Interal structure and surfaces of solid planets

Ulrich Christensen
Institut für Geophysik
University of Göttingen

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1. Seismology and internal structure

1.1 Fundamentals

Body waves: P-waves, S-waves

$$v_P = \sqrt{\frac{k+\frac{4}{3}\mu}{\rho}}$$

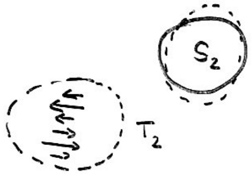
$$v_S = \sqrt{\frac{\mu}{\rho}}$$

k: incompressibility μ: shear modulus ρ: density

Surface waves: Rayligh waves, Love waves

Dispersion
$v(\lambda)$!

Free oscillations: spheroidal, toroidal



Earth: longest mode ${}_0S_2$: 54 min

Period depends on $v_P(r)$, $v_S(r)$, $\rho(r)$!

1.2 Body wave propagation in a spherically symmetric Earth

Continuous variation $v_P(r)$, $v_S(r)$
→ curved ray paths

At discontinuities: Refraction, Reflexion,
Conversion ($P \rightarrow S$, $S \rightarrow P$)

Seismic phases
P, S, K: P-phase in core
PcP: reflected from core
PPP: twice reflected at surface

1.2 ....

- For radial symmetry, the travel time for a phase is only a function of epicentral distance!

- Evidence for core with reduced v_p: „Shadow zone" between $\Delta = 103°$ and $\Delta = 142°$

- No S-waves in (outer) core -> liquid.
- Weak PkIkP-arrivals in shadow zone -> inner core (solid)
- knowledge of $T(\Delta)$ allow determination of epicenter when 3 observations for an earthquake
- inversion of $T(\Delta) \rightarrow v_p(r), v_s(r)$

1.3 Earth structure

Crust	Oceanic	7 km	Basalt	Ca, Al-rich
	Continental	~35 km	(Granite)	SiO_2-rich

Mantle	- 2890 km	Olivine $(Mg_{0.9}Fe_{0.1})_2SiO_4$
Outer core	$r = 3480$ km	Fe (+Ni + light element) Liquid
Inner core	$r = 1220$ km	Fe (+...) solid

Mantle: weak discontinuities at 410, 660 km
solid - solid phase transitions of olivine

Density: not constrained by body waves
-> free oscillations (+ gravity + rotation data)

2. Gravity and rotation

2.1 Description of gravity field

Gravitational potential V

Gravity (acceleration) $\vec{g} = -\text{grad } V$

Point mass: $V = -\frac{GM}{r}$ (also spherically symmetric body)

Ellipsoid: $V = -\frac{GM}{r} \cdot \left(1 + \left(\frac{a}{r}\right)^2 \cdot J_2 \cdot P_2(\cos\vartheta) \ldots\right)$

a: equatorial radius $P_2(\cos\vartheta) = \frac{3}{2}\cos^2\vartheta - \frac{1}{2}$

General: $$V = -\frac{GM}{r}\left(1 + \sum_{\ell=2}^{\infty} \left(\frac{a}{r}\right)^{\ell} \sum_{m=0}^{\ell} P_\ell^m(\cos\vartheta) \times \left(C_\ell^m \cos m\varphi + S_\ell^m \sin m\varphi\right)\right)$$

ϑ: Colatitude φ: Longitude

2.2 Determination of gravity field

- Surface measurements of g (Earth)
- orbits of natural satellites, mutual perturbations of planetary orbits
- orbits of space probes, radio doppler tracking

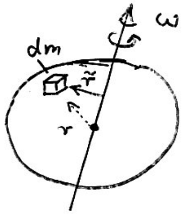
2.3 Moment of inertia and inferences on internal structure

Total mass M -> mean density $\bar{\rho} = \frac{M}{\frac{4\pi}{3} a^3}$

(no clue on internal density stratification)

Mass $M = \int dm$

Moment of inertia $I = \int \tilde{r}^2 dm$



For non-spherical bodies is I a tensor

$\vec{L} = \underline{\underline{I}} \cdot \vec{\omega}$

L : angular momentum
ω : frequency of rotation

3 principal components (preferred axes)

C (largest), B, A (smallest)

Formula of McCullagh :

general $$J_2 = \frac{C - \frac{1}{2}(A+B)}{Ma^2}$$

ellipsoid $$J_2 = \frac{C-A}{Ma^2}$$

wanted : C or C/Ma^2

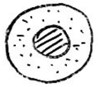
Dynamical ellipticity $H = \frac{C-A}{C}$

Can be uniquely determined from

- Precession data
- Nutation data (body with locked rotation)

$$\Rightarrow \frac{C}{Ma^2} = J_2 / H$$

Moment of inertia factor : Examples

		C/Ma^2
	homogeneous sphere	0.4
	thin hollow spherical shell	0.666..
	core radius $a_k = \frac{a}{2}$, density $\rho_k = 2\rho_M$:	0.347
	$\rho_k = 10\rho_M$	0.241

2.4 Models for terrestrial planets / Jovian satellites

	Earth	Moon	Mercury	Venus	Mars	
$\bar{\rho}$	5515	3341	5430	5245	3935	$\frac{kg}{m^3}$
$\bar{\rho}_{dekompr}$	4060	3315	5280	3990	3730	
C/Ma^2	0.3308	0.390	?	?	0.366	

	Jo	Europa	Ganymede	Callisto	
$\bar{\rho}$	3530	3020	1940	1850	$\frac{kg}{m^3}$
C/Ma^2	0.378	0.347	0.311	0.358	

Typical zero-pressure densities of candidate materials :

Mantle rock :	3300	Fe :	7800
Crustal rock :	2900	FeS :	4900

H_2O (ice) : 920

3. Planetary surfaces (solid planets)
Tour through the solar system

3.1 Moon   R ~ 1740 km ($0.27 \cdot R_E$)

Heavily cratered highlands : primordeal crust
Less cratered maria (mare) : basaltic lava

Crater statistics as indicator for age of planetary surfaces : calibrated in case of the moon (radioactive dating of samples) highlands : 4.3 - 3.8 Ga
maria : 3.8 - 3.3 Ga

elevation (relative to centre of mass) higher on far side -> thicker crust

surface covered by regolith : dust + breccia (shatterd, partly welded rock) -> effect of (micro) meteorite impact

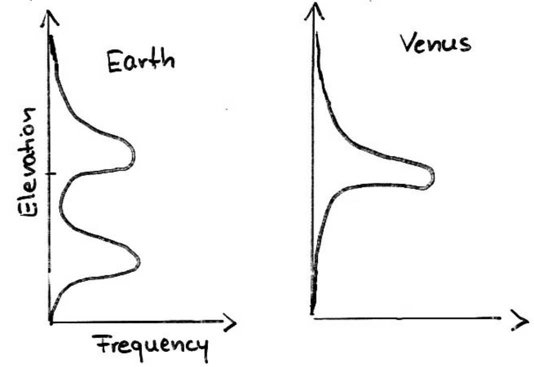
3.2 Mercury   R ~ $0.38 \cdot R_E$

Mariner flyby, half of surface mapped
heavily cratered (moon-like) surface ~ 4 Ga old
(but : high density -> very large core)
weak magnetic field
Rotation period 59 d = 2/3 orbital period
3 : 2 resonance !
(planned mission Bepi Colombo)

3.3 Venus   (R ~ $0.95 \cdot R_E$)

Thick cloud cover -> surface not optically visible
Several soft landings (Venera)
Atmospheric pressure 90 bar, T ~ 450°C
96% CO_2 (traces of H_2O)
Slow rotation (- 243 d, retrograde)

Radar mapping of surface (Magellan)
"Hypsometric curve" :



High-resolution radar images : volcanoes, lava flows, craters. Surface rocks basaltic.

Crater density : intermediate - low -> 500 Ma old surface
uniform ! -> global resurfacing event ?

3.4 Mars $R \sim 0.53 \cdot R_E$

Many probes (orbiter + soft landings)

Thin atmosphere (6 mbar, 95% CO_2) $T \sim -100° - 0°C$

Dust storms

Global topography : southern highlands (old)
northern lowlands (younger)
Tharsis bulge (younger)

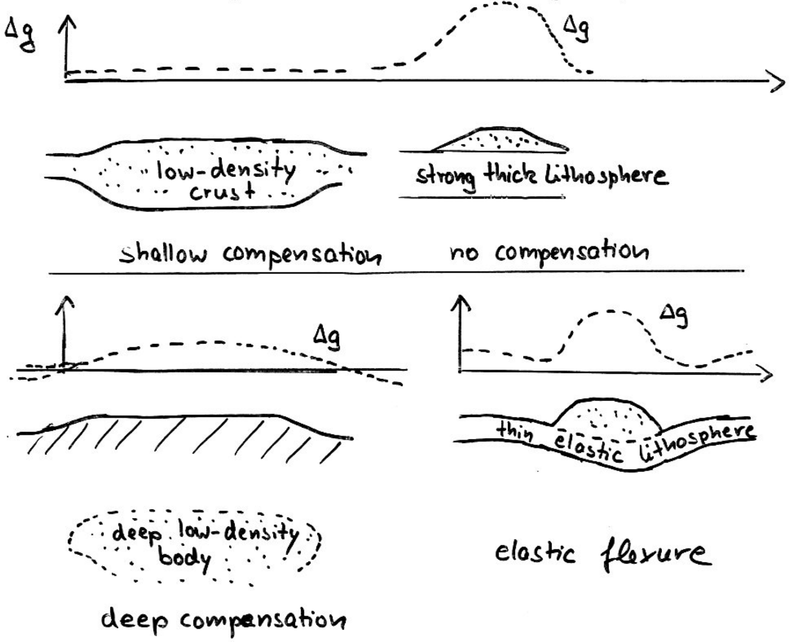
giant volcanoes : Olympus Mons ~ 25 km high
(low gravity + continued magma supply at one spot)

Valles marineris (rift structure)

Water : Polar cap (seasonal cap : CO_2-frost)
Permanent north polar cap : glacier

Running water (or mud) : erosional runoff channels

Gravity combined with topography :



3.5 Galilean satellites

Low density (except Io), Size : ~ Moon - Mercury

Ice (mainly H_2O) from IR-spectra (except Io)

3.5.1 Callisto : dark, heavily cratered

partly differentiated : Ice mantle, undifferentiated core ?

3.5.2 Ganymede : darker + brighter regions

Thick ice mantle, silicate + (probably) iron core

Some tectonic activity (old)

3.5.3 Europa : bright, very few craters

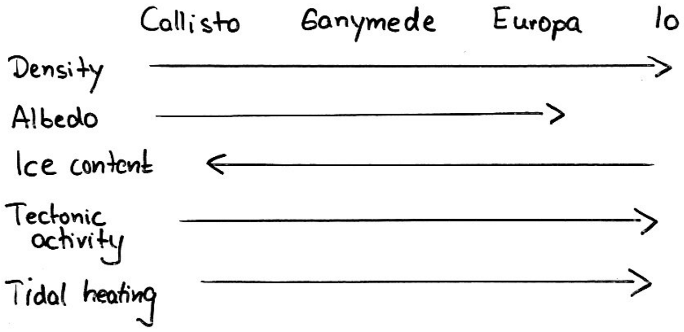
Large silicate + iron core, ~ 150 km
thick ice shell, rafted blocks of ice
→ liquid water ocean ?

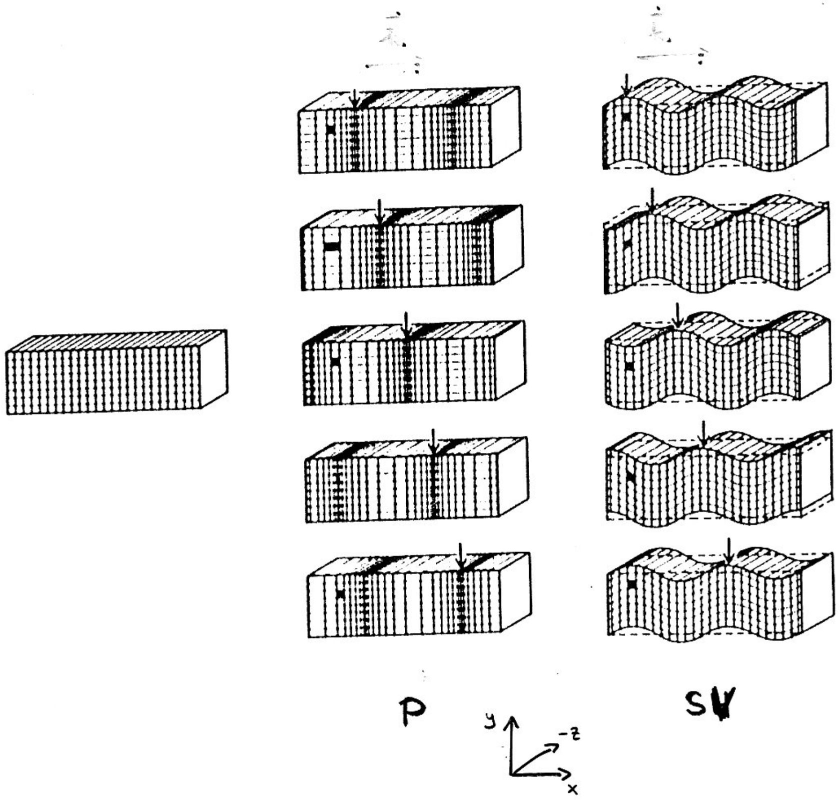
3.5.4 Io : No ice ! No craters !

Silicate mantle, iron core.

Silicic volcanism (+ S, SO_2-eruptions)
Most volcanically active body in solar system.

"Little planetary system"




P
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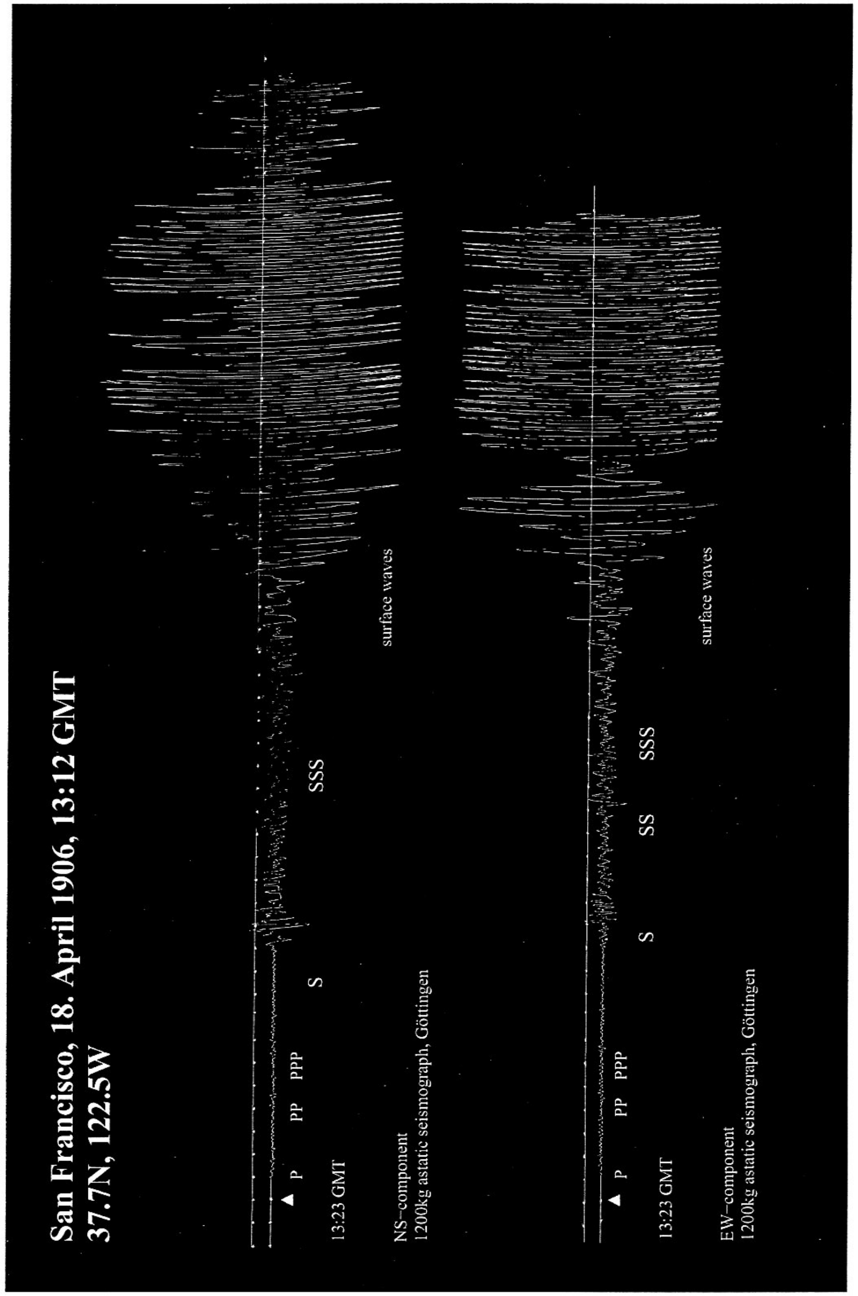
San Francisco, 18. April 1906, 13:12 GMT
37.7N, 122.5W
P
PP
PPP
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surface waves
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NS–component
1200kg astatic seismograph, Göttingen
P
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SSS
surface waves
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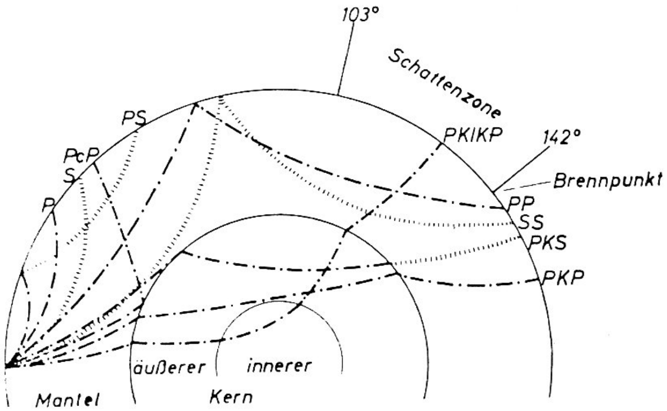
EW–component
1200kg astatic seismograph, Göttingen



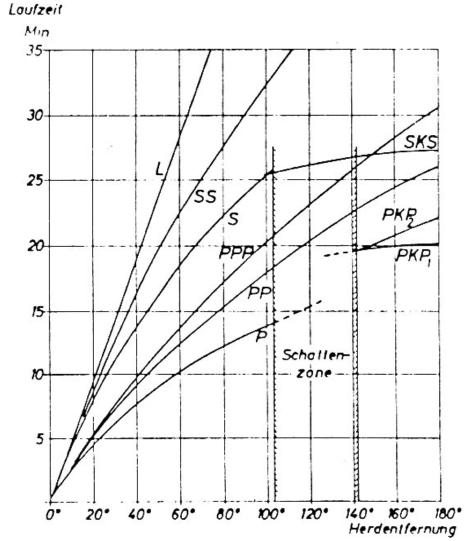
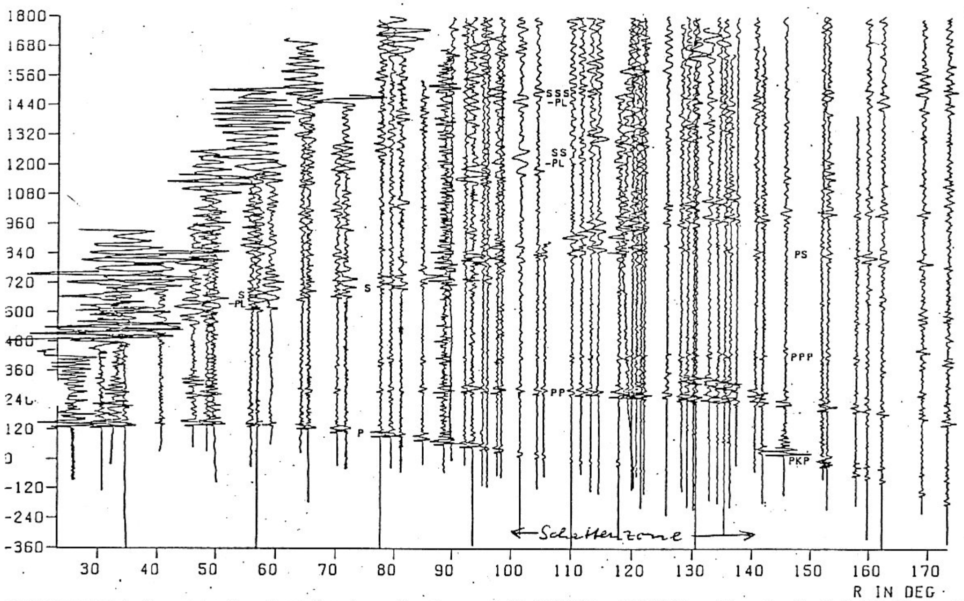


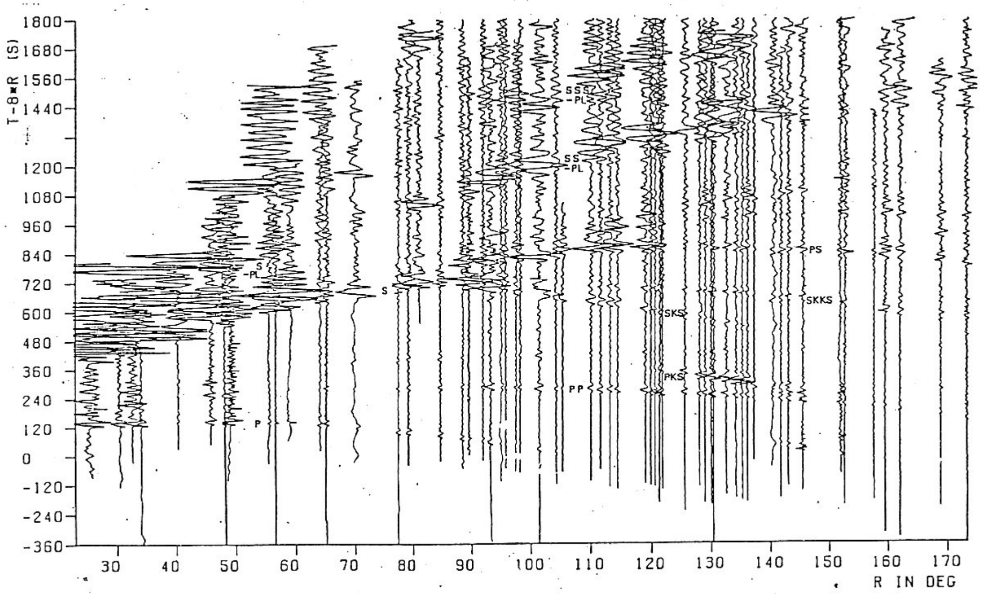
Fig. 18 Vereinfachte Laufzeitkurve für Erdbeben mit normaler Herdtiefe.

4*

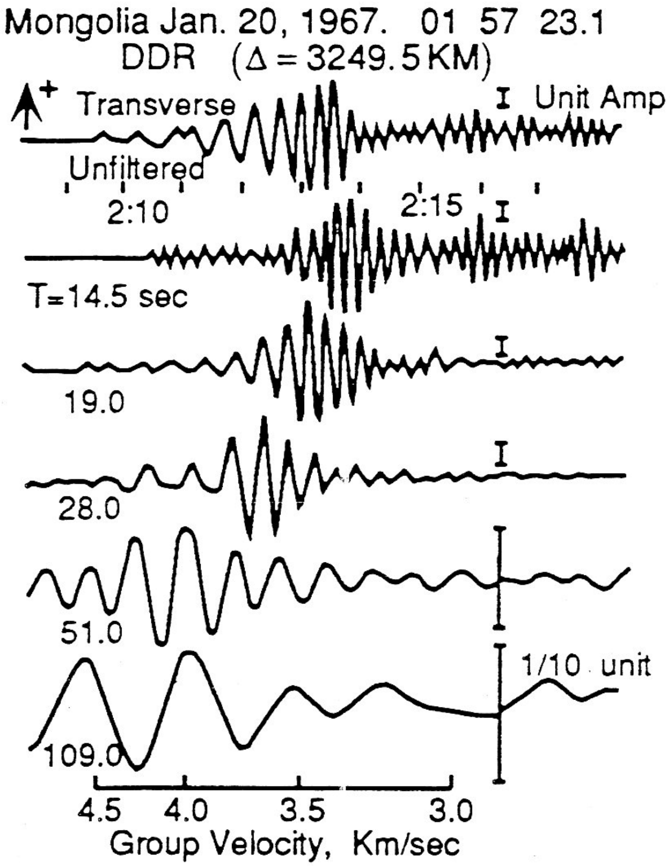
Seismische Raumwellenphasen :



Vertical component seismogram section of an earthquake near Sumatra, recorded by WWNSS and CSN stations. Upward motion to the left. The amplitud scales of all traces are the same. See text for more details.



2. Radial component seismogram section of the same earthquake. Motion towards the epicentre to the left. Amplitude scale is the same as in Fig. 1.



Love wave dispersion
Lay & Wallace, 1995
p. 143

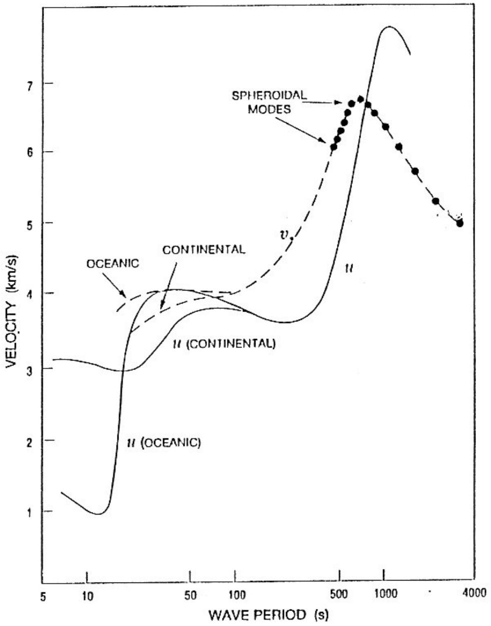


Figure 5.3(a). Fundamental mode Rayleigh wave dispersion. Group velocity, u, is shown by a solid line and inferred phase velocity, v, by a broken line, with the dispersion curve from free oscillation periods above 400s. Figure based on Oliver (1962).

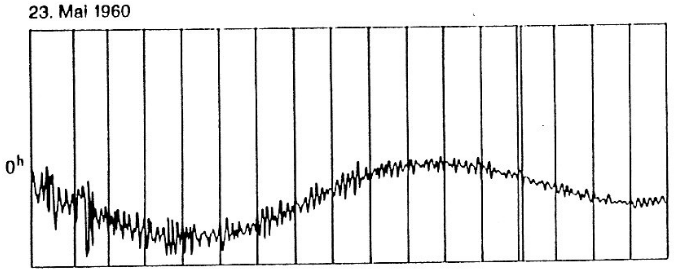


Abb. 5.45 Aufzeichnung des Ausschwingens der Erde nach dem großen Chile-Beben 1960. Die Schwingungen reiten auf der Gezeitenbewegung mit etwa halbtägiger Periodizität. Linienabstand 1 Stunde (nach Bolt 1982).

Blatt 8:

Oben: Dispersionskurven für Rayleighwellen. u: Gruppengeschwindigkeit, v: Phasengeschwindigkeit (Stacey)
Unten: Registrierung von Eigenschwingungen der Erde (Berckhemer)

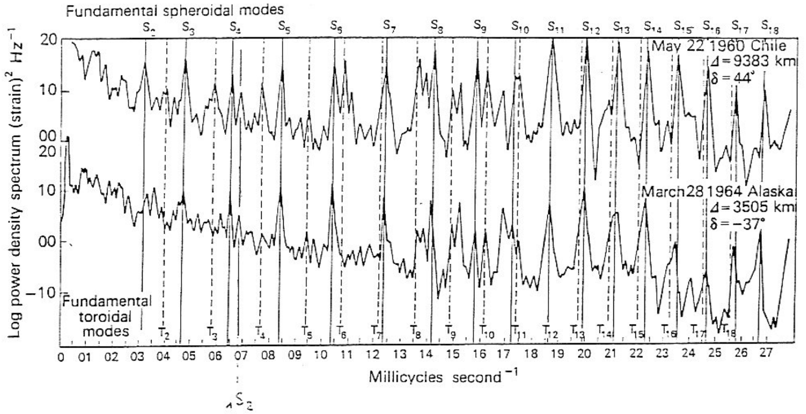


Fig. 4.9 Power spectral density of the Alaskan and Chilean earthquakes recorded on a strain seismometer at Isabella, California. The angle δ is the deviation of the great circle path from the axis of the strain seismometer. Redrawn from SMITH (1966), *J. geophys. Res.*, **71**, 1187.

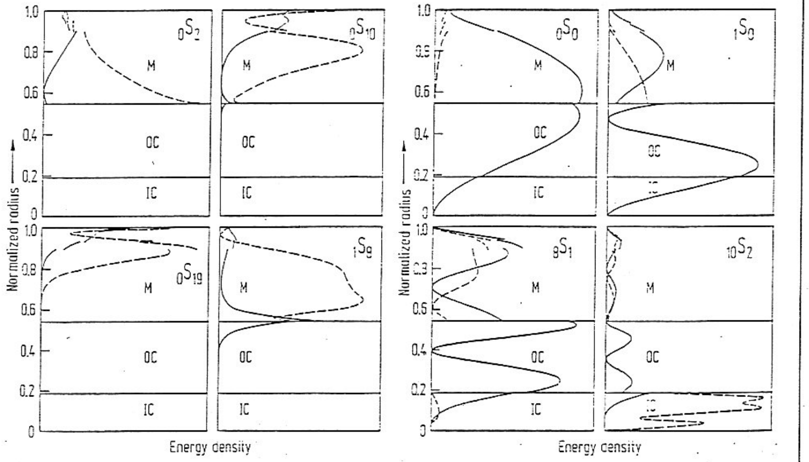
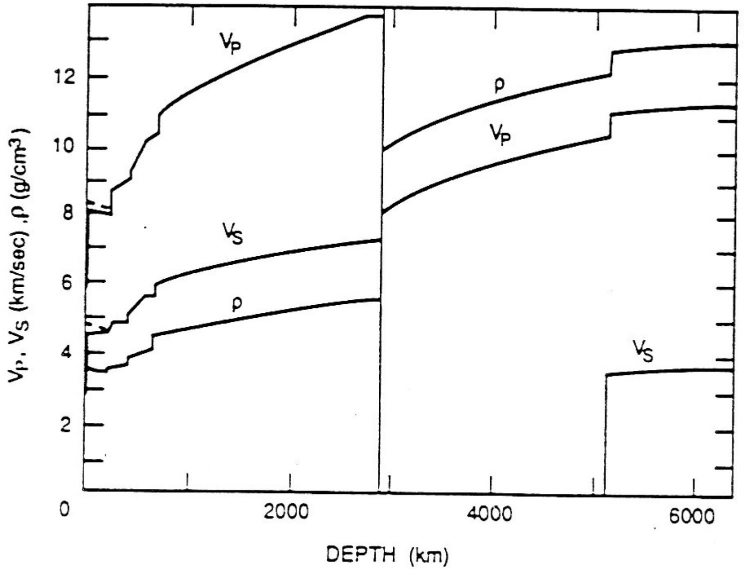
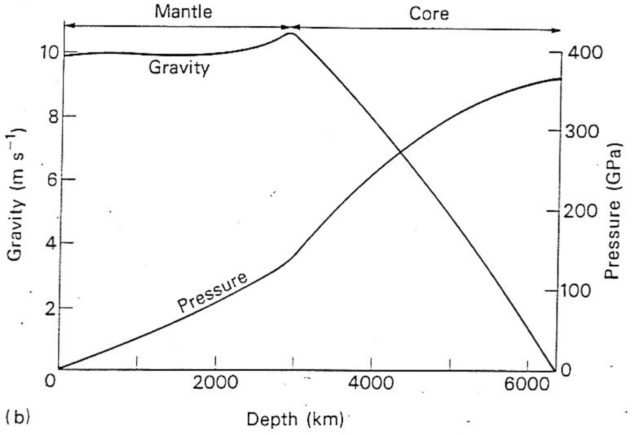


Fig. 15. Plots of compressional energy density (solid line) and shear energy density (broken line) as functions of normalized radius for modes ${}_0S_2$, ${}_0S_{10}$, ${}_0S_{19}$, ${}_1S_8$, ${}_0S_0$, ${}_1S_0$, ${}_8S_1$ and ${}_{10}S_2$ [80G]. The core-mantle boundary and the boundary between outer and inner core are indicated by solid horizontal lines. Energy densities are in relative units. (IC = inner core, OC = outer core, M = mantle.)

7 *Earth models*



7.2. PREM model: Seismic velocities and density profile (after Dziewonski and Anderson 1981).



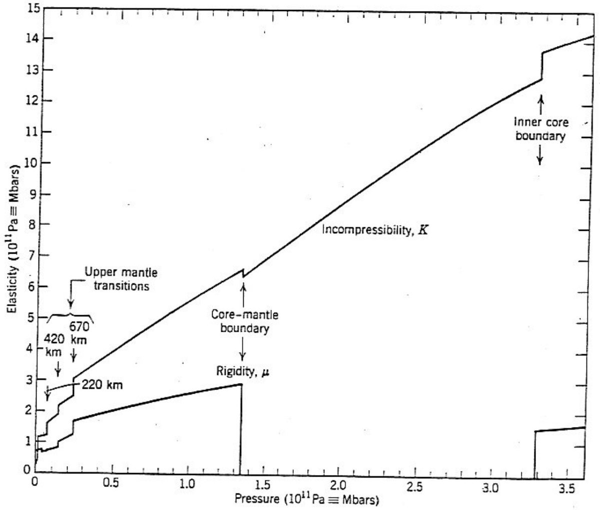
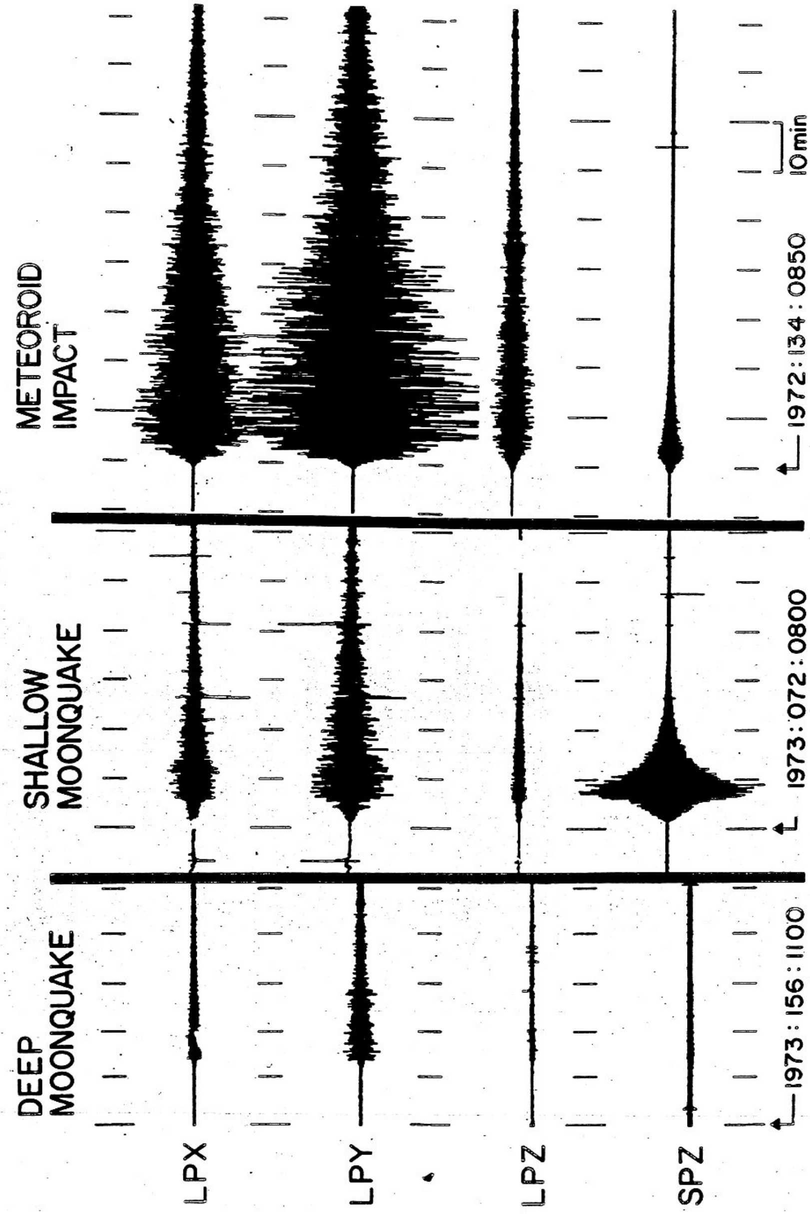
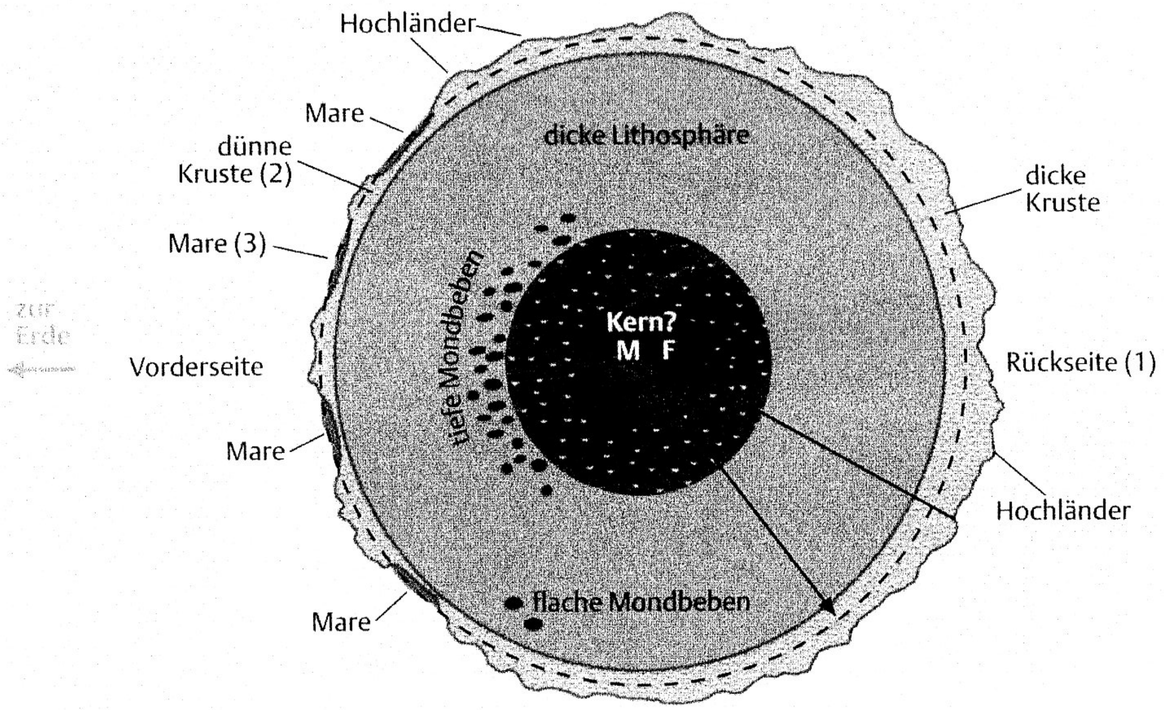


Figure 6.18. Variations of elastic constants with pressure in the interior of the Earth (model data by Dziewonski et al. 1975—Appendix G).





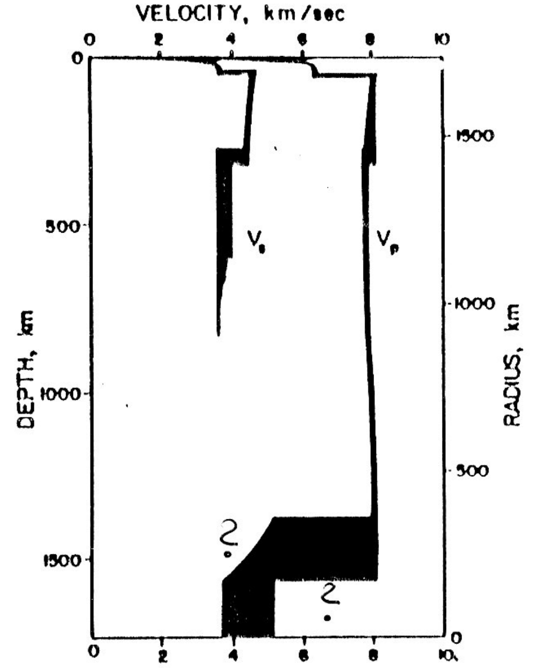


Fig. 3. Seismic velocity profiles of the lunar interior.

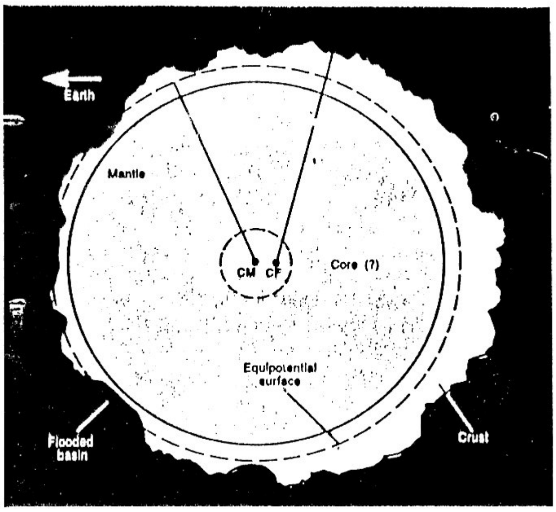
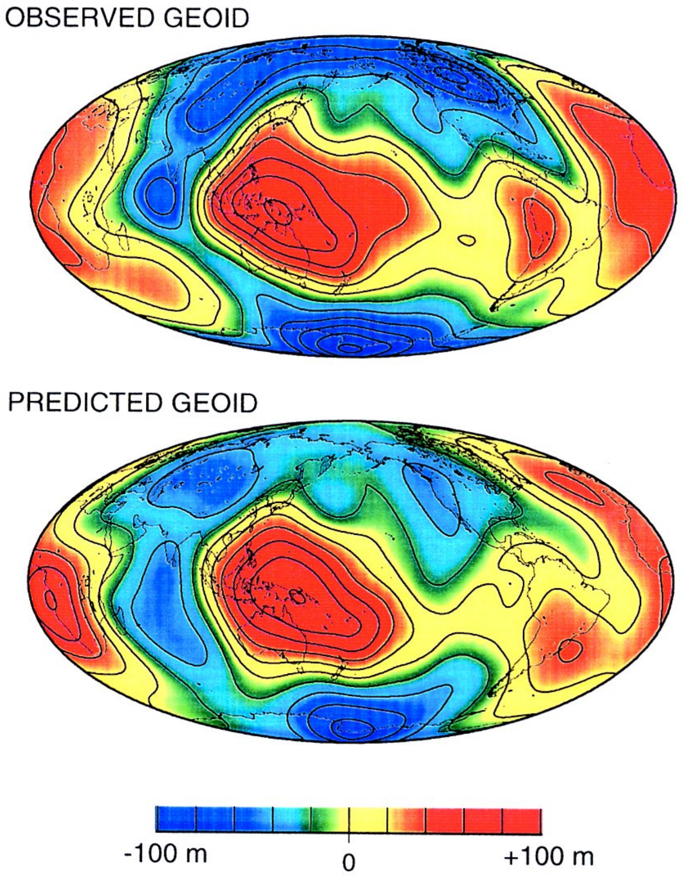
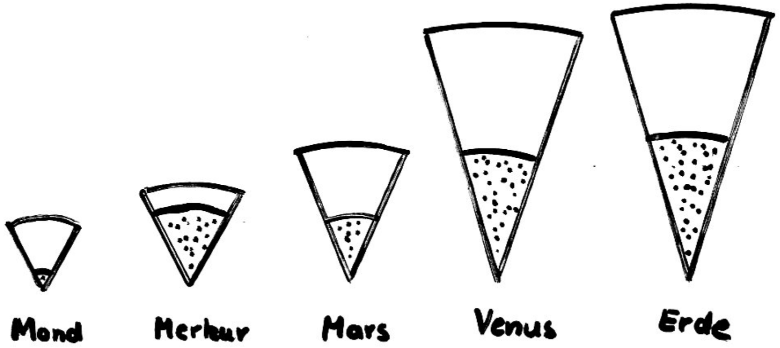


Figure 11. A schematic cross section of the lunar interior, which may or may not include a small metallic-iron core. The Moon's center of mass (*CM*) is offset by 2 km from its center of figure (*CF*), so an *equipotential surface* (which experiences an equal gravitational force at all points) lies closer to the lunar surface on the hemisphere facing Earth. Therefore, magmas originating at equipotential depths will have greater difficulty reaching the surface on the farside.





Relative Größe des Kerns

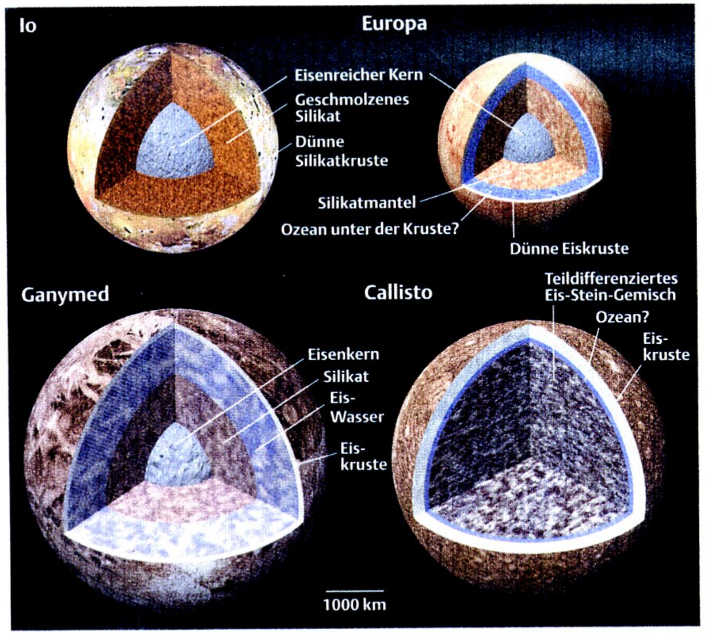
	Radius	Volumen	Masse	Kern: S/(Fe+S)
Erde	0.55	0.165	0.32	
Venus	0.53	0.14	0.29	
Mars	0.41	0.07	0.15	0
	0.50	0.125	0.22	0.15
	0.60	0.21	0.30	0.34
Merkur	0.80	0.50	0.70	
Mond	$\lesssim 0.25$	$\lesssim 0.02$	$\lesssim 0.05$	

Mantel

Fe/(Mg+Fe)

$\approx 0.25 - 0.30$

$\rho_0 \approx 3.5\ g/cm^3$


Io
Europa
Eisenreicher Kern
Geschmolzenes Silikat
Dünne Silikatkruste
Silikatmantel
Ozean unter der Kruste?
Dünne Eiskruste
Ganymed
Callisto
Teildifferenziertes Eis-Stein-Gemisch
Ozean?
Eis-kruste
Eisenkern
Silikat
Eis-Wasser
Eis-kruste
1000 km