Engineering Seismology and Seismic Hazard – 2019

Lecture 14

Measuring Earthquake Size

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Size Measure Types

There are basically two methods to quantify the earthquake size:

1) Maximum Intensity

- Outdated method based on damage description and human ground shaking perception
- Very subjective, not based on actual seismic recordings
- Still very used to quantify the size of historical (pre-instrumental) earthquakes

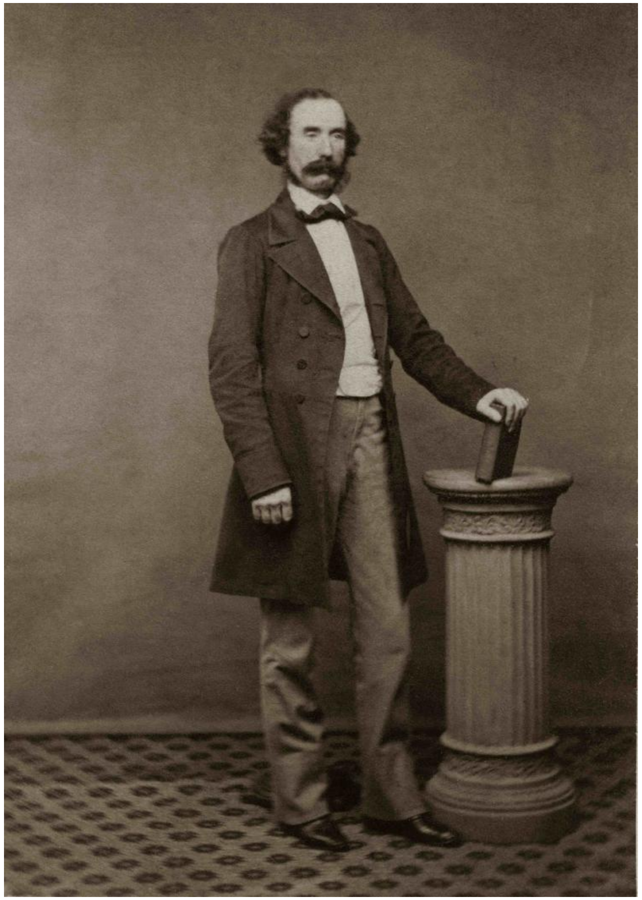
2) Magnitude

- Modern method based on measurable earthquake parameters
- Objective and reproducible
- Drawback: many variants, subject to various limitations and of not easy comparison

Macroseismic Intensity

Macroseismic intensity concept was introduced by Robert Mallet by studying the great earthquake occurred in Southern Italy in 1857.

He related the intensity of the earthquake to the human perceptions of the felt ground motion and the observed distribution of damage on buildings and territory.



In this way, the maximum (observed) intensity I_0, often called **epicentral intensity**, gives an rough estimate of the size of the earthquake.

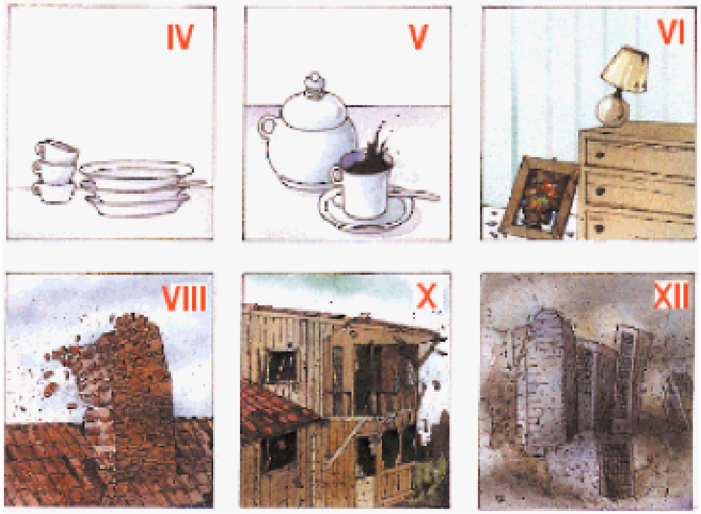
Macroseismic Scales

1. Mercalli – Cancani – Seiberg (MCS): 12 – level scale used in southern Europe;
2. Modified Mercalli (MM): 12 – level scale proposed in 1931 by Wood and Neumann, who adapted the MCS scale to the California data set. It is used in North America and several other countries;
3. Medvedev – Sponheuer – Karnik (MSK): 12 – level scale developed in Central and Eastern Europe and used in several other countries;
4. European Macroseismic Scale (EMS): 12 – level scale adopted since 1998 in Europe. It is a development of the MM scale;
5. Japanese Meteorological Agency (JMA): 7 – level scale used in Japan. It has been revised over the years and has recently been correlated to maximum horizontal acceleration of the ground.

Mercalli Scale

TABLE 13-1 Modified Mercalli Intensity Scale

Intensity Level	Description
I	Not felt.
II	Felt only by a few people at rest. Suspended objects may swing.
III	Felt noticeably indoors. Many people do not recognize it as an earthquake. Parked cars may rock slightly.
IV	Felt indoors by many, outdoors by few. Dishes, windows, doors rattle. Parked cars rock noticeably.
V	Felt by most; many awakened. Some dishes, windows broken. Unstable objects overturned.
VI	Felt by all. Some heavy furniture moves. Damage slight.
VII	Slight to moderate damage in well-built structures; considerable damage in poorly built structures; some chimneys broken.
VIII	Considerable damage in well-built structures. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls.
IX	Damage great in well-built structures, with partial collapse. Buildings shifted off foundations.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed. Rails bent.
XI	Few if any masonry structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Damage total. Lines of sight and level are distorted. Objects thrown into the air.

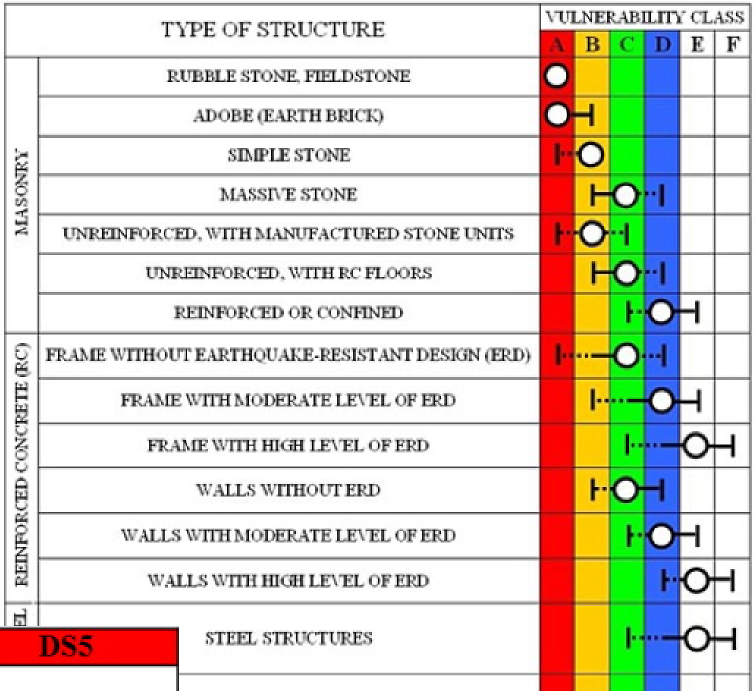


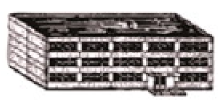
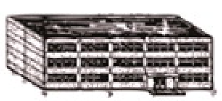
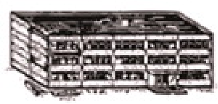
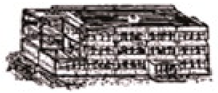
Giuseppe Mercalli

Subjective damage evaluation because of its qualitative nature, related to population density, familiarity with earthquake and type of constructions.

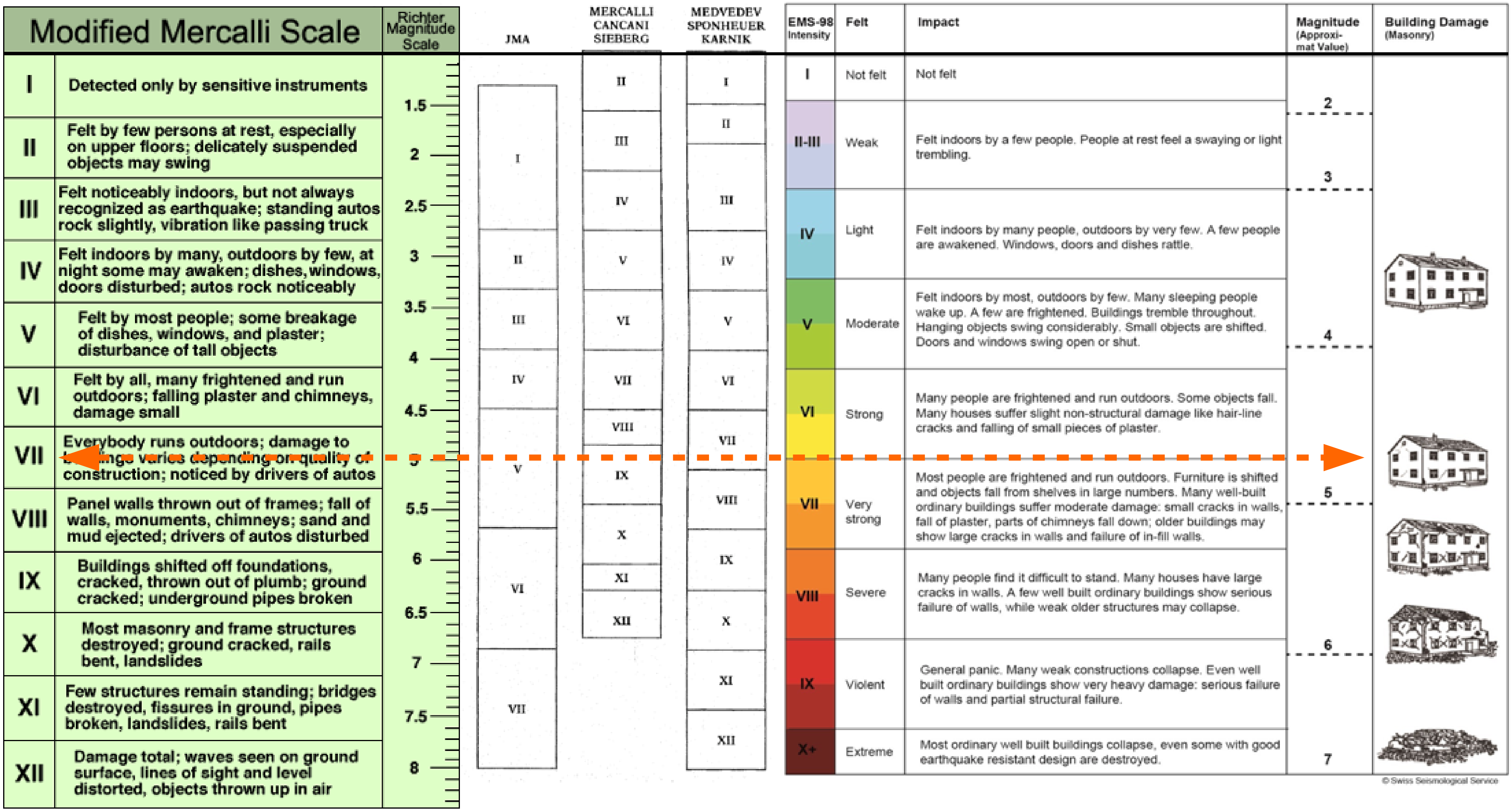
Improvements of the EMS98

Scaling to building category and vulnerability type



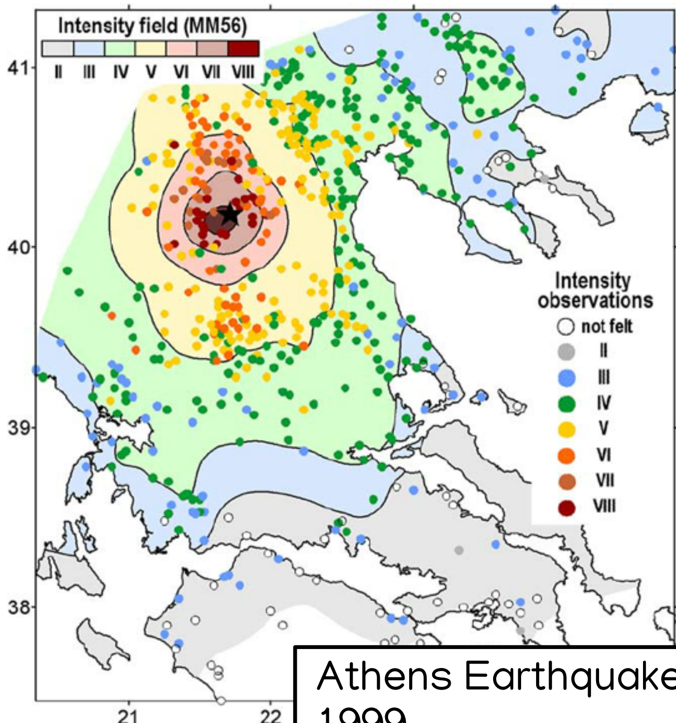
DS1	DS2	DS3	DS4	DS5
				
Grade 1: Negligible to slight damage *(no structural damage, slight non-structural damage)*	**Grade 2: Moderate damage** *(slight structural damage, moderate non-structural damage)*	**Grade 3: Substantial to heavy damage** *(moderate structural damage, heavy non-structural damage)*	**Grade 4: Very heavy damage** *(heavy structural damage, very heavy non-structural damage)*	**Grade 5: Destruction** *(very heavy structural damage)*
Fine cracks in plaster over frame members or in walls at the base. Fine cracks in partitions and infills	Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling mortar from the joints of wall panels	Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of concrete cover, buckling of reinforced rods. Large cracks in partition and infill walls, failure of individual infill panels	Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor	Collapse of ground floor or parts (e. g. wings) of buildings
$\min\left(\Delta^{inf}_{cr}\,;\,\Delta^{RC}_{cr}\right)$	$\min\left(\Delta^{inf}_{max}\,;\,\Delta^{RC}_{y}\right)$	$\min\begin{pmatrix}\Delta^{inf}_{ult}\,;\,\Delta^{RC}_{spalling}\,; \\ \Delta^{RC}_{buckling}\end{pmatrix}$	Δ^{RC}_{ult}	Δ^{RC}_{coll}

Head to Head Scales



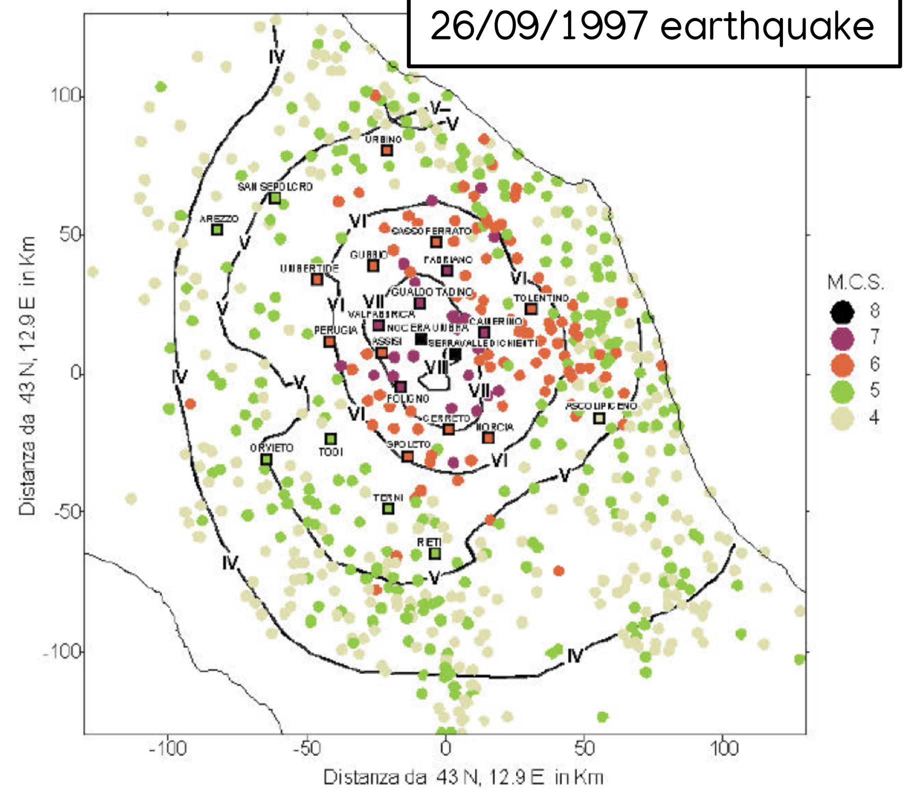
Isoseismals & Contour Maps

By tracing lines on maps joining the points in which the intensity was similar (isolines, isoseismals, isointensity line), it is possible to determine the centre on the shaking (called macroseismic centre), which is characterized by the highest damage and corresponds to a small area.



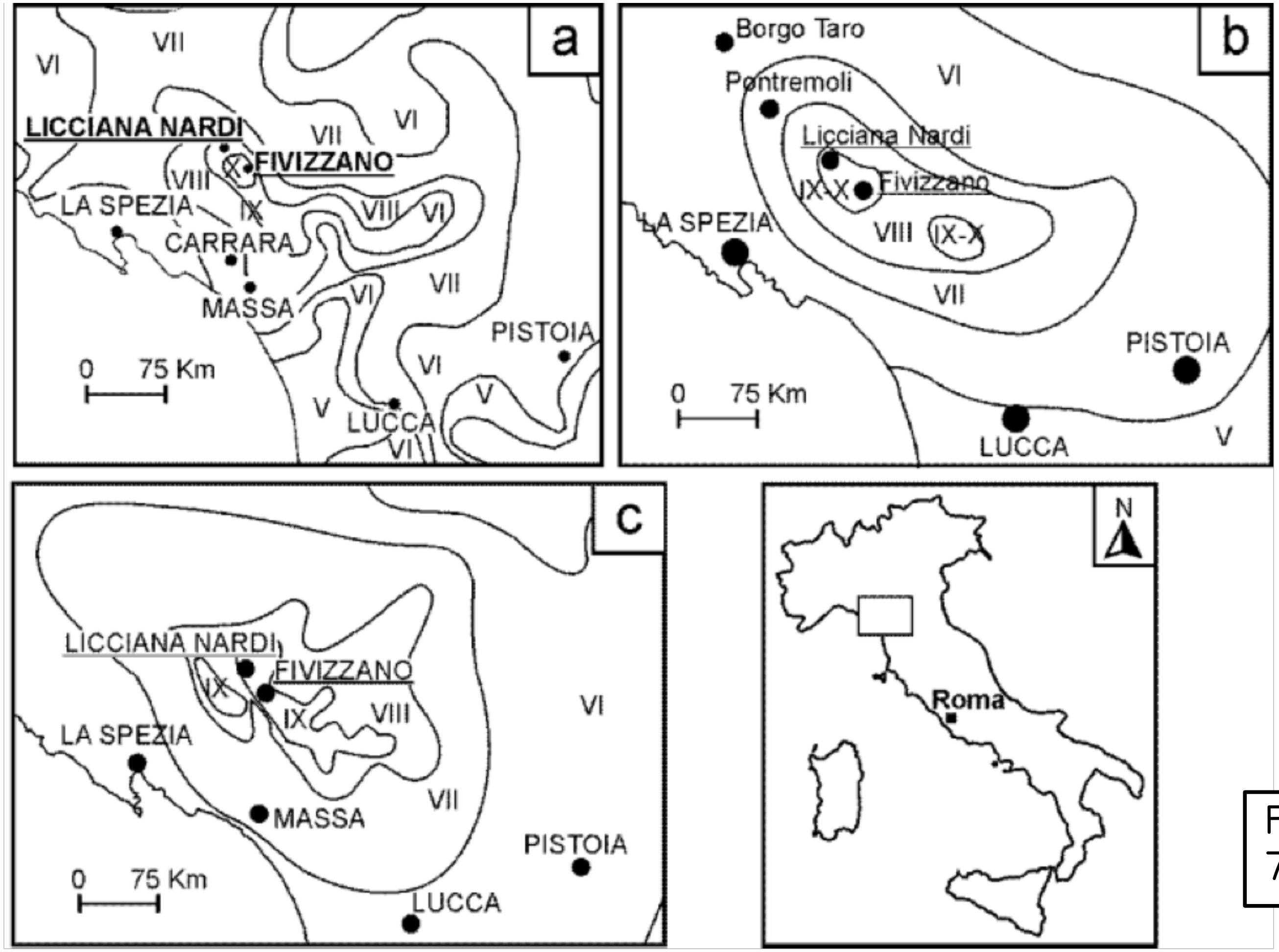
Athens Earthquake 1999

Umbria-Marche 26/09/1997 earthquake



Uncertainty and Subjectivity

Tracing of isoseismals is highly subjective. Given the same damage description, intensity maps from different analysts can be very different.

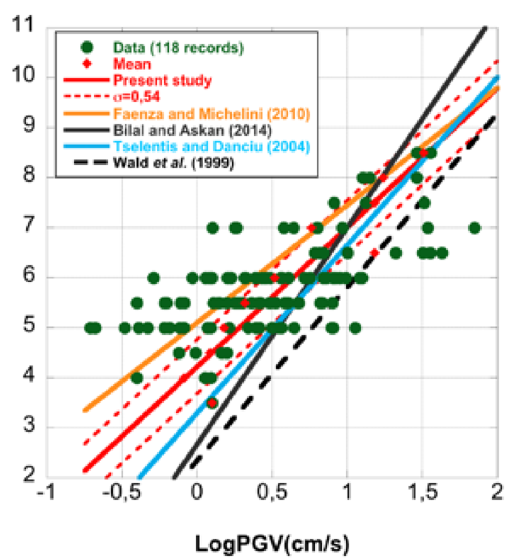


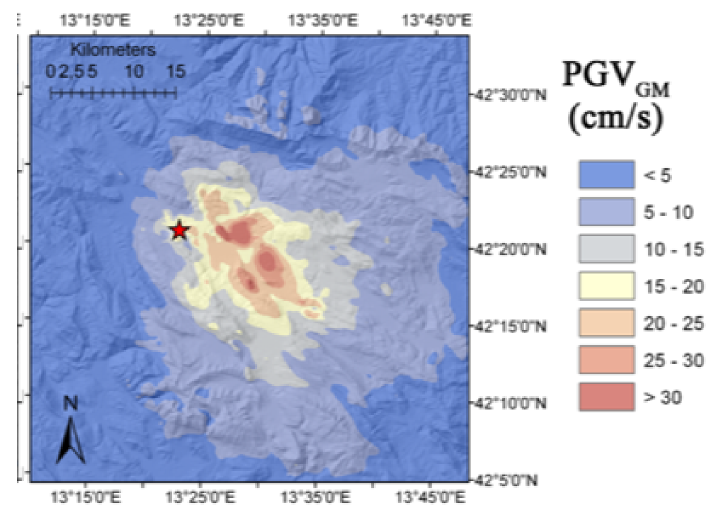
Fivizzano (MS) ,
7/9/1920 earthquake

Historical Earthquakes

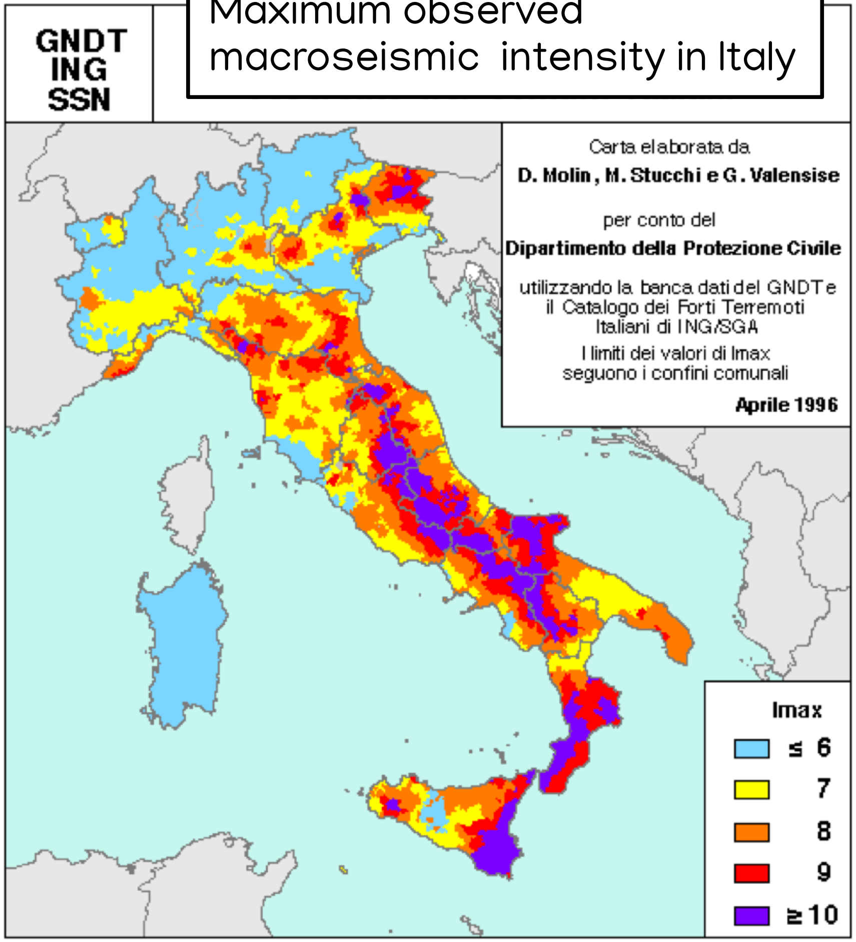
Links past with the future: Intensity – ground motion relationships are essential for the use of historical earthquakes for which no instrumental records exist.

These relations must be calibrated on present day recordings.

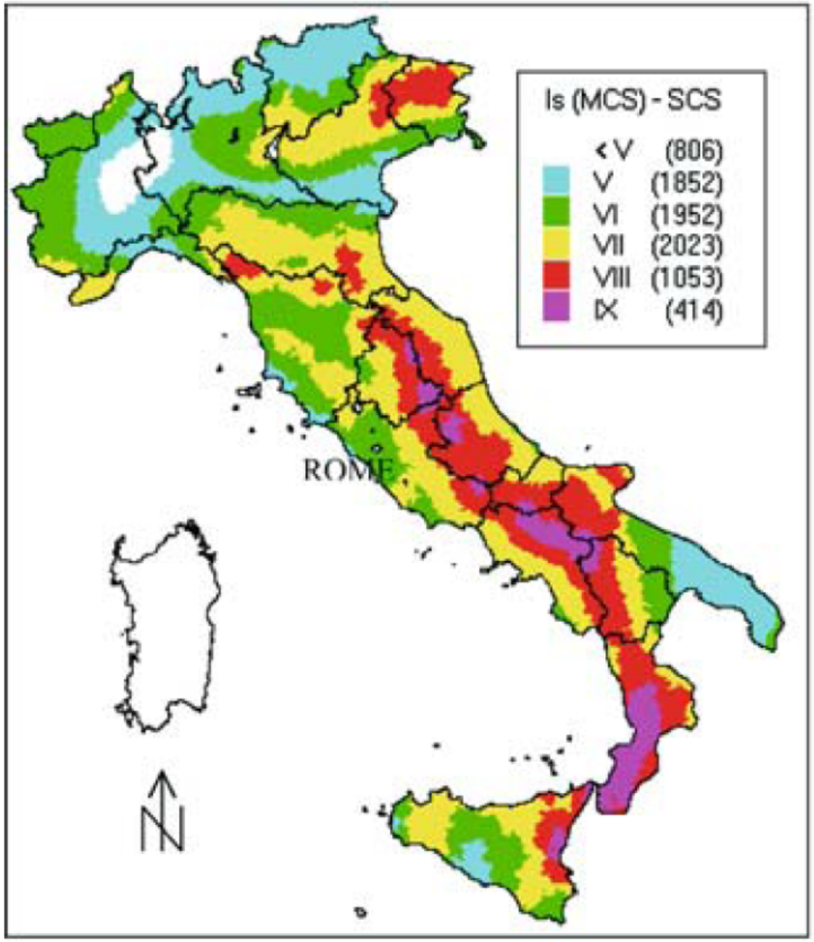




Examples in Italy



Maximum observed macroseismic intensity in Italy



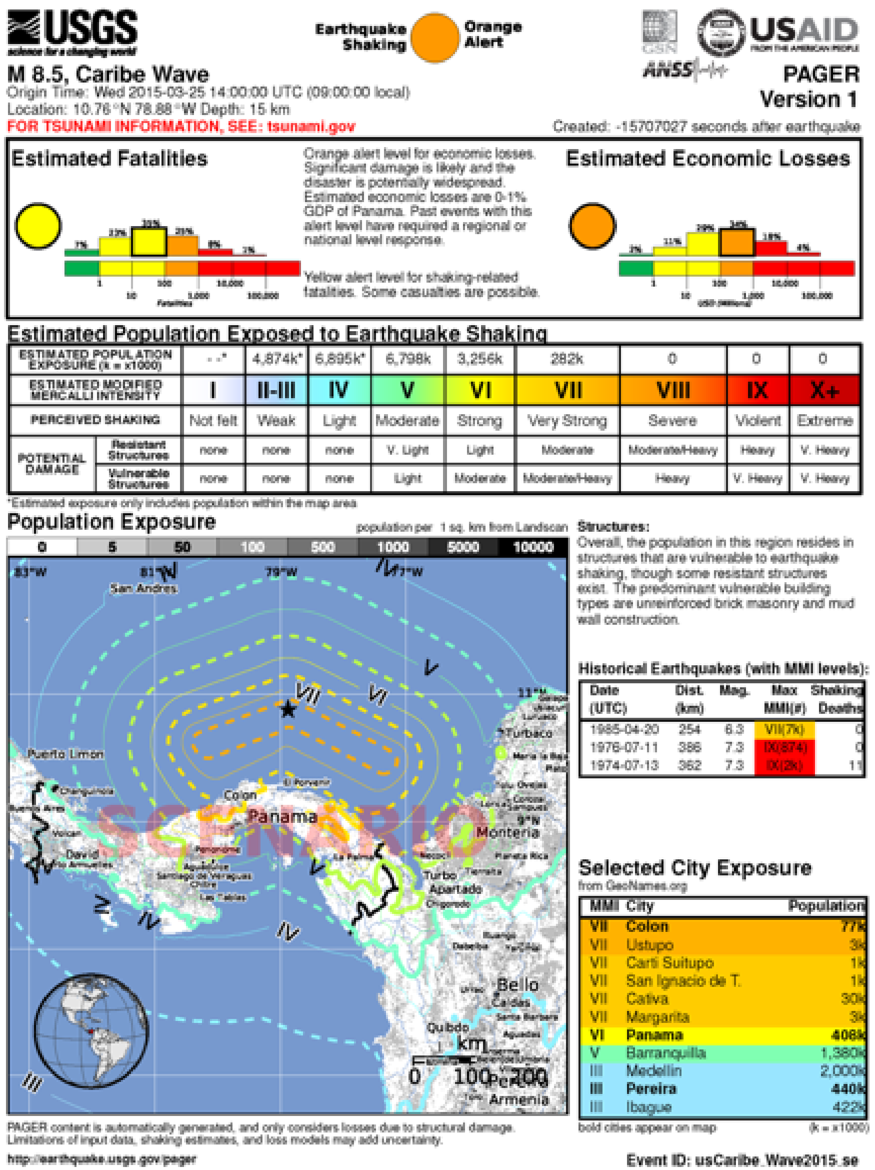
Probabilistic hazard map in MCS intensity (10% in 50 years)

Intensity in ShakeMaps

ShakeMap®, developed by the U.S. Geological Survey (USGS), portrays the distribution and severity of shaking.

Using macroseismic intensity facilitates communication of earthquake information beyond just magnitude and location for <u>emergency management and response.</u>

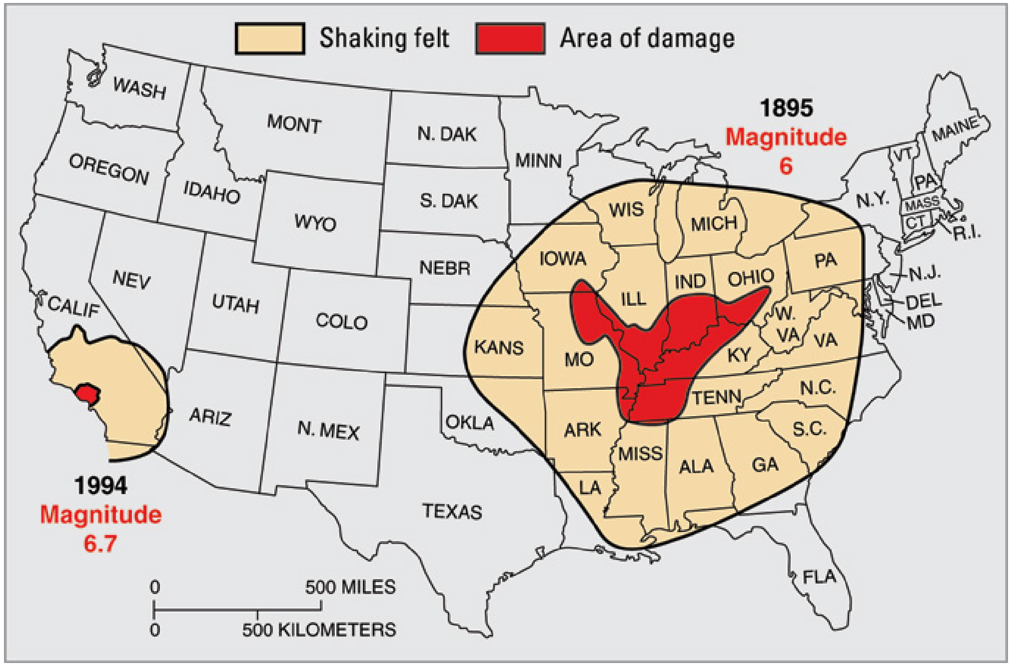
NOTE: Not a representation of actual damage distribution!



Limitations

The maximum intensity measure is biased by many factors not always directly dependent to the earthquake:

- Depth of the event
- Distribution of the population and personal perception
- Construction practice
- Effect of local geology (seismic site effects)
- Regional geology (path attenuation)



This makes earthquakes from different regions hardly comparable.

Local Magnitude

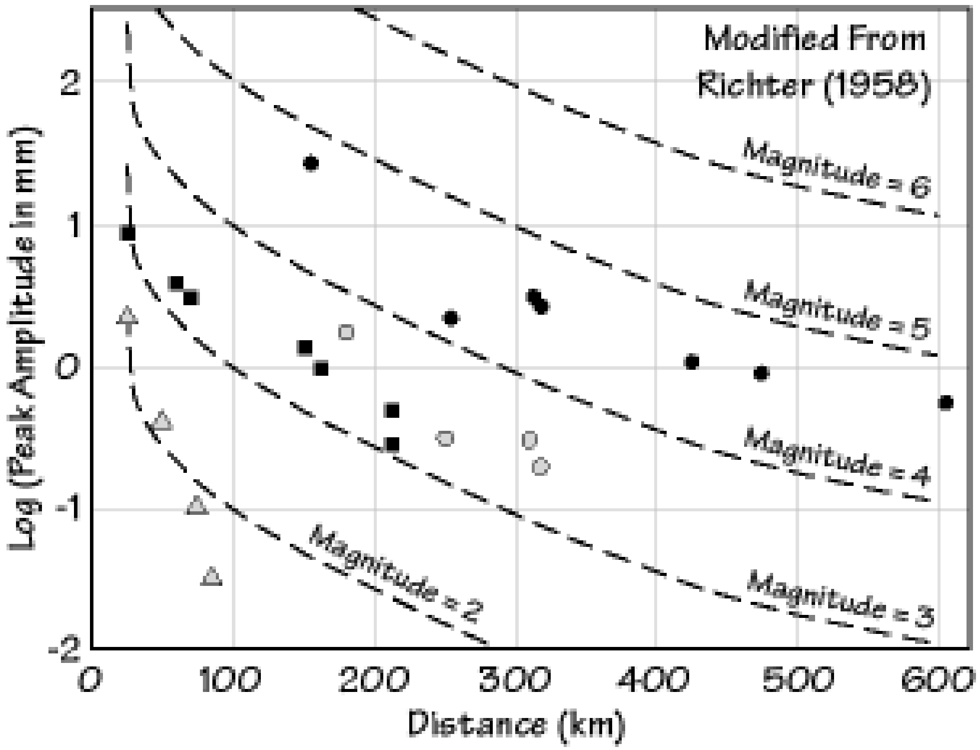
The concept of magnitude was introduced by Richter (1935) to provide an objective instrumental measure of the size of the earthquake.

Contrary to seismic intensity, the magnitude (M) uses instrumental measurements of the earth ground motion adjusted to epicentral distance and source depth.

Such magnitude estimate is called local (M_L) or simply Richter, from its inventor.

Local Magnitude

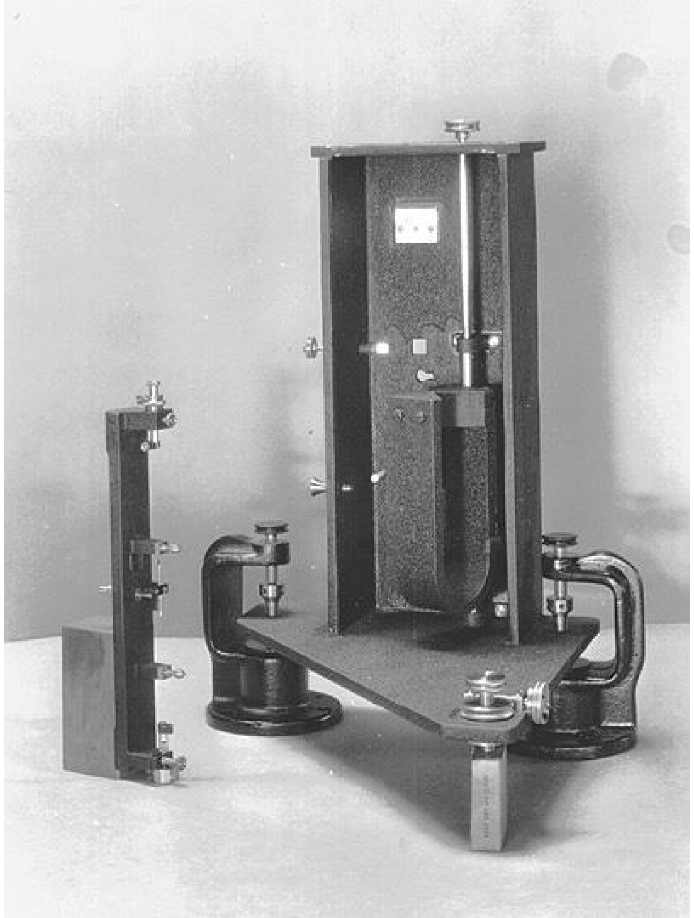
The original Richter scale was based on the observation that the (log) amplitude of seismic waves decreases with epicentral distance.

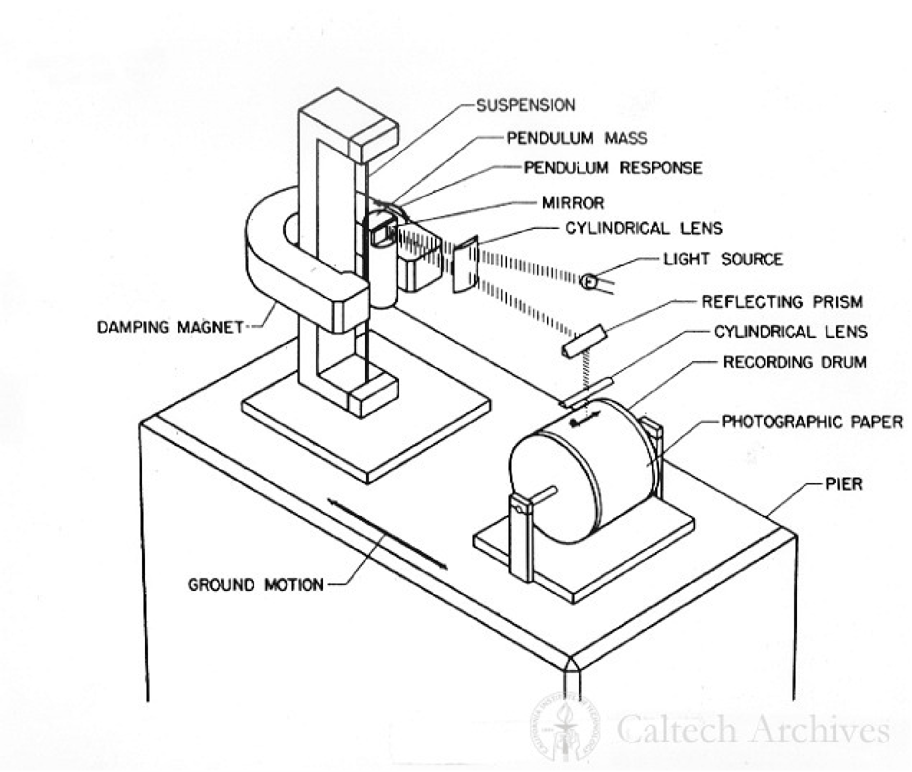


A magnitude 0 earthquake is defined as the size event that generates a maximum ground motion of 1 micrometer at epicentral distance f 100 km with a **Wood-Anderson instrument**.

Wood-Anderson Seismograph

The ML magnitude scale is based on the use of the Wood-Anderson seismograph, which is a torsion horizontal seismometer with period of about 0.8 seconds.

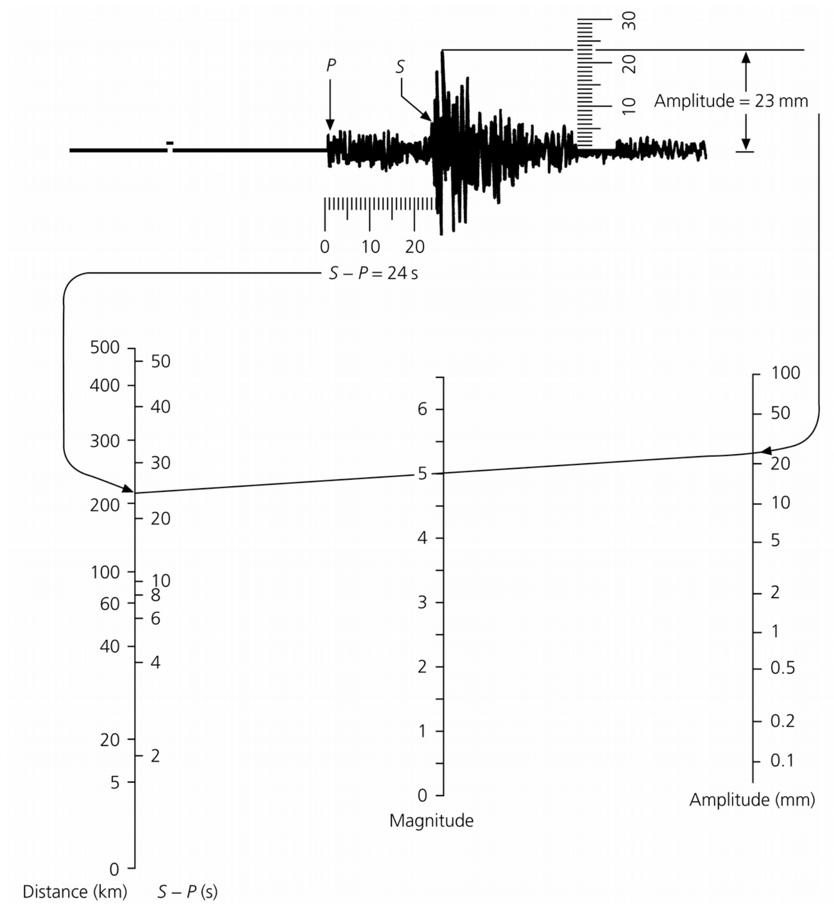




Magnitude Calculation

A for the original formulation, ML can be computed with respect to a reference amplitude, which depends on distance to the event:

$$M_L = \log_{10}(A) - \log_{10}(A_{ref})$$



Several empirical formulations exist as function of epicentral or hypocentral distance, e.g. the Lillie formulation:

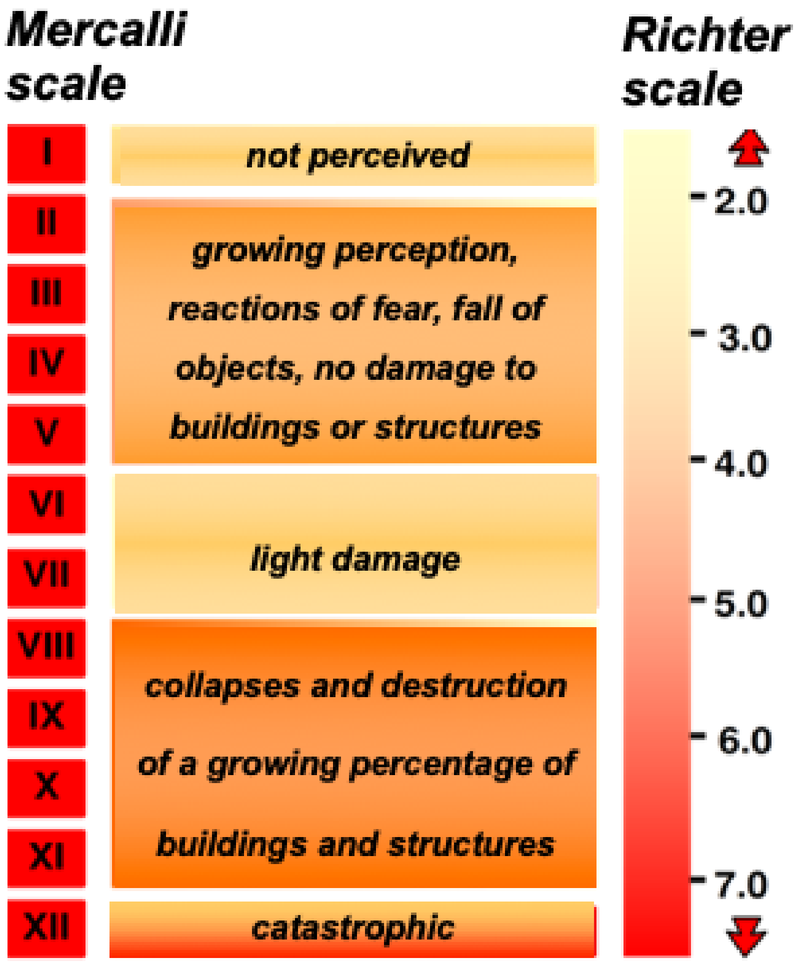
$$M_L = \log_{10}(A) - 2.48 + 2.76 \log_{10}(\Delta)$$

M_L vs Mercalli Intensity

Approximate relations between epicentral Mercalli intensity and Richter magnitude scale exist (e.g. Gutenberg and Richter, 1956):

$$M_L = \frac{2}{3} I + 1$$

This is useful to homogeneously quantify the size of historical earthquakes, but with large uncertainty.

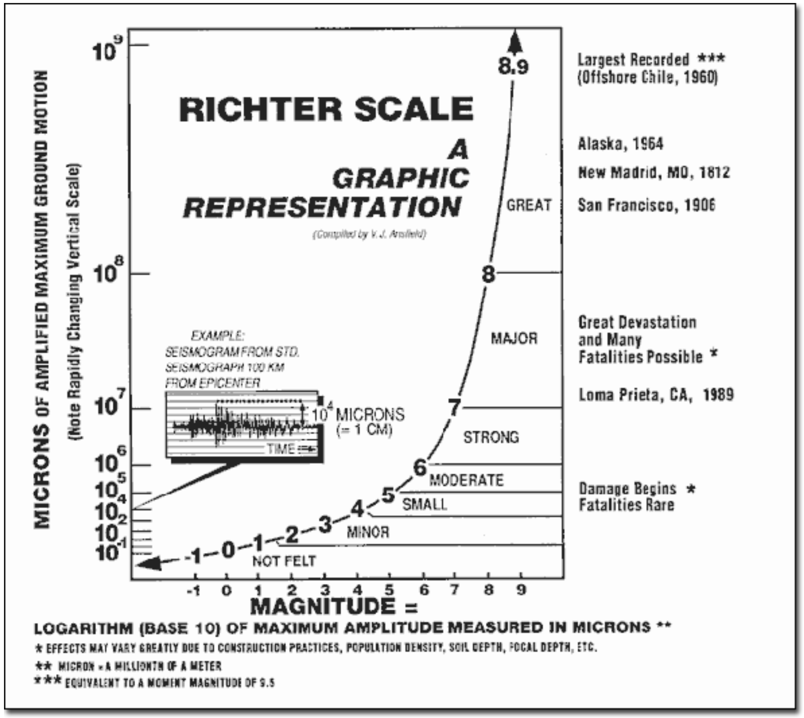


Problems with M_L

Richter Magnitude suffers from many limitations, such as:

- It is strictly valid only for Souther California (in original form) and adjustments are needed for other regions
- Depends on a specific type of seismometer, whose dominant periods limits the capability of the scale to resolve large magnitudes (the saturation problem)

Magnitude	Description	How it feels	Frequency
Less than 2.0	Micro	Not felt by people.	Millions per year.
2.0 to 2.9	Minor	No building damages.	More than 1 million per year.
3.0 to 3.9	Minor	Often felt, may shake objects inside buildings.	More than 100,000 per year.
4.0 to 4.9	Light	Indoor objects shake or fell to the floor. Not significant damage.	10,000 to 15,000 per year.
5.0 to 5.9	Moderate	Extensive damage to buildings not designed correctly.	1,000 to 1,500 per year.
6.0 to 6.9	Strong	Can cause damage up to	100 to 1500 per



Other Magnitude Scales

After local magnitude, the concept has been developed and extended so as to be applicable to a variety of wave types and distances.

In general form, all magnitude scales based on amplitude measurements are like:

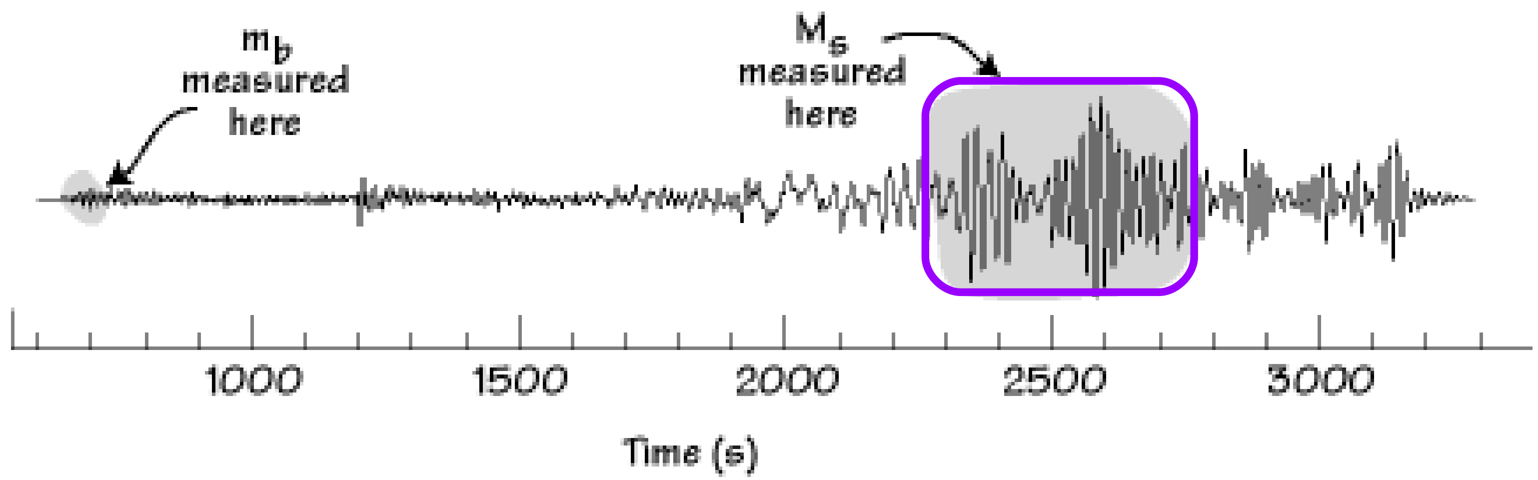
$$M = \log(A/T) + f(\Delta, h) + C_s + C_r$$

M = Magnitude
A = Amplitude
T = Period
f = Correction for distance and depth
Cs = Correction for site
Cr = Correction for source region

Surface Wave Magnitude

For distances 20°<Δ<160° with hypocentres in the uppermost 50 km
Measured by the amplitude of the Rayleigh waves
Dominant period of around 20 seconds.

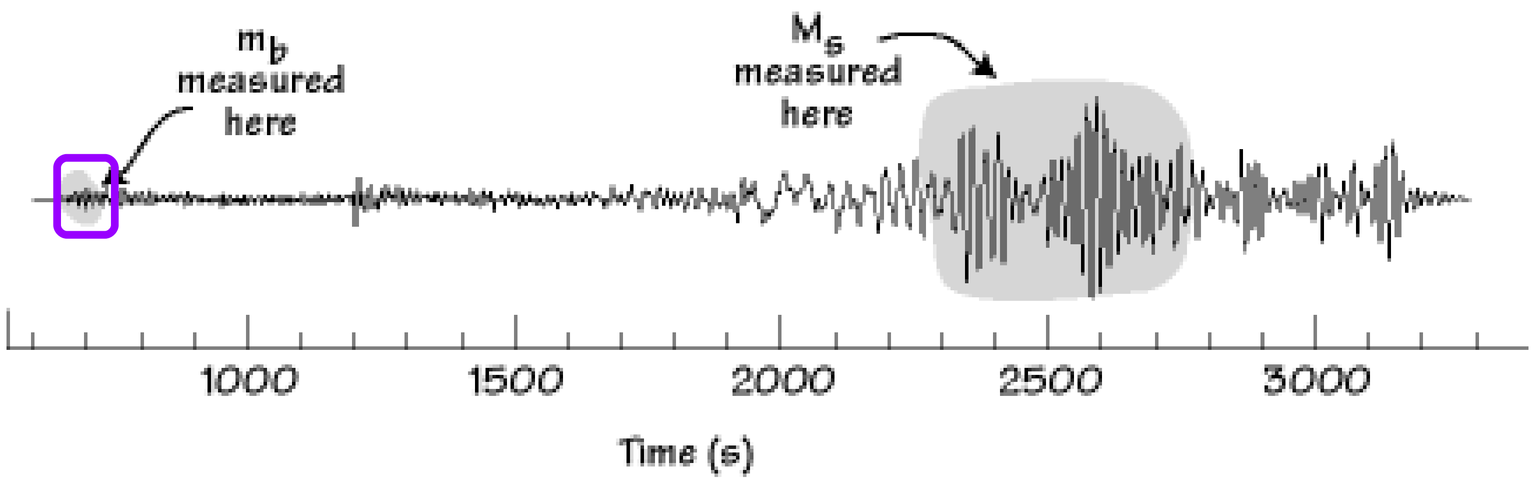
$$M_S = \log_{10}(A/T)_{max} + 1.66\log_{10}\Delta + 3.3$$



Body Wave Magnitude

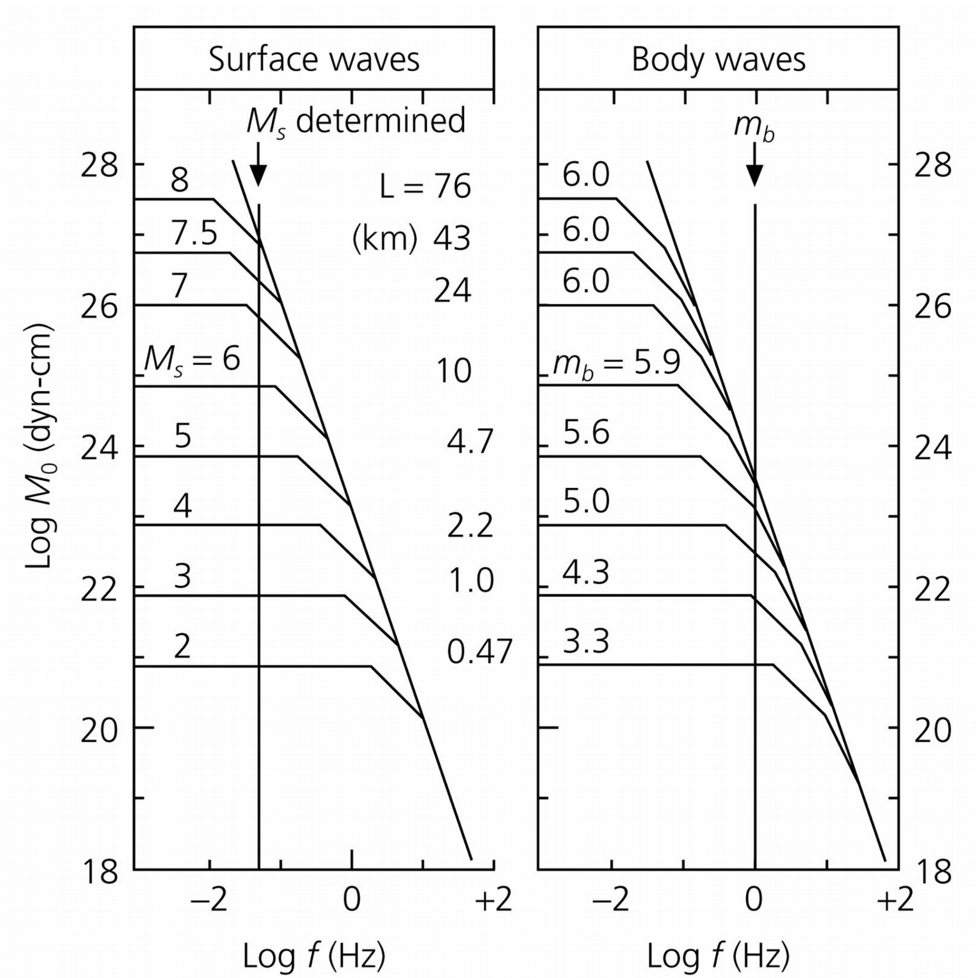
Used for deep earthquakes and earthquakes measured at distances > 600 km (teleseismic events)
Measured by the amplitudes of the first arrivals of P-waves
Dominant period of around 1 second

$$mb = \log_{10}(A/T)_{max} + g(\Delta, h)$$



Magnitude Saturation

The frequency (or period) at which the earthquake spectrum is "sampled" strongly controls the resolving power of a specific magnitude type.



For instance, mb saturates above 6, while Ms never gets above 8.2–8.3

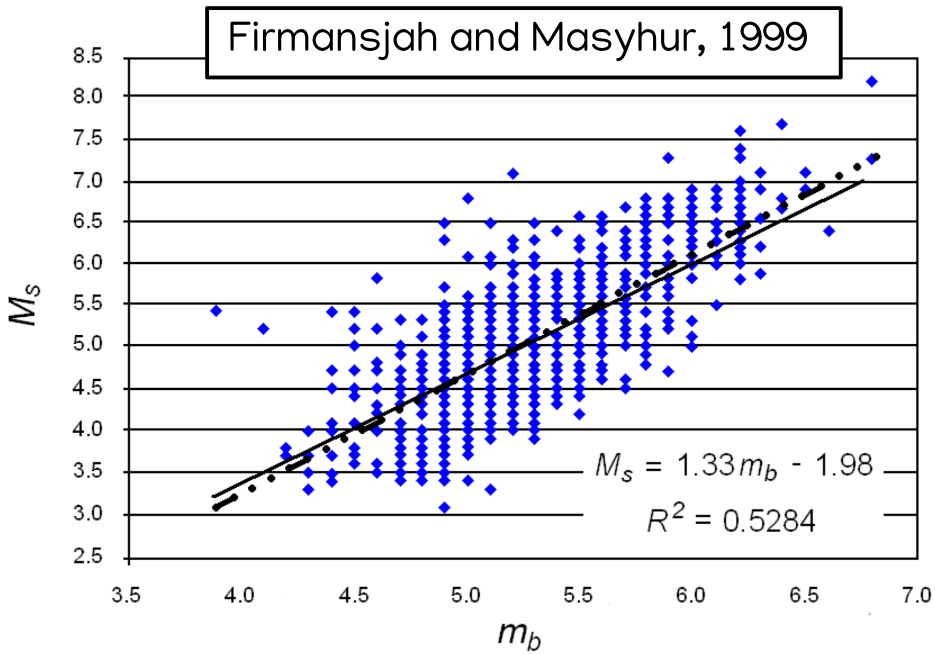
Conversion Relations

As earthquake is a complex phenomenon, different magnitude scale might provide inconsistent estimates for the same event.

Example:

- Turkey 8/17/1999: Ms = 7.8, mb = 6.3
- Taiwan 9/20/1999: Ms = 7.7, mb = 6.6

Magnitude conversion relations are often necessary (e.g. in hazard analysis). Although global relations exists (e.g. Di Giacomo, Weatherill), relations calibrated ad-hoc for specific region are to be preferred.



Are ML, mb and Ms useful?

These scales are still routinely used nowadays, first of all for their simplicity, but also because, being sensitive to different characteristics of the earthquake (different waves, different periods), they bring useful information in specific analysis (e.g. nuclear test verification)

ISC-REV_Africa_20170713.isf

```
Event  1737346 Central Mediterranean Sea
   Date       Time        Err   RMS Latitude Longitude  Smaj  Smin  Az Depth   Err Ndef Nsta Gap  mdist  Mdist Qual   Author
OrigID
2000/07/05 17:12:09.70   1.42        34.9080   21.6260  27.3  10.5 165  33.0         14                                MOS
3025203
2000/07/05 17:12:20.20        1.100  36.1300   21.4000                  69.0              15                           BJI
3019870
2000/07/05 17:12:20.50        1.100  36.0200   21.9800   8.2   7.9  -1   5.0         17       224                    ATH
3970846
2000/07/05 17:12:21.92   1.23 0.990  36.0450   22.1210  10.4   8.3 213  49.9  10.6   33   33  86   5.16 120.64    se NEIC
3665165
2000/07/05 17:12:22.14               35.9440   21.7350                  10.0                                           THE
3816063
2000/07/05 17:12:23.62        1.240  36.0200   22.0720  10.2   5.9  23  48.5   6.7  127  124                     ke EHB
11208813
2000/07/05 17:12:25.16   0.07        36.4360   21.5310  66.7  19.0  -1   9.8  11.1         9 350                    PDG
3080621
2000/07/05 17:12:26.22   3.30 0.790  36.1298   22.0459  19.6  16.6  64  67.9  29.9   18   17 101   9.24 120.71    uk IDC
3882300
2000/07/05 17:12:45                  40.0000   27.0000                                                             NAO
3608388
2000/07/05 17:12:19.80   0.36 1.470  35.9480   21.9990   4.2 3.145   0  33.0f       125  127  68   0.90 120.72 m i    ISC
4127018
 (#PRIME)

Magnitude  Err Nsta Author      OrigID
mb      4.7       4 MOS        3025203
mb      4.5         BJI        3019870
MD      4.1      14 ATH        3970846
ML      4.2         ATH        3970846
mb      3.9      12 NEIC       3665165
ML      3.9         THE        3816063
mb      3.8 0.1  14 IDC        3882300
ML      3.5 0.1   2 IDC        3882300
MS      3.4 0.1   8 IDC        3882300
Mb      3.7         NAO        3608388
mb      4.3      23 ISC        4127018
MS      3.1       4 ISC        4127018
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The ISC Reviewed Bulletin

Energy Magnitude Relation

MS and mb magnitudes represents different parts of the frequency spectrum of seismic waves, therefore different phisical parameters of an earthquake. Gutenberg and Richter's studies suggests that, being related, they can be used to represent the fundamental physical parameter of seismic waves: ENERGY.

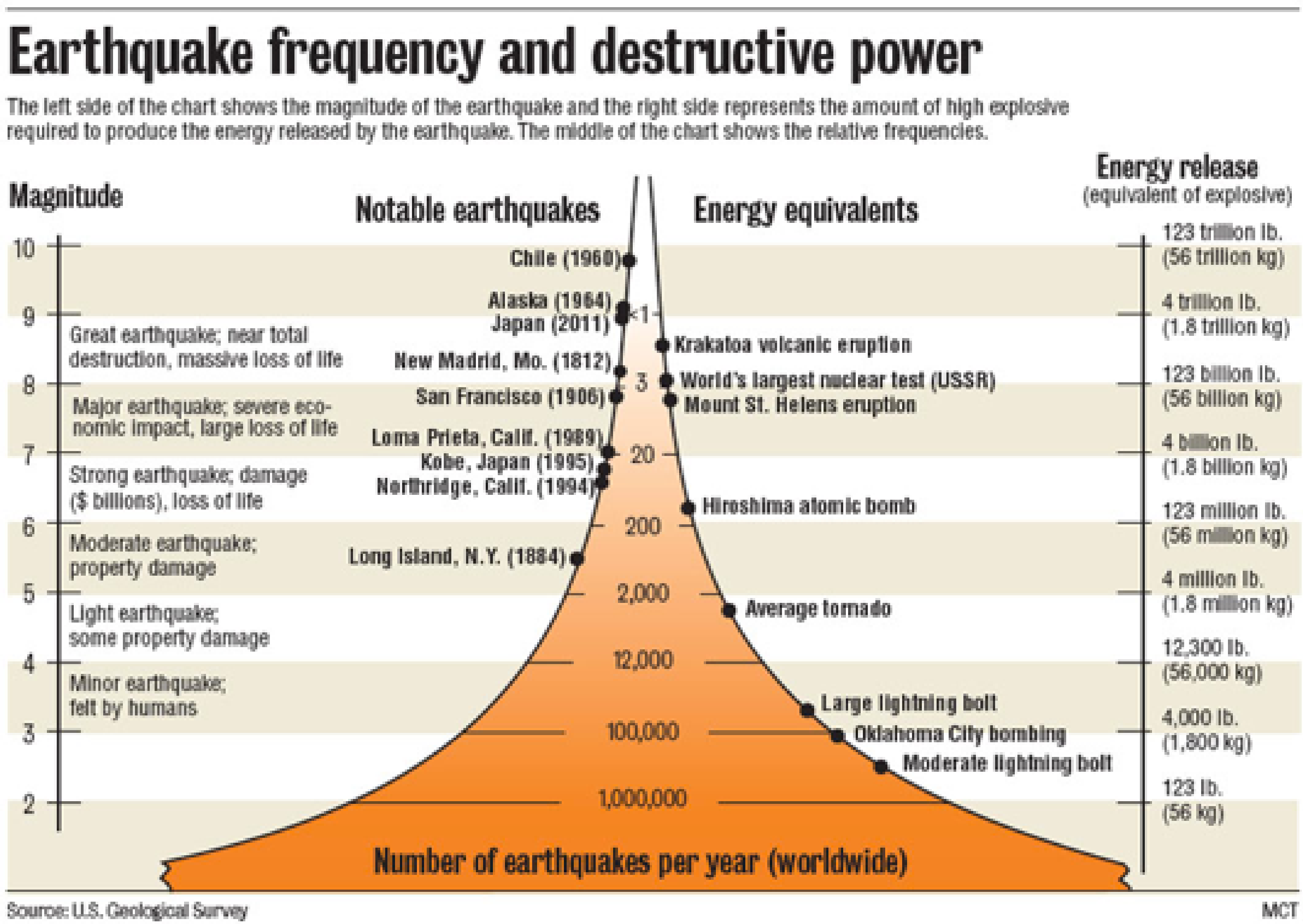
They obtain the following relationship:

$$\log E = 1.5\, Ms + 11.8$$

This is a rapid estimate of the energy of seismic waves associated with an earthquake.

Energy Equivalents

Note that an increase of one magnitude unit corresponds to about 32 times increase in the amount of energy released



Seismic Moment Recap

From elastic dislocation theory (Aki 1962) we recall the concept of scalar seismic moment:

$$M_0 = \mu A D$$

Seismic moment is one of the most reliable seismological parameters that represents the 'size' of an earthquake.

M_0 does not saturate, it is therefore a more suitable parameter to represent the size of great earthquakes than the conventional magnitude scales such as Ms.

Moment Magnitude

Moment magnitude (Mw) was first introduced by Hiro Kanamori in 1977 as:

$$M_w = \frac{2}{3}\log(M_0) - 10.7$$

Mw measures the size of events in terms of seismic moment , and therefore of how much energy is released.

Mw can be easily compared to magnitude values for other events.

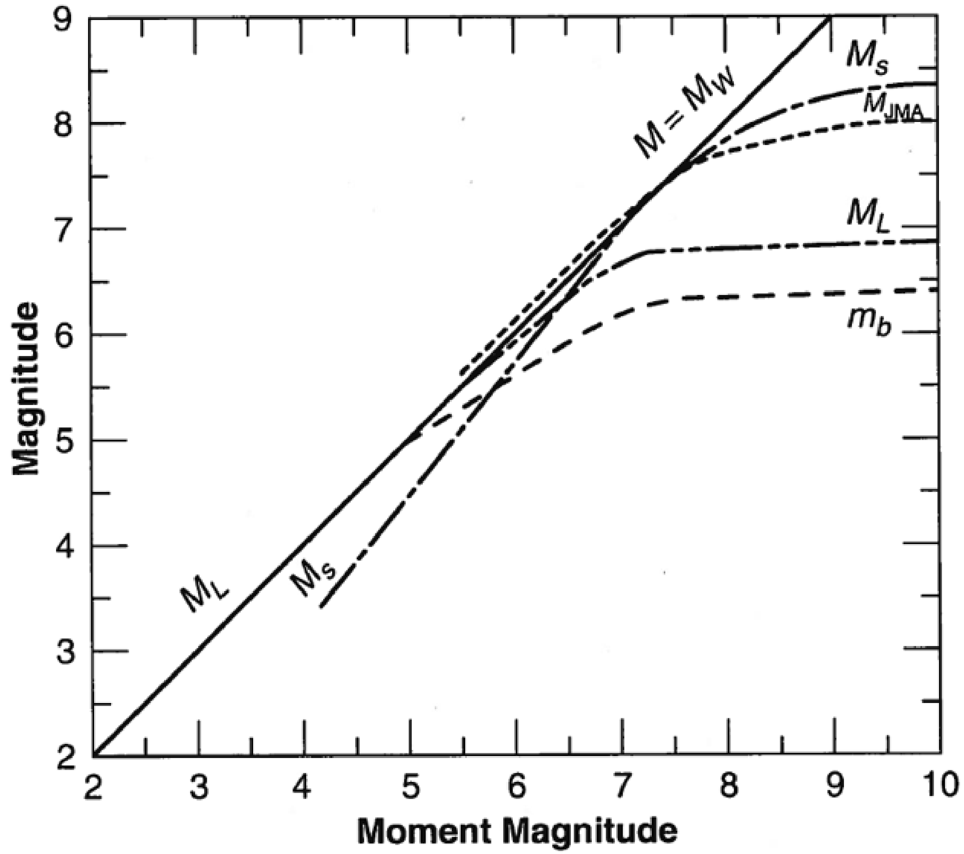
Comparing Scales to Mw

Scale type	Author	Earthquake size	Earthquake depth	Epicentre distance (km)	Reference parameter	Applicability	Saturation
M_L	Richter (1935)	Small	Shallow	<600	Wave amplitude	Regional (California)	✓
m_b	Gutenberg and Richter (1956)	Small-to-medium	Deep	>1,000	Wave amplitude (P-waves)	Worldwide	✓
M_S	Richter and Gutenberg (1936)	Large	Shallow	>2,000	Wave amplitude (LR-waves)	Worldwide	✓
M_w	Kanamori (1977)	All	All	All	Seismic moment	Worldwide	n.a.

Key: n.a. = not applicable; ✓ = saturation occurs.

Comparing Scales to Mw

Moment magnitude does not saturate because it is derived from seismic moment as opposed to an amplitude on a seismogram.



- The local magnitude ML and the short-period body wave magnitude mb are essentially equal to moment magnitude up to M = 6.
- The surface wave magnitude MS is essentially equal to moment magnitude in the range of M = 6 to 8.

Measuring Mw

M_0 is proportional to the far-field earthquake spectrum at long periods. Mw can then be obtained by spectral fitting.