teleseismic events: $\Delta > 12,000 \text{ km}$

Criterion for classification
Anatomy of Seismograms

Separation according to distance:

- **local events:** $\Delta < 600$ km (150 km)
- **regional events:** $600$ km $< \Delta < 12,000$ km
- **teleseismic events:** $\Delta > 12,000$ km

Criterion for classification

$\Rightarrow$ Duration!!
Aufbau der Seismogramme
Aufbau der Seismogramme
Aufbau der Seismogramme
Anatomy of Seismograms

Why are they looking so different?
Anatomy of Seismograms

Why are they looking so different?

- differences in propagation (direct, reflected, refracted, diffracted)
Anatomy of Seismograms

Why are they looking so different?

- differences in propagation (direct, reflected, refracted, diffracted)
- focal depth influences the overall shape of a seismogram significantly (depth phases, surface waves)
Anatomy of Seismograms

Local & regional events ($\Delta < 10^\circ$):

Kulhanek, 1990
Anatomy of Seismograms

Local & regional events ($\Delta < 10^\circ$):

Kulhanek, 1990
Anatomy of Seismograms

Local & regional events ($\Delta<10^\circ$):

Kulhanek, 1990
Anatomy of Seismograms

phases (IASPEI):

- P: longitudinal wave (undae primae)
- K: longitudinal wave through outer core
- I: longitudinal wave through inner core
- S: transversal wave (undae secundae)
- T: wave partially propagating as acoustic wave in the ocean
- J: transversal wave through inner core
- N: n-times reflected waves
- p/s (small): depth phases
- L: surface waves unspecified
- R: Rayleighwave
- Q: Lovewave
- G: (long period) global (mantel) Lovewave
Aufbau der Seismogramme

Phasenkonvention (crust - IASPEI):

Pg  At short distances, either an upgoing P wave from a source in the upper crust or a P wave bottoming in the upper crust. At larger distances also arrivals caused by multiple P-wave reverberations inside the whole crust with a group velocity around 5.8 km/s.
Pb  (alt: P*) Either an upgoing P wave from a source in the lower crust or a P wave bottoming in the lower crust
Pn  Any P wave bottoming in the uppermost mantle or an upgoing P wave from a source in the uppermost mantle
PnPn Pn free surface reflection
PgPg Pg free surface reflection
PmP  P reflection from the outer side of the Moho
PmPN PmP multiple free surface reflection; N is a positive integer. For example, PmP2 is PmPPmP
PmS  P to S reflection from the outer side of the Moho
Aufbau der Seismogramme

Phasenkonvention (crust - IASPEI):

*Sg*  At short distances, either an upgoing S wave from a source in the upper crust or an S wave bottoming in the upper crust. At larger distances also arrivals caused by superposition of multiple S-wave reverberations and SV to P and/or P to SV conversions inside the whole crust.

*Sb*  (alt:S*) Either an upgoing S wave from a source in the lower crust or an S wave bottoming in the lower crust

*Sn*  Any S wave bottoming in the uppermost mantle or an upgoing S wave from a source in the uppermost mantle

*SnSn*  Sn free surface reflection

*SgSg*  Sg free surface reflection

*SmS*  S reflection from the outer side of the Moho

*SmSN*  SmS multiple free surface reflection; N is a positive integer. For example, SmS2 is SmSSmS

*SmP*  S to P reflection from the outer side of the Moho

*Lg*  A wave group observed at larger regional distances and caused by superposition of multiple S-wave reverberations and SV to P and/or P to SV conversions inside the whole crust. The maximum energy travels with a group velocity around 3.5 km/s

*Rg*  Short period crustal Rayleigh wave
Aufbau der Seismogramme

Phasenkonvention (near source - IASPEI):

- **pPy**: All P-type onsets (Py) as defined above, which resulted from reflection of an upgoing P wave at the free surface or an ocean bottom; WARNING: The character "y" is only a wild card for any seismic phase, which could be generated at the free surface. Examples are: pP, pPKP, pPP, pPcP etc

- **sPy**: All Py resulting from reflection of an upgoing S wave at the free surface or an ocean bottom; For example: sP, sPKP, sPP, sPcP etc

- **pSy**: All S-type onsets (Sy) as defined above, which resulted from reflection of an upgoing P wave at the free surface or an ocean bottom. For example: pS, pSKS, pSS, pScP etc

- **sSy**: All Sy resulting from reflection of an upgoing S wave at the free surface or an ocean bottom. For example: sSn, sSS, sScS, sSdif etc

- **pwPy**: All Py resulting from reflection of an upgoing P wave at the ocean's free surface
Anatomy of Seismograms

Local & regional events ($\Delta<10^{\circ}$):
Anatomy of Seismograms

Local & regional events ($\Delta < 10^\circ$):

- Duration < 5 min
- seismogram complex (compared to 1 to 3 layers)
- dominant signal is $S_g$ followed by waves with decreasing amplitude (Coda). Explosions may generate large Rayleigh waves
- order of arrival: $P_g$, $P_b$, $P_n$ for $t_{s-p} < 20s$
  $P_n$, $P_b$, $P_g$ für $t_{s-p} < 25s$
- “rule of thumb”: $t_{s-p}[s] \cdot 8 = \Delta$ in [km] if $P_g$ and $S_g$ first, in in case of $P_n$ and $S_n$ first: $t_{s-p}[s] \cdot 10 = \Delta$
BOX 1: General rules for local and regional events

- The frequency content of local events (D < 2°) is usually high (f ≈ 0.2 - 100 Hz). Therefore they are best recorded on SP or SP-filtered BB instruments with sampling rates f ≥ 80 Hz. The overall duration of short-period local and regional (D < 20°) seismograms ranges between a few seconds and to several minutes.

- Strong local/regional sources radiate long-period energy too and are well recorded by BB and LP seismographs. In the far regional range the record duration may exceed half an hour (see Fig. 1.2).

- Important seismic phases in seismograms of local sources are Pg, Sg, Lg and Rg and in seismograms of regional sources additionally Pn and Sn, which arrive beyond 1.3°-2° as the first P- and S-wave onsets. The P waves are usually best recorded on vertical and the S waves on horizontal components.

- Note that Pg is not generally seen in records from sources in the oceanic crust. Also, deep (sub-crustal) earthquakes lack local and regional crustal phases.

- For rough estimates of the epicentral distance D [km] of local sources, multiply the time difference Sg-Pg [s] by 8, and in the case of regional sources the time difference Sn-Pn [s] by 10. For more accurate estimates of D use local and regional travel-time curves or tables or calculations based on more appropriate local/regional crustal models.

- The largest amplitudes in records of local and regional events are usually the crustal channel waves Lg (sometimes even beyond 15°), and for near-surface sources the short-period fundamental Rayleigh mode Rg. For near-surface explosions or mining-induced earthquakes, Rg, with longer periods than Sg, may dominate the record, however usually not beyond 4°.

- For routine analysis the following station/network readings should be made: (1) the onset time and polarity of observed first motion phases; (2) onset times of secondary local and regional phases; (3) local magnitude based either on maximum amplitude or duration. If local/regional calibration functions, properly scaled to the original magnitude definition by Richter (1935), are not available it is recommended to use the original Richter equation and calibration function, together with local station corrections.
Anatomy of Seismograms

teleseismic events ($\Delta > 10^\circ$):
Anatomy of Seismograms

teleseismic events (Δ>10°):
Anatomy of Seismograms

teleseismic events ($\Delta > 10^\circ$):

- wave propagation mainly in mantel
- mantel less heterogeneous than the crust
- large distances correspond with deeper penetration of waves into mantel
- surface waves are dominating the seismogram depending on focal depth
- ray parameter needs re-definition because of spherical symmetry
Anatomy of Seismograms

teleseismic events ($\Delta > 10^\circ$):

$$s \cdot r \sin i = r \sin i / v \equiv p,$$
### Anatomy of Seismograms

**teleseismic events ($\Delta > 10^\circ$):**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>A longitudinal wave, bottoming below the uppermost mantle; also an upgoing longitudinal wave from a source below the uppermost mantle</td>
</tr>
<tr>
<td>PP</td>
<td>Free surface reflection of P wave leaving a source downwards</td>
</tr>
<tr>
<td>PS</td>
<td>P, leaving a source downwards, reflected as an S at the free surface. At shorter distances the first leg is represented by a crustal P wave.</td>
</tr>
<tr>
<td>PPP</td>
<td>analogous to PP</td>
</tr>
<tr>
<td>PPS</td>
<td>PP to S converted reflection at the free surface; travel time matches that of PSP</td>
</tr>
<tr>
<td>PSS</td>
<td>PS reflected at the free surface</td>
</tr>
<tr>
<td>PcP</td>
<td>P reflection from the core-mantle boundary (CMB)</td>
</tr>
<tr>
<td>PcS</td>
<td>P to S converted reflection from the CMB</td>
</tr>
<tr>
<td>PcPN</td>
<td>PcP multiple free surface reflection; N is a positive integer. For example PcP2 is PcPPcP</td>
</tr>
<tr>
<td>Pz+P</td>
<td>(alt: PzP) P reflection from outer side of a discontinuity at depth $z$; $z$ may be a positive numerical value in km. For example P660+P is a P reflection from the top of the 660 km discontinuity.</td>
</tr>
<tr>
<td>Pz-P</td>
<td>P reflection from inner side of discontinuity at depth $z$. For example, P660-P is a P reflection from below the 660 km discontinuity, which means it is precursory to PP.</td>
</tr>
<tr>
<td>Pz+S</td>
<td>(alt: PzS) P to S converted reflection from outer side of discontinuity at depth $z$.</td>
</tr>
<tr>
<td>Pz-S</td>
<td>P to S converted reflection from inner side of discontinuity at depth $z$.</td>
</tr>
<tr>
<td>PScS</td>
<td>P (leaving a source downwards) to ScS reflection at the free surface</td>
</tr>
<tr>
<td>Pdif</td>
<td>(old: Pdiff) P diffracted along the CMB in the mantle</td>
</tr>
</tbody>
</table>
Anatomy of Seismograms

teleseismic events ($\Delta > 10^\circ$):

PKP (alt:P') unspecified P wave bottoming in the core
PKPab (old:PKP2) P wave bottoming in the upper outer core; ab indicates the retrograde branch of the PKP caustic
PKPbc (old:PKP1) P wave bottoming in the lower outer core; bc indicates the prograde branch of the PKP caustic
PKPdf (alt:PKIKP) P wave bottoming in the inner core
PKPpre (old:PKhKP) a precursor to PKPdf due to scattering near or at the CMB
PKPdif P wave diffracted at the inner core boundary (ICB) in the outer core

PKS Unspecified P wave bottoming in the core and converting to S at the CMB
PKSab PKS bottoming in the upper outer core
PKSbc PKS bottoming in the lower outer core
PKSdf PKS bottoming in the inner core

P'P' (alt:PKPPKP) Free surface reflection of PKP
P'N (alt:PKPN) PKP reflected at the free surface N-1 times; N is a positive integer. For example P'3 is P'P'P'
P'z-P' PKP reflected from inner side of a discontinuity at depth z outside the core, which means it is precursory to P'P'; z may be a positive numerical value in km
PS' (alt:PKPSKS) PKP to SKS converted reflection at the free surface; other examples are P'PKS, P'SKP
PS' (alt:PSKS) P (leaving a source downwards) to SKS reflection at the free surface
# Anatomy of Seismograms

**teleseismic events ($\Delta > 10^\circ$):**

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKKP</td>
<td>Unspecified P wave reflected once from the inner side of the CMB</td>
</tr>
<tr>
<td>PKKPa</td>
<td>PKKP bottoming in the upper outer core</td>
</tr>
<tr>
<td>PKKPbc</td>
<td>PKKP bottoming in the lower outer core</td>
</tr>
<tr>
<td>PKKPdf</td>
<td>PKKP bottoming in the inner core</td>
</tr>
<tr>
<td>PNKP</td>
<td>P wave reflected N-1 times from inner side of the CMB; $N$ is a positive integer</td>
</tr>
<tr>
<td>PKKPpre</td>
<td>A precursor to PKKP due to scattering near the CMB</td>
</tr>
<tr>
<td>PKiKP</td>
<td>P wave reflected from the inner core boundary (ICB)</td>
</tr>
<tr>
<td>PKNIKP</td>
<td>P wave reflected N-1 times from the inner side of the ICB</td>
</tr>
<tr>
<td>PKJKP</td>
<td>P wave traversing the outer core as P and the inner core as S</td>
</tr>
<tr>
<td>PKKS</td>
<td>P wave reflected once from inner side of the CMB and converted to S at the CMB</td>
</tr>
<tr>
<td>PKKSab</td>
<td>PKKS bottoming in the upper outer core</td>
</tr>
<tr>
<td>PKKSbc</td>
<td>PKKS bottoming in the lower outer core</td>
</tr>
<tr>
<td>PKKSdf</td>
<td>PKKS bottoming in the inner core</td>
</tr>
<tr>
<td>PcPP'</td>
<td>(alt:PcPPKP) PcP to PKP reflection at the free surface; other examples are PcPS', PcSP', PcSS', PcPSKP, PcSSKP</td>
</tr>
</tbody>
</table>
Anatomy of Seismograms

teleseismic events ($\Delta > 10^\circ$):

- **L**: Unspecified long period surface wave
- **LQ**: Love wave
- **LR**: Rayleigh wave
- **G**: Mantle wave of Love type
- **GN**: Mantle wave of Love type; $N$ is integer and indicates wave packets traveling along the minor arcs (odd numbers) or major arc (even numbers) of the great circle
- **R**: Mantle wave of Rayleigh type
- **RN**: Mantle wave of Rayleigh type; $N$ is integer and indicates wave packets traveling along the minor arcs (odd numbers) or major arc (even numbers) of the great circle
- **PL**: Fundamental leaking mode following P onsets generated by coupling of P energy into the waveguide formed by the crust and upper mantle
- **SPL**: S wave coupling into the PL waveguide; other examples are SSPL, SSSPL
Anatomy of Seismograms

teleseismic events ($\Delta > 10^\circ$):
Anatomy of Seismograms

teleseismic events ($\Delta > 10^\circ$):
Anatomy of Seismograms

teleseismic events ($\Delta > 10^\circ$):

PKPab, PKPbc and PKPdf

SKSac and SKSdf
Anatomy of Seismograms

Caustic?:
Anatomy of Seismograms
Anatomy of Seismograms
Analysis of Seismograms

“... jede Zacke, jede Zunge zu erklären ...”
‘... to explain each wiggle ...’
Emil Wiechert
## Analysis of Seismograms

<table>
<thead>
<tr>
<th>Single station</th>
<th>Classical type of seismic station with its own data processing. Event location only possible by means of three-component records.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station network</td>
<td>Local, regional or global distribution of stations that are as identical as possible with a common data center (see Chapter 8). Event location is one of the main tasks.</td>
</tr>
</tbody>
</table>
| Seismic array  | Cluster of seismic stations with a common time reference and uniform instrumentation. The stations are located close enough to each other in space for the signal waveforms to be correlated between adjacent sensors (see Chapter 9). Benefits are:  
  - extraction of coherent signals from random noise;  
  - determination of directional information of approaching wavefronts (determination of backazimuth of the source);  
  - determination of local slowness and thus of epicentral distance of the source. |
Analysis of Seismograms

Tools - single station

- digital filtering will improve SNR
- phase identification using simple relations (t\text{S-P}) or better travel time tables it is in principle possible to estimate the distance and the depth
- polarization analysis (3C-seismometers) may lead to azimuth
- nowadays only rarely done **BUT**: agencies are not able to perform a detailed analysis!
Analysis of Seismograms

1. Are you **NEAR** (D < 20°) or **TELESEISMIC** (D > 20°)?
   Criteria:
   • Frequencies on SP records \( f \geq 1 \) Hz \( f \leq 1 \) Hz
   • Amplitudes on LP records not or weaker large, also for later phases
   • Record duration < 20 min > 20 min
   (for magnitudes < 5; may be longer for strong earthquakes; see Fig. 1.2)

2. Is your **D < 100° or D > 100°**?
   Criteria:
   • Surface wave max. after P arrival < 45 ± 5 min or > 45 ± 5 min (Table 5 in DS 3.1)
   • Record duration on LP records < 1.5 hours or > 1.5 hours
   (may be larger for very strong earthquakes; see Fig. 1.2)

3. Are you **SHALLOW or DEEP** (> 70 km)?
   Criteria:
   • Surface waves on LP records strong weak or none
   • Depth phases usually not clear well separated and often clear
   • Waveforms usually more complex more impulsive

4. Is the first strong horizontal arrival **S or SKS**?
   Criteria:
   • Time difference to P < 10 ± 0.5 min ≈ 10 ± 0.5 min
   • Polarization large horiz. A in R and/or T in R only
   **Warning**! If the first strong horizontal arrival follows P after ≈ 10 ± 0.5 min it may be SKS. Check polarization! (see Fig. 11.14). Misinterpreting SKS as S may yield D estimates up to 20° too short. Look also for later multiple S arrivals (SP, SS, SSS) with better D control.
Analysis of Seismograms

Network - Localization:

• Geiger method:
Analysis of Seismograms

Network - Localization:

- Geiger method:

  How much information is needed
Analysis of Seismograms

Network - Localization:

- Geiger method:

  How much information is needed

\[ \Delta = v_c \cdot (t - T_0) \]

\[ \Rightarrow \text{Estimation of origin time} \]
Analysis of Seismograms

Network - Localization:

Wadati-Diagram: Estimation of origin time and $v_p/v_s$
Analysis of Seismograms

Network - Localization:

Epicenter
Analysis of Seismograms

Network - Localization:

Epicenter
Analysis of Seismograms

Network - Localization:

Epicenter
Analysis of Seismograms

Network - Localization:

Epicenter
Analysis of Seismograms

Network - Localization:

Epicenter
Analysis of Seismograms

Network - Localization:

Epicenter
Analysis of Seismograms

Network - Localization:

Epicenter
Analysis of Seismograms

Network - Localization:

Epicenter
Analysis of Seismograms

Network - Localization:

Depth

h
Analysis of Seismograms

Network - Localization:

- non linear inversion:
Analysis of Seismograms

Network - Magnitude:

- Station A
- Station B
- Station C
- Station D
Analysis of Seismograms

Network - Magnitude:

Leading equation of all magnitudes:

\[ M = \log (A_d/T)_{\text{max}} + \sigma(\Delta, h) + C_r + C_s. \]

with:

- \( A_d \) ground displacement measured at period \( T \)
- \( \sigma(\Delta, h) \) calibration factor, which refers to the distance (geometrical spreading) and absorption (intrinsic and scattering) dependent damping of the amplitude. In most cases the calibration refers to a reference amplitude of an earthquake with a fixed magnitude (e.g., 3 or 0): \( \sigma(\Delta, h) = -\log A_0(\Delta, h) \)
- directivity (regional) of the source (\( C_r \)) and station correction (\( C_s \))
Analysis of Seismograms

Network - Magnitude:

General steps:

Magnitudes can be determined on the basis of Eq. (1) by reading \((A/T)_{\text{max}}\) for any body wave (e.g., P, S, Sg, PP) or surface waves (LQ or Lg, LR or Rg) for which calibration functions for either vertical (V) and/or horizontal (H) component records are available. If the period being measured is from a seismogram recorded by an instrument whose response is already proportional to velocity, then \((A_d/T)_{\text{max}} = A_{\text{vmax}}/2\pi\), i.e., the measurement can be directly determined from the maximum trace amplitude of this wave or wave group with only a correction for the velocity magnification. In contrast, with displacement records one may not know with certainty where \((A/T)_{\text{max}}\) is largest in the displacement waveform. Sometimes smaller amplitudes associated with smaller periods may yield larger \((A/T)_{\text{max}}\). In the following we will always use \(A\) for \(A_d\), if not otherwise explicitly specified.

- the trace amplitude \(B\) of a seismic signal on a record is defined as its largest peak (or trough) deflection from the baseline of the record trace;

- for many phases, surface waves in particular, the recorded oscillations are more or less symmetrical about the zero line. \(B\) should then be measured either by direct measurement from the base-line or - preferably - by halving the peak-to-trough deflection (Figs. 3.9 a and c - e). For phases that are strongly asymmetrical (or clipped on one side) \(B\) should be measured as the maximum deflection from the base-line (Fig. 3.9 b);

- the corresponding period \(T\) is measured in seconds between those two neighboring peaks (or troughs) - or from (doubled!) trace crossings of the base-line - where the amplitude has been measured (Fig. 3.9);

- the trace amplitudes \(B\) measured on the record should be converted to ground displacement amplitudes \(A\) in nanometers (nm) or some other stated SI unit, using the A-T response (magnification) curve \(\text{Mag}(T)\) of the given seismograph (see Fig. 3.11); i.e., \(A = B /\text{Mag}(T)\). (Note: In most computer programs for the analysis of digital seismograms, the measurement of period and amplitude is done automatically after marking the position on the record where \(A\) and \(T\) should be determined);
General steps:

• amplitude and period measurements from the vertical component (Z = V) are most important. If horizontal components (N - north-south; E - east-west) are available, readings from both records should be made at the same time (and noted or reported separately) so that the amplitudes can be combined vectorially, i.e., \(A_H = \sqrt{A_N^2 + A_E^2}\);

• when several instruments of different frequency response are available (or in the case of the analysis of digital broadband records filtered with different standard responses), \(A_{\text{max}}\) and \(T\) measurements from each should be reported separately and the type of instrument used should be stated clearly (short-, medium- or long-period, broadband, Wood-Anderson, etc., or related abbreviations given for instrument classes with standardized response characteristics; see Fig. 3.11 and Tab. 3.1). For this, the classification given in the old Manual of Seismological Observatory Practice (Willmore 1979) may be used;

• broadband instruments are preferred for all measurements of amplitude and period;

• note that earthquakes are often complex multiple ruptures. Accordingly, the time, \(t_{\text{max}}\), at which a given seismic body wave phase has its maximum amplitude may be quite some time after its first onset. Accordingly, in the case of P and S waves the measurement should normally be taken within the first 25 s and 40-60 s, respectively, but in the case of very large earthquakes this interval may need to be extended to more than a minute. For subsequent earthquake studies it is also essential to report the time \(t_{\text{max}}\) (see Fig. 3.9).

• for teleseismic (\(\Delta > 20^\circ\)) surface waves the procedures are basically the same as for body waves. However, \((A/T)_{\text{max}}\) in the Airy phase of the dispersed surface wave train occurs much later and should normally be measured in the period range between 16 and 24 s although both shorter and longer periods may be associated with the maximum surface wave amplitudes (see 2.3).
Analysis of Seismograms

Network - Magnitude:

General steps

- note that in displacement proportional records \((A/T)_{\text{max}}\) may not coincide in time with \(B_{\text{max}}\). Sometimes, in dispersed surface wave records in particular, smaller amplitudes associated with significantly smaller periods may yield larger \((A/T)_{\text{max}}\). In such cases also \(A_{\text{max}}\) should be reported separately. In order to find \((A/T)_{\text{max}}\) on horizontal component records it might be necessary to calculate A/T for several amplitudes on both record components and select the largest vectorially combined value. In records proportional to ground velocity, the maximum trace amplitude is always related to \((A/T)_{\text{max}}\). Note, however, that as compared to the displacement amplitude \(A_d\), the velocity amplitude is \(A_v = A_d \frac{2\pi}{T}\).

- if mantle surface waves are observed, especially for large earthquakes (see 2.3), amplitudes and periods of the vertical and horizontal components with the periods in the neighborhood of 200 s should also be measured;

- on some types of short-period instruments (in particular analog) with insufficient resolutions it is not possible to measure the period of seismic waves recorded from nearby local events and thus to convert trace deflections properly to ground motion. In such cases magnitude scales should be used which depend on measurements of maximum trace amplitudes only;

- often local earthquakes will be clipped in (mostly analog) records of high-gain short-period seismographs with insufficient dynamic range. This makes amplitude readings impossible. In this case magnitude scales based on record duration (see 3.2.4.3) might be used instead, provided that they have been properly scaled with magnitudes based on amplitude measurements.
Analysis of Seismograms

Network - Magnitude:
Local-Magnitude (period @ 1 s; Δ < 600 km):

\[ M_l = \log A_{\text{max}} - \log A_0 \]

**Note:** in this case the amplitude is NOT divided by the period of the signal.

The Ml is measured at the Lg waves of the seismogram.

Network - Magnitude:
Analysis of Seismograms

Network - Magnitude:

Distance corrections:

- Richter (1956), Southern California
- Hutton & Boore (1987), Southern California
- Alsaker et al. (1991), Norway/Fennoscandia
- Kim (1988), Eastern North America
- Kiratzi & Papazachos (1984), Greece (ML>3.7)
- Greenhalgh & Singh (1986), Southern Australia
- Wahlstroem & Strauch (1984), Central Europe
Analysis of Seismograms

Network - Magnitude:

Problem: saturation of the magnitudes
Better: estimation of the seismic moment

Definition:

\[ M_0 = \mu \bar{D} A \]

Estimated via:

\[ M_0 = 4\pi \Delta \rho v_{p,s} u_0/R_{p,s,\theta,\phi}^3 \]

with:

- \( u_0 \) spectrale amplitude of ground displacement at frequency 0 (spectral plateau)
- \( v_{p,s} \) P- or S-wave speed
- \( \Delta \) hypo-central distance
- \( R_{p,s,\theta,\phi} \) radiation pattern and free surface correction
- \( \rho \) density of the medium

**Note**: only valid in homogenous half space
Analysis of Seismograms

Network - Magnitude:

Definition Moment-Magnitude:

\[ M_w = \frac{2}{3} (\log M_0 - 9.1) \]
Analysis of Seismograms

Network - Source Mechanism:

Types of sources

- Natural Events:
  - Tectonic Earthquakes
  - Volcanic Tremors and Earthquakes
  - Rock Falls / Collapse of Karst Cavities
  - Storm Microseisms

- Man-Made Events:
  - Controlled Sources (Explosions, Vibrators...)
  - Reservoir Induced Earthquakes
  - Mining Induced Rock Bursts / Collapses
  - Cultural Noise (Industry, Traffic etc.)
Analysis of Seismograms

Network - Focal Mechanism:

Schematic diagram of a focal mechanism

A View from side

B Strike slip

1. Normal
2. Reverse
3. Oblique reverse
Analysis of Seismograms

Network - Moment Tensor:

Seismogram might be written as:

\[ u_n(x,t) = M_{pq}(\xi,\tau) \ast G_{np;q}(\xi,x,t); \]

with: \( M_{pq}(\xi,\tau) \triangleq \) moment-tensor (incl. “source time function”)
\( G_{np;q}(\xi,x,t) \triangleq \) Green’s function of elementary source (couples)
Analysis of Seismograms

Network - Moment Tensor:
Analysis of Seismograms

Network - Moment Tensor:

\[ mxx_i = \frac{\partial u_x}{\partial x}, \]
\[ myy_i = \frac{\partial u_y}{\partial y}, \]
\[ mzz_i = \frac{\partial u_z}{\partial z}, \]
\[ mxy_i = \left( \frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y} \right), \]
\[ mxz_i = \left( \frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z} \right), \]
\[ myz_i = \left( \frac{\partial u_z}{\partial y} + \frac{\partial u_y}{\partial z} \right), \]
Der moment tensor might be written as:

\[ \mathbf{M} = \mathbf{M}_{\text{isotrop}} + \mathbf{M}_{\text{deviatoric}} \]

with

\[ \mathbf{M}_{\text{deviatoric}} = \mathbf{M}^{DC} + \mathbf{M}^{CVLD} \]
Streuung und Quell-Mechanismus

VTB (Long)

VTB (Short)

rel. Misfit

0.34 0.33 0.31 0.29

0.165 0.162 0.157 0.152
Streuung und Quell-Mechanismus

VTB (Long) [Diagram]

VTB (Short) [Diagram]
Streuung und Quell-Mechanismus

VTB (Long)

VTB (Short)

rel. Misfit
- 0.34
- 0.33
- 0.31
- 0.29

rel. Misfit
- 0.165
- 0.162
- 0.157
- 0.152
Streuung und Quell-Mechanismus

VTB (Long)

VTB (Short)
Streuung und Quell-Mechanismus

VTB (Long)

VTB (Short)

rel. Misfit

0.34  0.33  0.31  0.29

0.165  0.162  0.157  0.152
Streuung und Quell-Mechanismus

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0.165  0.162  0.157  0.132
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Streuung und Quell-Mechanismus

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Streuung und Quell-Mechanismus
Streuung und Quell-Mechanismus
Streuung und Quell-Mechanismus

VTB (Long)

VTB (Short)

rel. Misfit

0.34 0.33 0.31 0.29

0.165 0.162 0.157 0.152
LongPeriod/Explosion
LongPeriod/Explosion
Erdbebendienst
Bayern
Felt Earthquakes in Bavaria (1300 - present)
Goal: state wide monitoring of EQ MI>2.0
Netzwerk Design

Goal:
wide monitoring of EQ MI>2.0
Seismicity in Bavarian Alps
1713 earthquakes in 10 years !!
earthquakes (M≥0.3) - rain (2002-2008)
Rate - State & Diffusion

Setting at active plate boundaries

(a) $A\sigma=10$ kPa; $\dot{S}=10$ kPa/yr

(b) $A\sigma=0.1$ kPa; $\dot{S}=0.365$ kPa/yr

Intraplate setting
Rate - State & Diffusion & ????
Deformation of the Molasse

Kommission für Erdmessung und Glaziologie - BADW

bay. Landesamt für Vermessung und Geoinformation
induced earthquakes

- 1982: -30km
- 1981: -20km
- 2003: -23km
- 2004: -5km
- 2007: -10km
- 2008: -30km
geothermic events

> 400 induced EQs

felt earthquakes
Location Using Sparse Networks
Location Using Sparse Networks
Improving Locations - HypoDD

\[ dr_{ij}^k = (t_{k}^i - t_{k}^j)^{obs} - (t_{k}^i - t_{k}^j)^{cal} \]

Requires: slowness \( s_{ik} = s_{jk} \)

If not, the local slowness has to be taken into account:

\[ dr_{ij}^k = \frac{\partial t_{k}^i}{\partial m} \Delta m^i - \frac{\partial t_{k}^j}{\partial m} \Delta m^j \]

To be solved iteratively!

Different weights applied during different inversion steps

Waldhauser and Ellsworth (2000)
The Use of HypoDD

(a) Absolute Locations (Map view)

(b) HypoDD Locations (Map view)

(c) HypoDD (Map view, detail)

(d) HypoDD (view from South, detail)
Deichmann and Garcia-Fernandez (1992)
Master-Event Technique
\[
\begin{pmatrix}
\frac{1}{dt_p} \\
\frac{1}{dt_s} \\
\vdots \\
\frac{1}{dt_p} \\
\frac{1}{dt_s}
\end{pmatrix}
= \begin{pmatrix}
1 & -\frac{1}{v_p} n_x & -\frac{1}{v_p} n_y & -\frac{1}{v_p} n_z \\
1 & -\frac{2}{v_s} n_x & -\frac{2}{v_s} n_y & -\frac{2}{v_s} n_z \\
\vdots & \vdots & \vdots & \vdots \\
1 & -\frac{1}{v_p} n_x & -\frac{1}{v_p} n_y & -\frac{1}{v_p} n_z \\
1 & -\frac{1}{v_s} n_x & -\frac{1}{v_s} n_y & -\frac{1}{v_s} n_z
\end{pmatrix}
\begin{pmatrix}
\Delta T \\
x \\
y \\
z
\end{pmatrix}
\]
Cluster-1 (KLT0-Z)

Stack of all Cluster (KLT0-Z)
Coherence attributes (Lüschen et al. 2011)