Seismic Sources

- Earthquake sources
  - Faults
  - Moment tensor and magnitudes
- Controlled sources in seismic exploration
  - Requirements
  - Principles
  - Onshore, offshore

- Reading:
  - Shearer, 9.1-9.3
  - Telford *et al*., Section 4.5

Sources of seismic energy

- Natural (earthquakes)
  - Mostly shear-wave ("double-couple")
  - Result from sudden slipping of blocks of rock along faults ("stress release")
- Artificial (used in seismic exploration)
  - Mostly *P*-wave (pressure)
  - Produced by explosives or various kinds of mechanical impacts

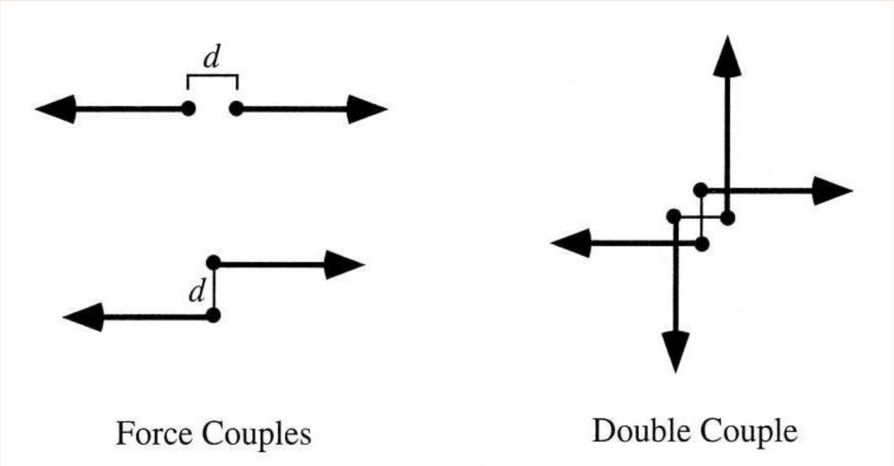
Basic idea about earthquake source

- Generally, a force **f** applied at point $\mathbf{x}_0$ causes displacement **u** that is proportional to the force:

$$u_i(x,t) = G_{ij}(x,t;x_0,t_0)\, f_j(x_0,t_0)$$

"Green's function"

- A single point force could only be applied from the outside;
- An *internal* source would have to conserve the momentum and angular momentum, and thus it cannot exist alone
- Seismic source forces always exist in mutually compensated *force couples:*



Earthquake faults

- In terms of slip motion, faults are identified as predominantly “strike-slip” (horizontal motion) and “dip-slip” (vertical-motion) faults

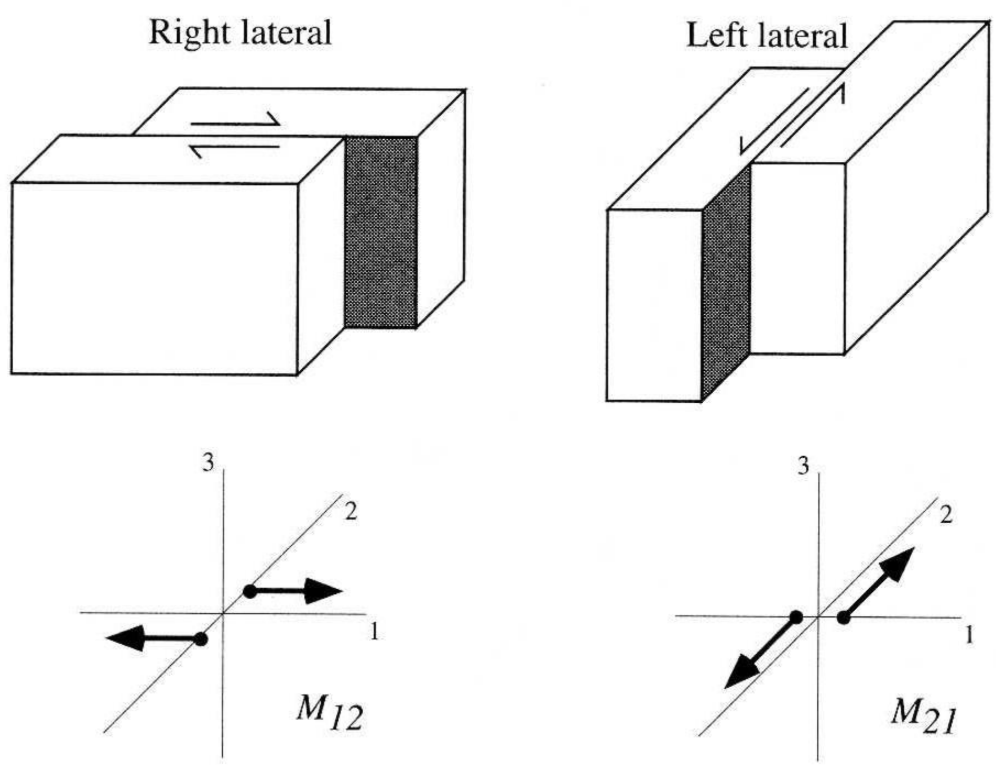


Fig. 9.4. Owing to the symmetry of the moment tensor, these right-lateral and left-lateral faults have the same moment tensor represention and the same seismic radiation pattern.

Double-couple

- Displacement and seismic wave fields produced by a slip on a fault are equivalent to those caused by orthogonal pressure and tension:

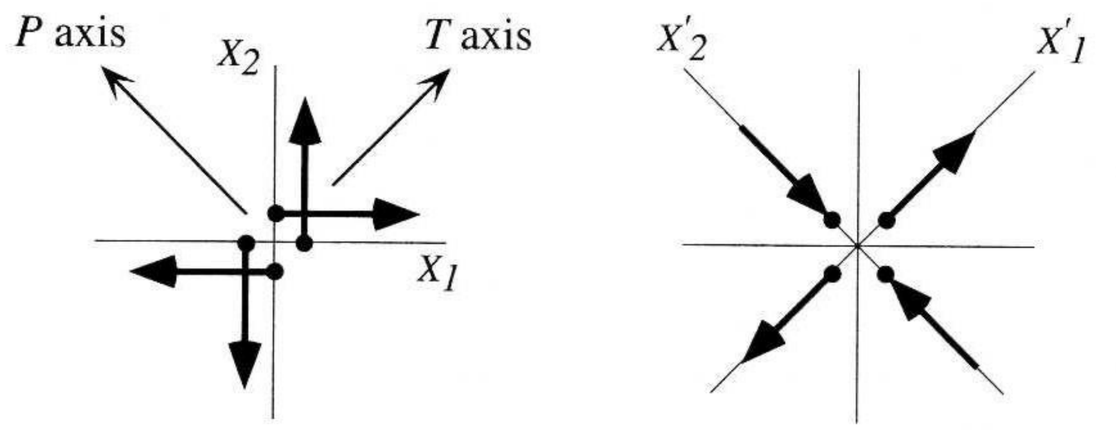
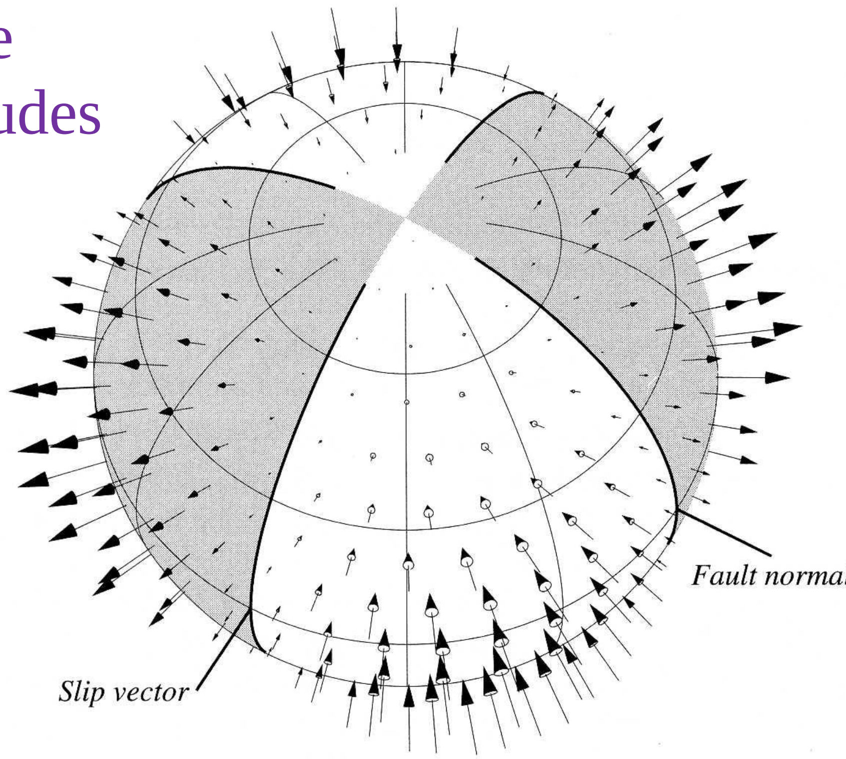


Fig. 9.5. The douple-couple pair on the left is represented by the off-diagonal terms in the moment tensor, M_{12} and M_{21}. By rotating the coordinate system to align with the P and T axes, the moment tensor in the new coordinate system is diagonal with opposing M_{11} and M_{22} terms.

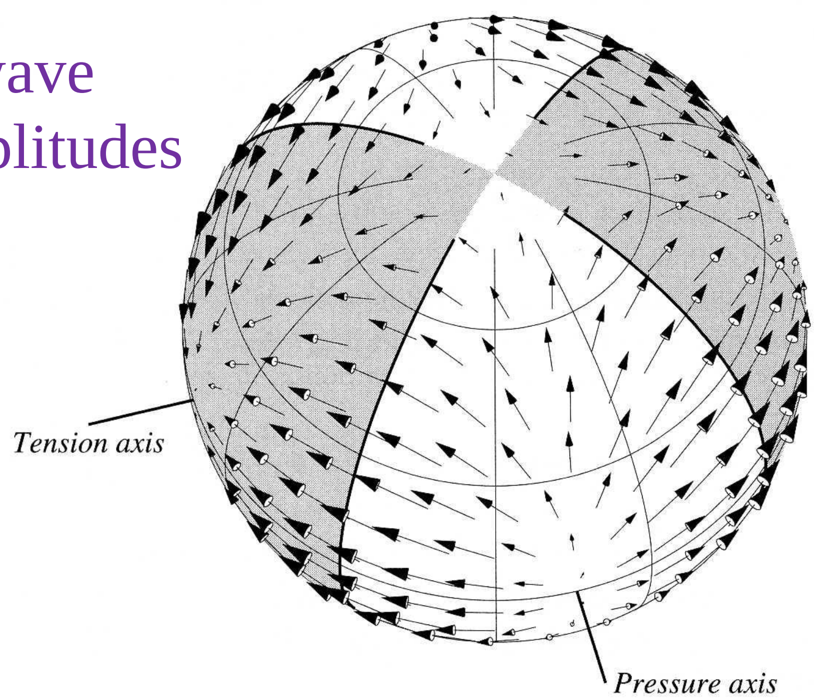
Radiation patterns

("earthquake beach balls")

P-wave amplitudes



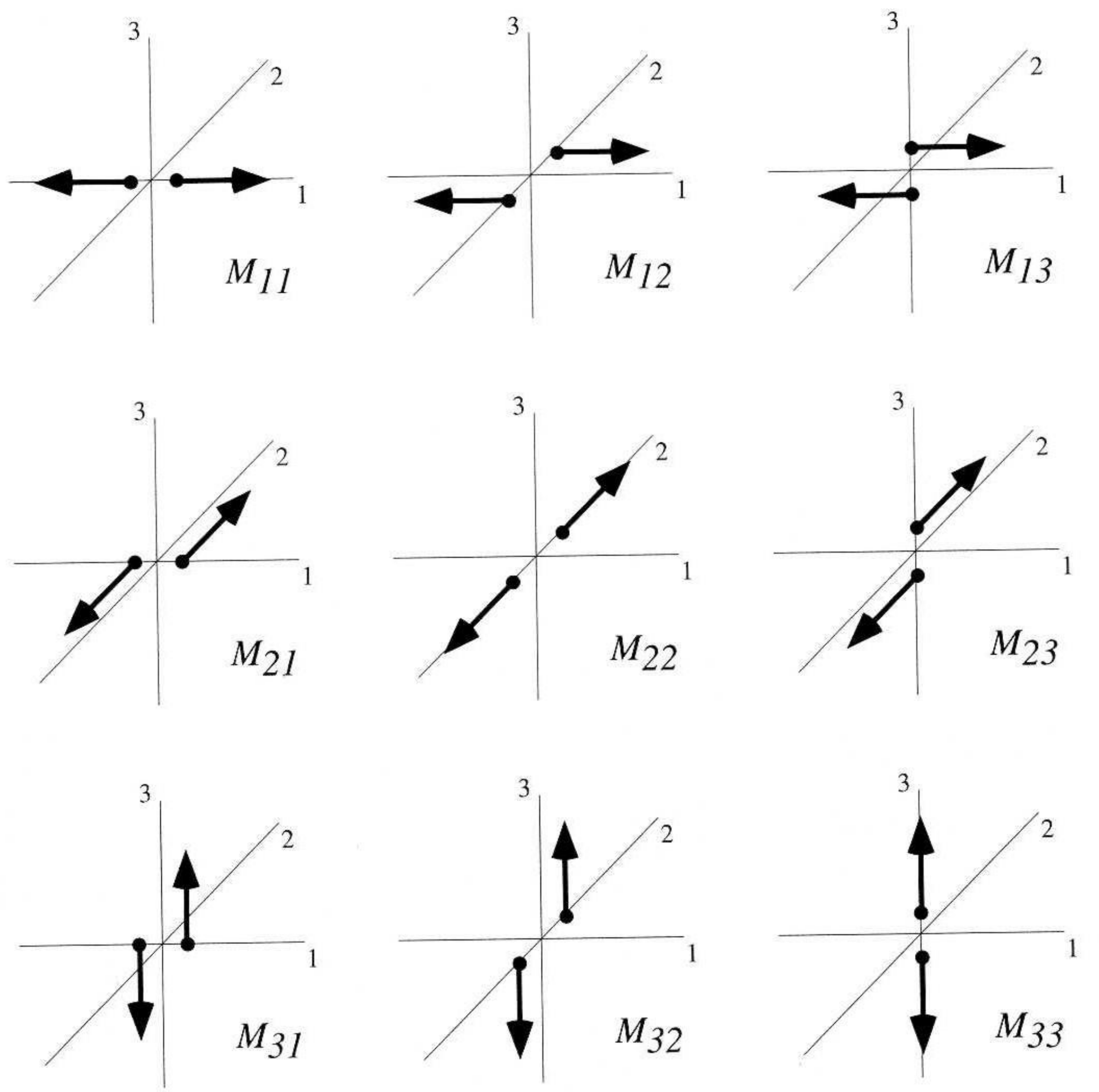
S-wave amplitudes



Moment tensor

- Nine different possible force couples form the source *moment tensor* M_{ij}:

In each of these plots, $f = M_{ij}d$



Seismic Moment

- For a right-lateral movement on a vertical fault oriented along the *x* direction, the moment tensor is:

$$\mathbf{M} = \begin{bmatrix} 0 & M_0 & 0 \\ M_0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

where the *scalar seismic moment*:

$$M_0 = \mu D A$$

(μ is the shear modulus of rock, D – fault displacement, and A – slip area)

- M_0 measures the energy release and is related to seismic magnitude

Earthquake classification

- Based on “magnitude” numbers

Magnitude	Type	Effect	Frequency
< 2.0	Micro	Not felt	~8,000/day
2.0 - 2.9	Minor	Recorded, not felt	~1,000/day
3.0 - 3.9		Felt, damage rare	50,000/year
4.0 - 4.9	Light	Noticeable shaking; no significant damage	6,200/year
5.0 - 5.9	Moderate	Damages poor buildings in local areas	800/year
6.0 - 6.9	Strong	Can be destructive over ~100 miles in populated areas	120/year
7.0 - 7.9	Major	Serious damage over large areas	18/year
8.0 - 8.9	Great	Serious damage over several hundred miles	1/year
9.0 - 9.9		Devastating in ~1000 miles across	1 per 20 years
10.0+	Massive	Planetwide (never recorded)	Unknown

Seismic Magnitude
Richter scale

- The Richter scale ("local magnitude") measures the combined horizontal displacement on "Wood-Anderson torsion" seismometer

$$M_L = \log_{10} \frac{A_{\text{shaking}}}{A_0(\Delta)}$$

Empirical correction for distance from the source, Δ

- The energy release scales with the power of 3/2 of A_{shaking}
  - Thus, a difference of 1.0 in magnitude scale M_L corresponds to a factor $10^{3/2} \approx 31.6$ in energy

Seismic Magnitude

"Moment Magnitude" scale (M_w)

- From 1970's, supersedes the Richter scale
- Reflects real physical parameters of earthquake source
- Based on the seismic moment M_0 above in dyne·cm (10^{-7} N·cm):

$$M_W = \frac{2}{3}\log_{10} M_0 - 10.7$$

- As with the Richter scale, an increase of 1.0 in M_W corresponds to $10^{3/2} \approx 31.6$ times increase in energy
- Earthquake energy in Joules:

$$E = 10^{9+1.5M_w}$$

Controlled Source in Seismic Exploration

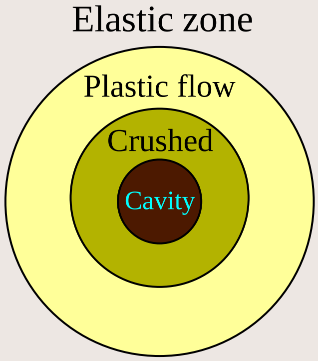
- Localized region within which a sudden increase in elastic energy leads to rapid stressing of the surrounding medium.
- Most seismic sources preferentially generate *P*-waves
    - Easier to generate (pressure pulse);
    - Easier to record and process (earlier, more impulsive arrivals).
- Requirements
    - Broadest possible frequency spectrum;
    - Sufficient energy;
    - Repeatability;
    - Safety - environmental and personnel;
    - Minimal cost;
    - Minimal coherent (source-induced) noise.

Land Source

- Explosives – chemical base
  - Steep pressure pulse.
  - Shotguns, rifles, blasting caps;
  - …bombs dropped from aircraft, nuclear blasts…
- Surface (mechanical)
  - Weight drop, hammer;
  - Piezoelectric borehole sources (ultrasound);
- Continuous signal
  - Vibroseis (continuously varying frequency, 10-300 Hz)
  - Mini-Sosie (multiple impact);
    - Combination with Vibroseis (Swept Impact Seismic Technique, SIST)
  - Drill bit ('Seismic While Drilling’);
  - sparkers, ...truck spark plugs.

Mechanism of generation of seismic waves by explosion

- **Stage 1**: Detonation.
  - Start of explosion - electric pulse ignites the *blasting cap* placed inside the charge. The pulse is also transmitted to recorder to set $t = 0$;
  - Disturbance propagates at ~ 6-7 km/s (supersonic velocity); surrounding medium is unaffected;
  - The explosive becomes hot gas of the same density as the solid - hence its pressure is very high (several GPa)
- **Stage 2**: Pressure pulse spreads out spherically as an *inelastic shock wave*
  - Stresses >> material strength;
  - Extensive cracking in the vicinity of the charge.
- **Stage 3**: At some distance, the stress equals the elastic limit
  - Pressure pulse keeps spreading out spherically as an *elastic wave*.



Important parameters of an explosion

- Radius of the cavity created by explosion:

$$R[ft] = BW^{1/3}$$

Weight in lbs

Rock type	*Granite*	*Chalk*	*Limestone*	*Soft Sandstone*	*Clay*
B	0.46	0.6	0.3-1.0	1.3	1.3

- Pulse width: $T[ms] = 2.8 \cdot W^{1/3}$
  - Frequency *decreases* for larger charges.
- Energy:
  - Only 4 % (soft sandstone), 9% (clay) to 10-20 % (granite) of chemical energy is radiated as seismic waves;
  - Absorption and scattering cause energy loss:
    - At 3 m from the source, there remains 2.5 % of available energy;
    - At 30 m - 0.5 %.
- Effects of shot depth:
  - If water table is shallow - place shots below it;
  - Seismic amplitude increases as the shot depth decreases
    - However, ground roll becomes broadband and hard to attenuate.

Criteria for selecting seismic explosives

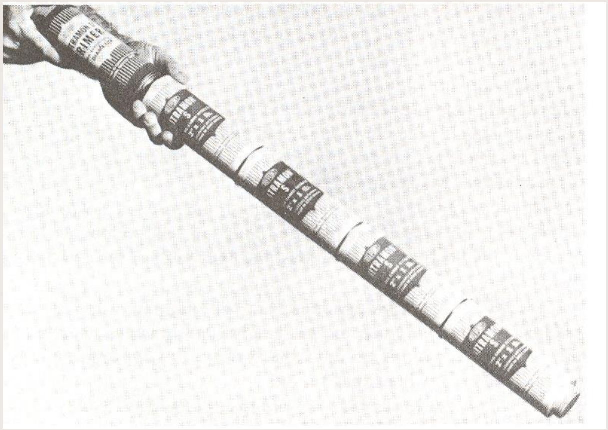
- **Density**
  - Higher density means the explosive column length is shortened, resulting in an energy pulse of higher frequency. Higher frequency means better data quality.
    Typical values are 1.2-1.8 g/cc
- **Velocity**
  - Higher velocity means a higher frequency energy pulse will be generated because the explosive column detonates more quickly.
    Typical values are 6-8 km/sec
- **Detonation pressure**
  - Detonation pressure is an indication of energy released by the detonation. High detonation pressure is beneficial in seismic blasting.
    Typical range - 2-4 GPa (70-250 kBar)
- **Self-disarming**
  - Unexploded charges left in the ground could be hazardous to future drilling or excavation. Seismic explosives that self-disarm are the best choice

Standard for minimum distances from seismic sources

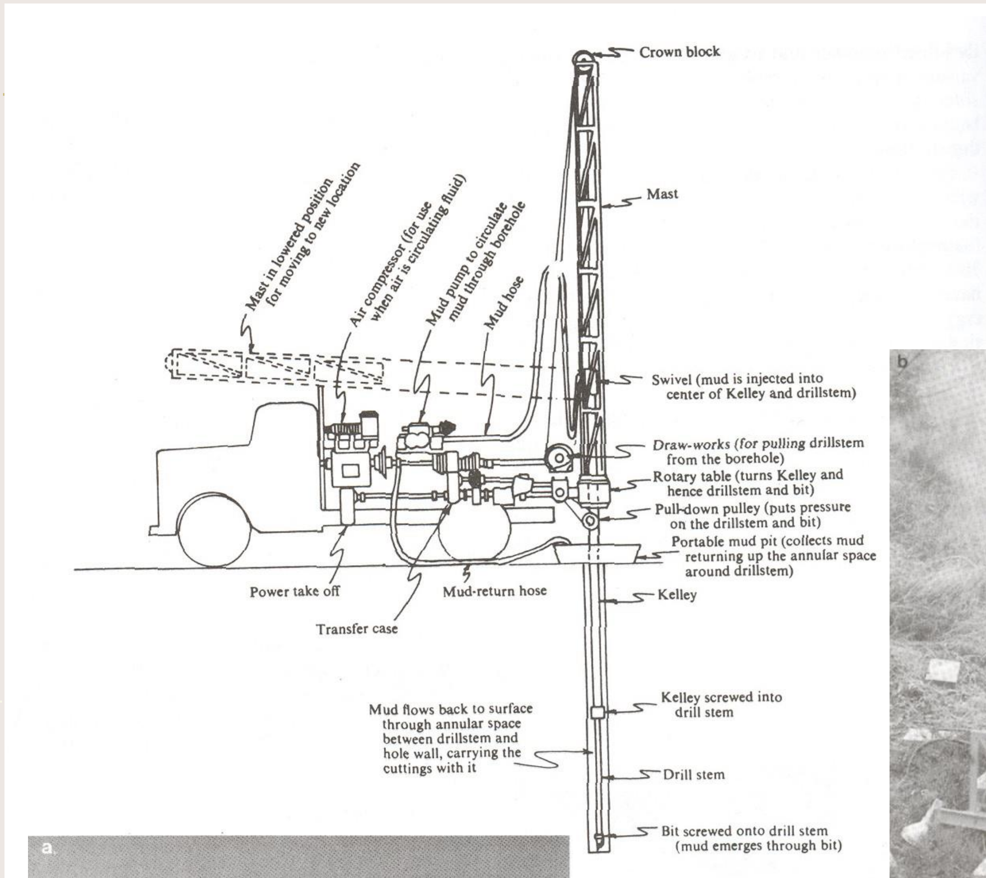
- International
  Association of Geophysical Contractors:
  - Pipelines - 60 m;
  - Telephone lines - 12 m;
  - Railroad tracks - 30 m;
  - Electric lines - 24 m;
  - Oil wells - 60 m;
  - Water wells, cisterns, masonry buildings - 90 m.
- Ground velocity of 5 cm/s is considered 'safe' for structures
  - For seismic explosives, achieved at distances $x = 23m^{1/3}$ m, where m is the charge in kg

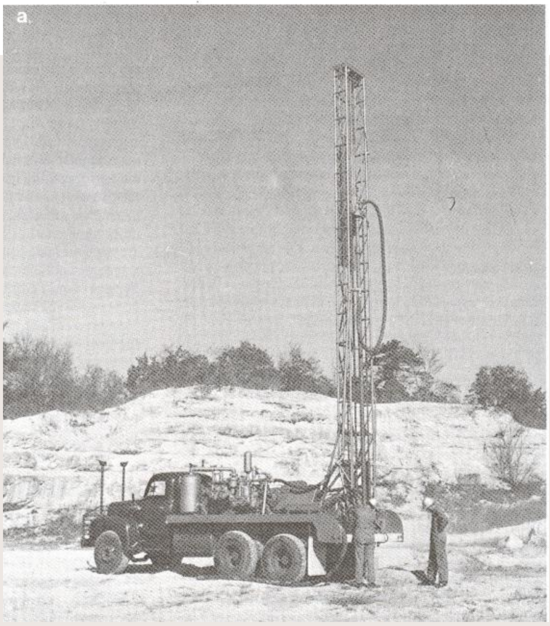
Explosive materials

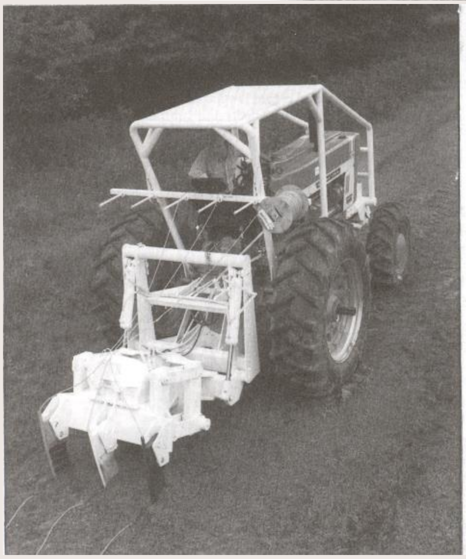
- Gelatin dynamite, ammonium nitrate, pentolite (SEIS-X)
- Packaged in tins, cardboard or plastic tubes ~5 cm in diameter (0.5-5 kg each)
- Connected to make desired charges
- Activated by an electrical detonator (“blasting cap”



Charge emplacement







Surface Energy Sources
(less powerful, easier access)

- Thumper/weight dropper

Bison Accelerated Weight Dropper

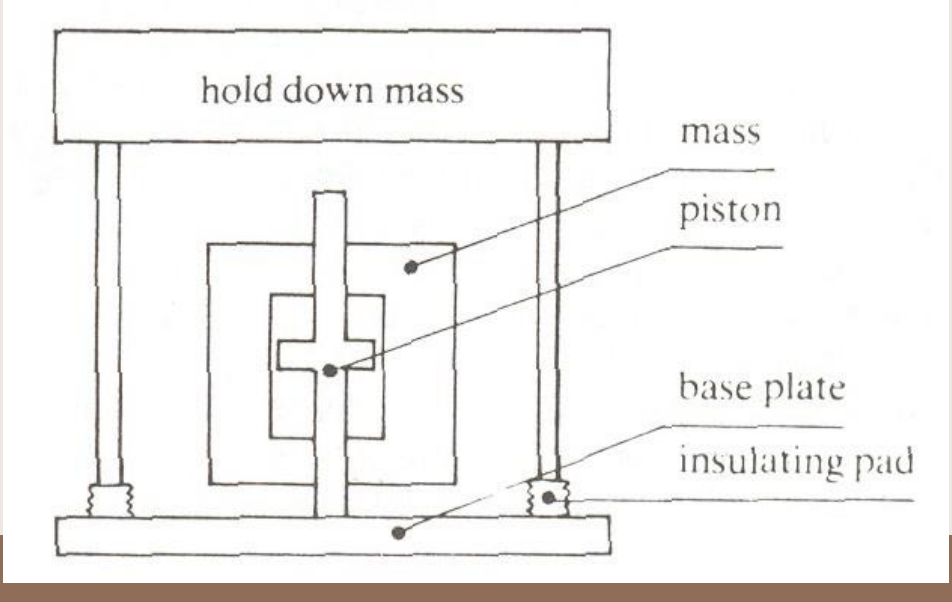
DIGPULSE 1180

- Dynoseis
  - Mixture of O_2 and propane exploded in an expandable chamber with a metal plate as the bottom
  - Mounted on a truck or used as a buried explosive charge
  - Self-disarming (the metal plate rusts through and the gas dissolves)

Vibroseis

Used in > ½ of land seismic exploration

- Vibroseis
  - Energy introduced into the Earth in the form of a *sweep* of varying frequency for several seconds
    - Typical sweep time - 7-35 s;
      - ~45 minutes in recent mantle investigations
    - Typical frequencies - 12 -> 60 Hz (upsweep) or 60 -> 12 Hz (downsweep);
    - Low energy density - environmentally friendly;
    - Time-Distributed signal - lower noise requirements.
  - A control signal causes a vibrator to exert variable pressure on a steel plate pressed against the Earth.
    - Radio-controlled hydraulics allows *syn-phase* vibration of a *group* of vibrators;
    - Shear-wave vibrators also shake the ground in horizontal directions

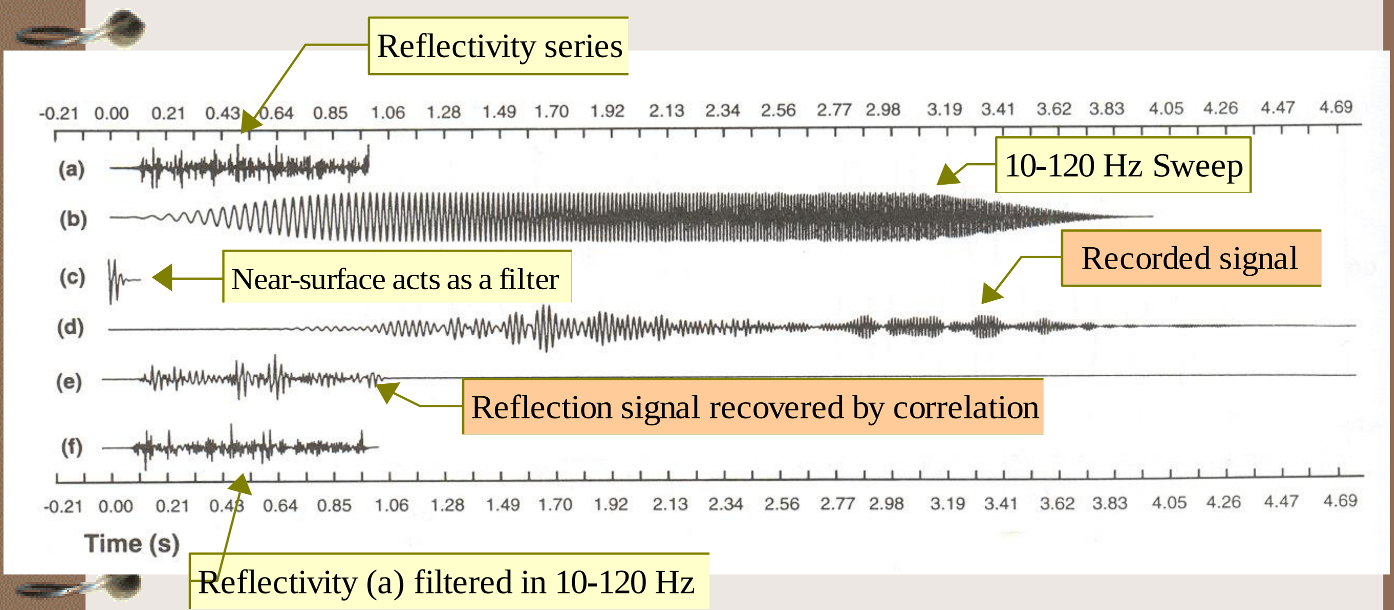


Vibroseis

Mini-Vibroseis
(for shallow work)

Vibroseis Correlation

- Recorded signal is *cross-correlated* with the *sweep* sent into the ground
  - As a result, matching waveform patterns (caused by reflections) are identified;
  - The signal is compressed in time - the energy of the entire sweep is condensed into a single pulse.



Other Land Sources
(for shallow or in-mine work)

- Sosie, Mini-Sosie, SIST
  - Impactor hits ground 5-15 times per second, in ~3-min long, *pseudo-random* series

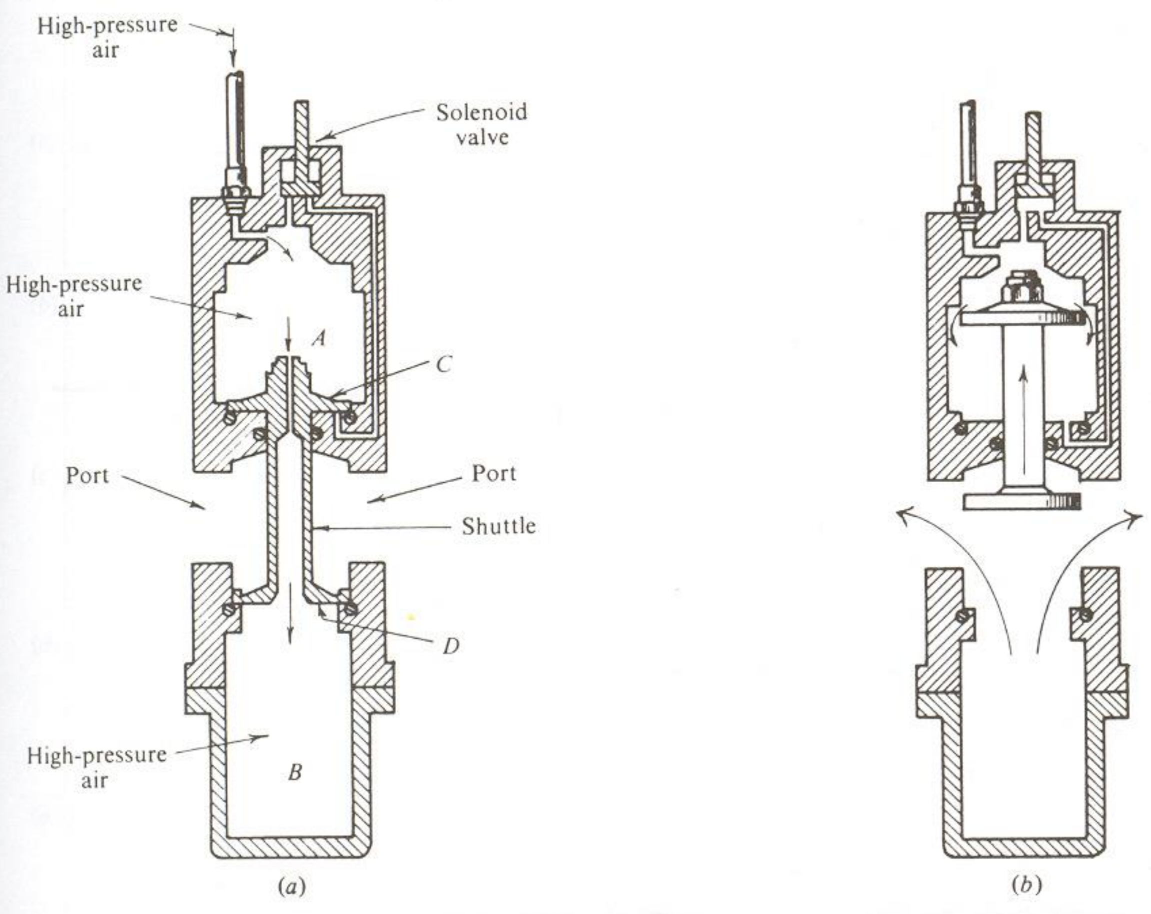



- Sparkers

Air Gun

Primary marine source

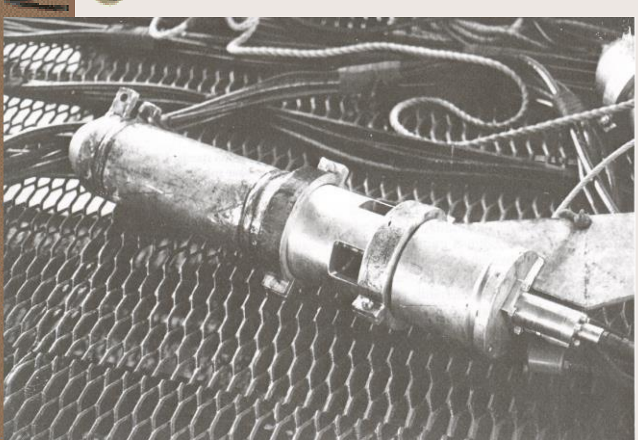
- High pressure bubble of air is released into the water
  - Operating pressure 10-15 MPa, in 1-4 ms;
  - Size (volume of the lower chamber) 10-2000 in^3 (0.16-33 liters)
  - Primary pulse is followed by a *surface ghost* and a train of *bubble pulses*

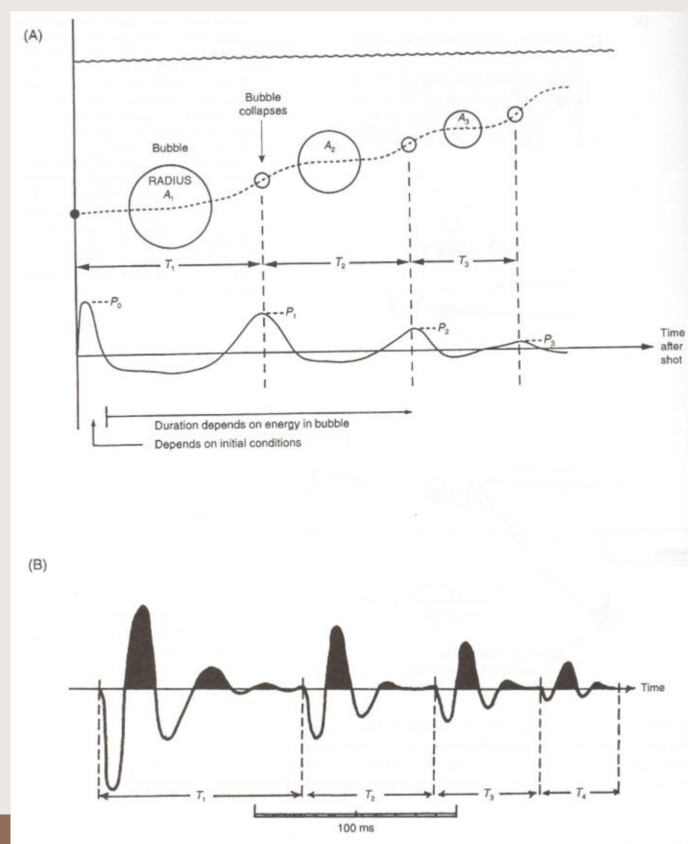


Air Gun

Bubble oscillations

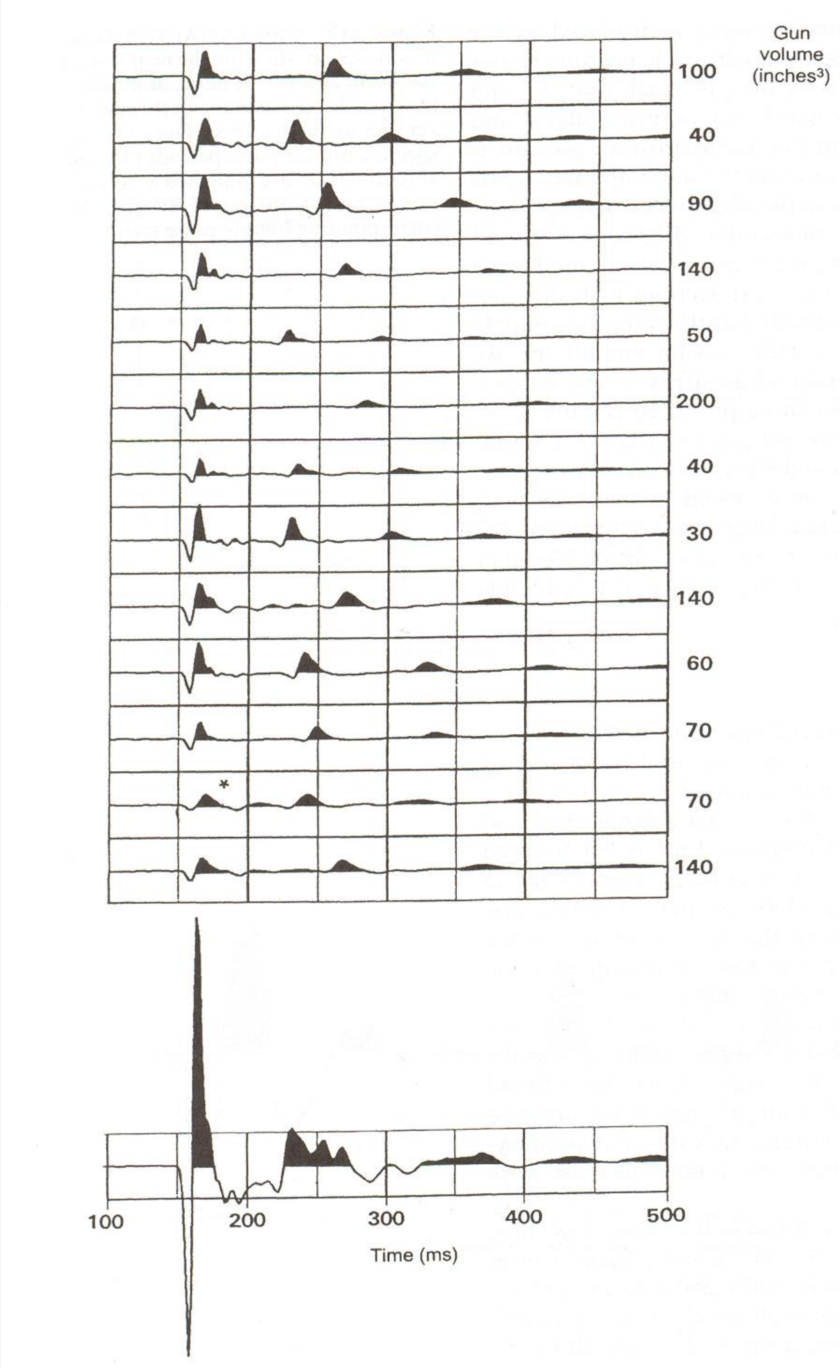
- Over-pressured bubble expands expelling water radially
  - ... and becomes.. under-pressured;
- Under-pressured bubble collapses under water pressure
  - ... and becomes over-pressured again.
- This cycle is repeated until the energy dissipates and/or bubble vents into through the surface.





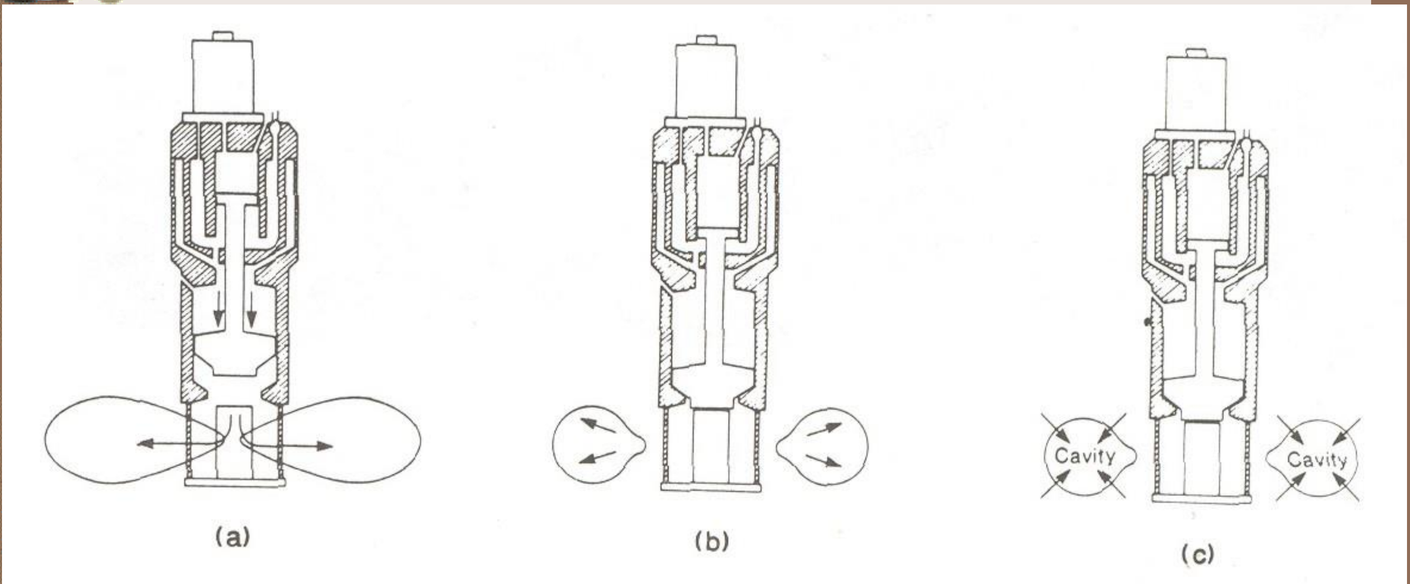
Suppression of bubble pulses

- Bubble pulses can be suppressed in two ways:
  - Use array of air guns with different dimensions;
  - Shallow firing (~2 m) - bubble vents to the surface
- During digital processing, the wavelet is further compressed by using *deconvolution*



Other Marine Sources

- Water gun
  - Compressed air drives a piston that ejects a jet into the surrounding water;
  - Vacuum cavity created behind the jet causes an implosion generating a strong pulse.
  - No bubble pulse.



- Piezoelectric transducers
  - *e.g.*, barium titanate - change their volume when subjected to electric field;
  - Up to 2-10 kHz frequency for shallow water work