MAGNITUDES
Why still important? Why such a variety? How to manage?

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Part 1. Why old-style magnitudes are and will be important

Moment magnitude M_w, is a mere transcription of the physical parameter – seismic moment M_0 measured in N·m. This measure of earthquake size seems to be quite sufficient.

So why any other M can be important, and why even new magnitudes still appear?

(1) Yes: the concept of magnitude M is an inheritance from times of photo recording; it is becoming outdated. Why?
(a) Old M is not a physical parameter
(b) It is tied to a specific instrument and wave type etc.

(2) Yes: M_w covers many uses of older magnitudes.

(3) But: M_w is not universal: old-style magnitudes keep to be needed, and new versions can appear.

Uses of magnitude: Mw and/or M-old (1)

- **1. The relative size of earthquakes. Old M or Mw is a simple, quantitative single measure for this goal.**

Used in: *Earthquake catalogs*

Frequency-M distributions (recurrence plots)

When known, M_w can replace old M.

Two problematic cases are:

1A. ***Small earthquakes***

Mw calibration is often problematic,

and the **use of ML is inevitable**

1B. ***Old earthquakes***,

only scarce Mw data exist for these,

conversion of old M is uncertain

Uses of magnitude: Mw and/or M-old (2)

2. Earthquake/tsunami early warning.

Immediate quantification of an earthquake is needed, but the time limit does not permit an inversion for M_0, thus:

true Mw is absent, some proxy is a must

3. Prediction of ground motion parameters (use in GMPE).

Mw has positively replaced ML and M_S in modern ground motion prediction equations (GMPE).

Problems with Mw. **1A. Smaller earthquakes *).**

To provide Mw values for **all** small earthquake data is hardly attainable.

- *Issue 1.* Nodal planes (i.e components of M0ij tensor) often cannot be determined,
- *Issue 2.* Accurate reduction of amplitudes to the source is hampered by uncertain attenuation law/structure.

An empirical calibration function or attenuation law can be used instead, but in this manner you can produce only old-style magnitude or some proxy-Mw, but not the M0ij tensor.

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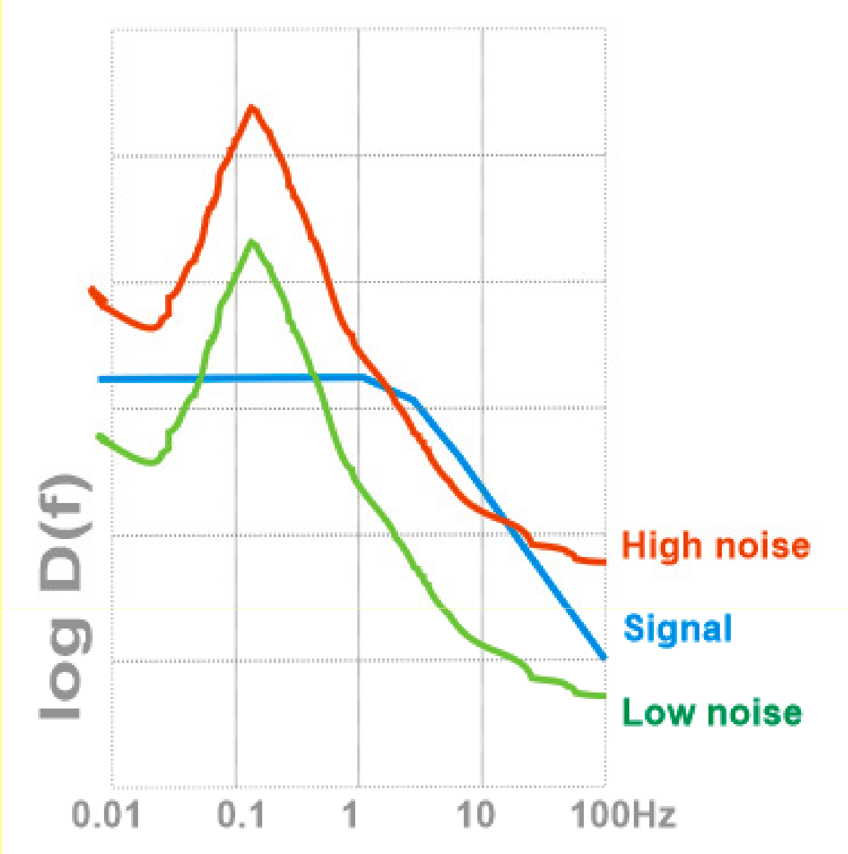
* *The boundary between "larger" and "smaller" earthquakes depends on station network density.*

It changes from country to country and from province to province, and, most prominently, between on-land and ocean-bottom areas.

Problems with Mw. **1A. Smaller earthquakes (continued)**

- *Issue 3*. The signal-to-noise (S/N) ratio of a record can be prohibitively low at lower frequencies LF; this **obstructs** determination of M0ij ***(especially when a cyclone is passing by).***
  Still, S/N may be well tolerable at 2-10 Hz permitting
  quite sound ML



Problems with Mw. **1B. Quantification of older earthquakes.**

Earthquake hazard studies strongly need ***historical data.***

These may use:
- **macroseismic information**,
- early seismological **records with insufficient f range**

One cannot find true Mw from these data. Still, ML or some other older magnitude can well be determined and then converted to some proxy-Mw.

To substantiate such a conversion, some thorough analysis must be done in advance

2. Earthquake/tsunami early warning: need for "fast and dirty" M

In real-time applications, one must get an idea of event size as soon as possible

Determination of M_0 or Mw cannot be done sufficiently fast because of incomplete or ***even non-existent*** information (*rupture may still run; we cannot wait it to finish*);
for fast provisional estimates, simple event size measures is a must.

Such "very proxy Mw" can be crude.

An estimate from below is quite tolerable, to be refined/updated in 1 - 3 - 10 minutes.

Part 2. Magnitude concept and its physical background. Variety of magnitudes

2.1. **Richter's (1935) idea of magnitude**: *for a given instrument (W-A)*, peak amplitude A decays with epicentral distance Δ in a standard way.

Amplitude decay or calibration function:

$a(\Delta) = \langle \log (A(\Delta)/A(\Delta=100km)) \rangle$ (1)

thus a(100km)=0.

Now if for a particular earthquake recorded at some Δ_1 with $A=A_1$

$\log A_1(100) \approx \log[A_1(\Delta 1) * \langle A(100km)/A(\Delta_1 \rangle] = \log A_1 (\Delta_1) - a(\Delta_1)$ (2)

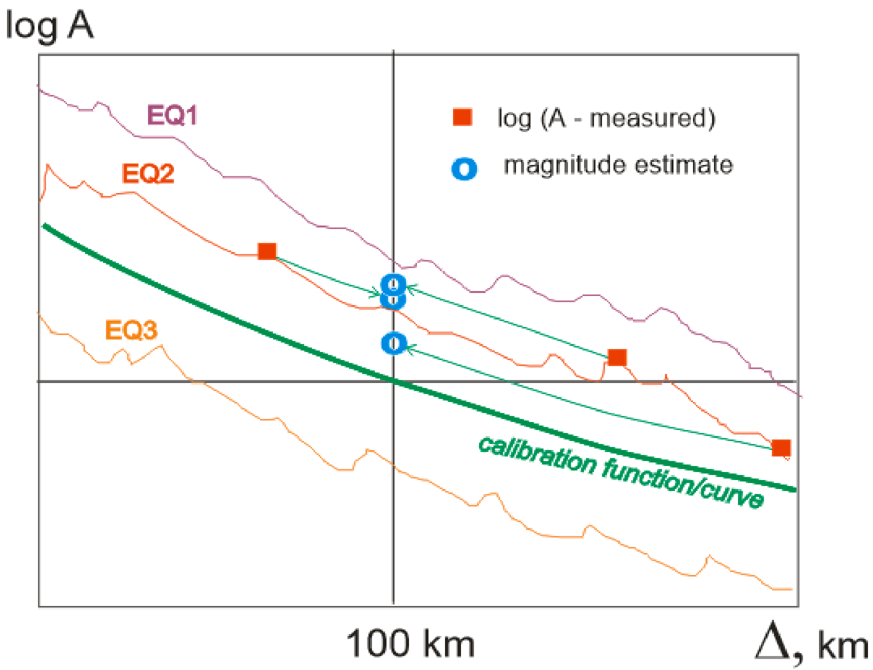
We can use logA(100) as a measure of strength of any earthquake if we have recorded it at any Δ.

For convenience add a positive constant to obtain MAGNITUDE:

$M = \log A_{obs} - a(\Delta) + B$.

or aggregating (-a(Δ)+B) as logA0(Δ)

$M = \log A_{obs} + \log A0(\Delta)$



2.2. Common variants of M scales. What was measured to produce M

(most frequent variants)

(1) S wave peak at a local/regional distance, at a **short-period** (1s) instrument; this makes local magnitude **ML** directly following Richter's approach.

(2) P wave peak at a teleseismic distance, at a **medium-period** (3-10 s) instrument; this makes **mB** magnitude after Gutenberg

(3) P wave peak at a teleseismic distance, at a **short-period** (1 s) instrument makes **mb** magnitude. The calibration function developed for mB is used.

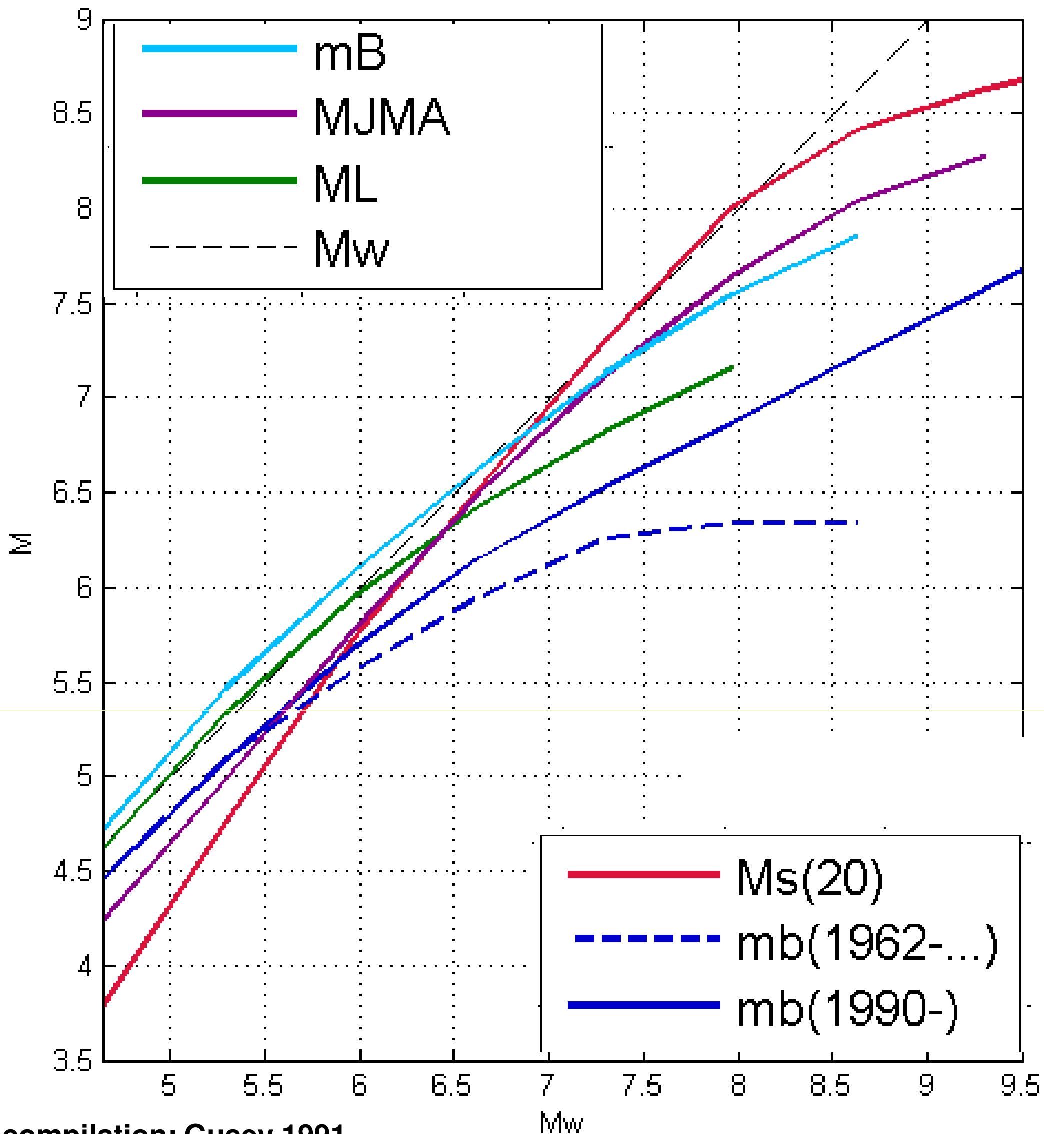
(4) maximum amplitude of dispersive teleseismic surface wave train **around the period of the 20s** at a teleseismic distance at **any** medium-to-long-period instrument; this makes **Ms** magnitude after Gutenberg. Not used for events with H>60 km. Before Mw, preferable scale for medium to great earthquakes.

Invention of M was a great breakthrough, with lots of applications, but it had weak points.

The magnitudes mB, mb and Ms were originally tied to ML, but outside the vicinity of the binding point, **they *systematically* diverge.**

Regular mismatch of M estimates created problems and considerable confusion.

Interrelationships between key old M and Mw



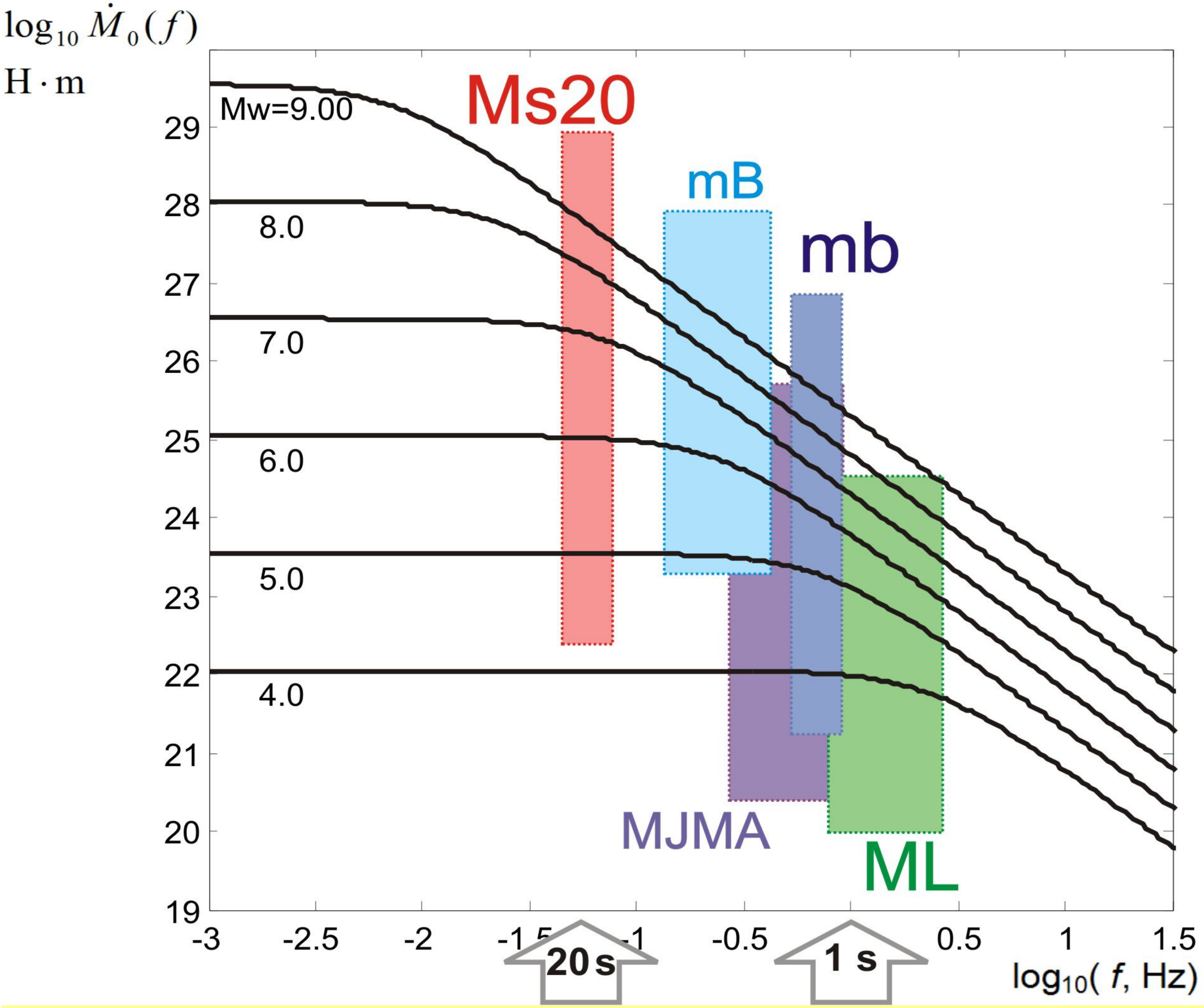
compilation: Gusev 1991

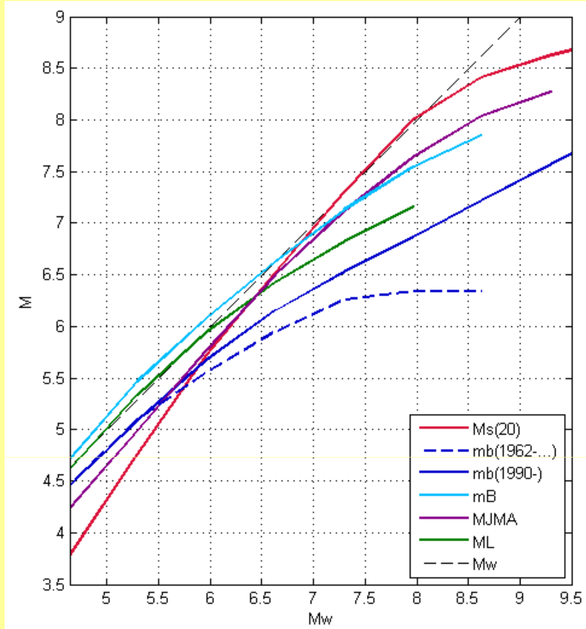
ML saturates (like PGV) when station is near to the source/fault (r/L<1)

- All trends are **nonlinear**
- Generally,
  no genuine saturation
  at high Mw
- **mb**[1962-90] saturates
  (no physics!)
- **ML** and **mb** parallel
- The longer period, the steeper trend:
-

(ML,mb) -	**(MJMA, mB) -**	**MS20**
0.5-1.5s	1 - 6	20 s

How these trends are formed





Case 1

Ms20(Mw) follows source spectral level (Okal 1989)

Case 2

mb,ML… are time-domain entities, they do not immediately follow spectral level because duration of body-wave group is involved. Duration is controlled by (1)Mw and (2)distance

Divergence of M scales

Discordant values is the most significant issue with older magnitudes.

Q. Why not to use single scale for all events?

A. Each scale covered a specific field:

- **ML** is good in a region, is not applicable to teleseismic case
- **Ms** is the best for larger events, does not work for deeper events, does not cover smaller distant events, no local use,
- **mB** is good for all depths; do not cover smaller distant events, no local use,
- **mb** does cover smaller distant events (including blasts), complications for large and great events, no local use,
- **no good scale at all** for great events

Thus, the parallel use of several scales was practical.

As a bonus, the value of Ms:mb misfit can separate nuclear blasts from earthquakes.

In addition to multiplicity, the serious problem of traditional M is conceptual: magnitude is not a physical entity.

M_w scale

When possibility arose, seismologists began to calibrate earthquakes using the physical variable, seismic moment M_0 [N·m]. To keep historical continuity, $\log M_0$ was translated into the M_w parameter designed to be compatible with ML/Ms.

$$M_w = \frac{2}{3}\log(M_0[\mathrm{N\ m}] - 9.1)$$

[**Kanamori 1977,** **IASPEI***(official)*;

[**not recommended:** *-9.05 after Hanks&Kanamori 1979*]

2.3. Variety of magnitudes

(for general orientation, no completeness, author's personal selection)

Regional/local

period range	*wave type*	*instrument*	*region*	*code*	*authors*
short	S	WA	California	ML	Richter 1935
short	S	many 1-s instruments	many regions	ML, K class	many
0.3-5s	S	JMA	Japan	MJMA	Tsuboi 1954
medium	surface	Kirnos	USSR	Ms(BB)	Vaniek, Soloviev 1962

Teleseismic

periods	*wave type*	*instrument*	*code*	*authors/originators*
20s	surface	medium/long-period	Ms(20)	Gutenberg 1942
10-25s	surface	medium-period	Ms(BB)	Vaniek, Soloviev 1962
2-10 s	P	medium-period	mB(mPVB)	Gutenberg 1942
~1s	P	short-period Benioff	mb(mPVA)	since 1962 *USCGS*
~1s	P	short-period SKM_3	mPVA	since 1963 *Obninsk*
100	surface	P-E	Mm	Brune&Engden 1968
30-250	surface	P-E, BB analog	Mm	Okal&Talandier1989
BB	P	digital	Me	Choy&Boatwright 1993
BB	P, S, surface	digital	Mw	Kanamori 1977

Variety of magnitudes (continued)

Mostly regional, mostly tsunami warning use

period range	*wave type*	*instrument*	*region*	*code*	*authors*
medium	surface	Kirnos	USSR	Ms(BB)	Vaniek, Soloviev 1962
30-250s	surface	BB	Polynesia	Mm	Talandier&Okal 1989
15-30s	surface	BB +filter	Mexico	M	Singh 1991
BB	P	BB	global	Mwp	Tsuboi 1998
BB	P-S interval	BB	global	Mww	Kanamori 2003
20s	surface	BB +filter	Russia	Ms(20R)	Chubarova&Gusev, 2011
40s, 80s	surface	BB +filter	Russia	Ms(40), Ms(80)	Gusev&Chubarova, 2016

Coda based

period range	*wave type*	*instrument*	*region*	*code*	*authors*
short	duration.	1s	Europe	Md	Bisztricsany 1957
short	duration	1s	California	DMAG	Lee et al 1972
short	coda ampl.	1s	US	?	Suteau&Whitcomb, 1979
short	coda ampl.	SKM-3	USSR	Mc	Rautian 1981
medium	coda ampl.	Kirnos	USSR	Mc	Rautian 1981
short	coda ampl.	1s	Kamchatka	Kc	Lemzikov&Gusev1989
short	coda ampl.	digital	Japan	M	Goto 2010

Variety of magnitudes (continued 2)

Multiband / spectral / ChISS magnitude
(a set of values per event using a set of bandpass filters, e.g. octave filters)

T-f range	*wave*	*instrument*	*dist. range*	*parameter*	*authors*
5s-40Hz	S	analog(ChiSS)	regional	?	Zapolsky, 1962-1997
2s-40Hz	coda	analog	regional	log(M0)	Aki&Chouet1975
1-120s	P	analog(ChiSS)	teleseismic	mB(mPV)	Zapolsky, Zhbrykunov 1972
65s -25Hz	coda	analog(ChiSS)	regional	log(Mo/μ)	Rautian&Khalturin1978
30s -25Hz	coda	digital	regional	log(M0)	Mayeda&Walter 1994
1-50 s	P	analog	teleseismic	mB(mPV)	Nortmann&Duda 1983
5s-40Hz	S&coda	digital	regional	log(M0)	Gusev et al , 2017, in preparation

Part 3. Relationships between magnitudes: theory-based and empirical. Conversion of old M into "proxy Mw".

3.1. Proxy- Mw and quasi-Mw

Any modern earthquake hazard study needs a catalog with a single event size variable. The common opinion at present is that Mw must be used. But one cannot convert old data into true Mw values, based on M0ij tensor.

Some replacement is needed, often called **"proxy-Mw".**

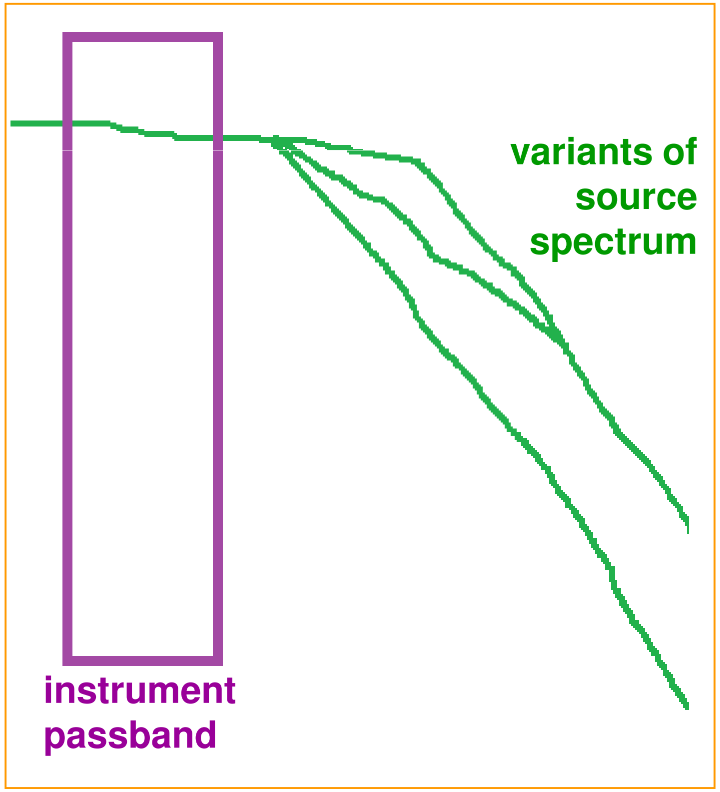
This terminology is seemingly too crude.

Case 1. Assume we wish to ascribe Mw estimate to an old shallow Ms=5.5 event. In this case, Ms represents the LF part of source spectrum **quite tolerably**. We can denote such Mw estimates as **"quasi-Mw",** or **qMw** . (Of course, qMw and Ms need not coincide numerically).

(this explains why Mt (from tsunami)

is a reasonable predictor for Mw

(i.e., it is quasi-Mw)

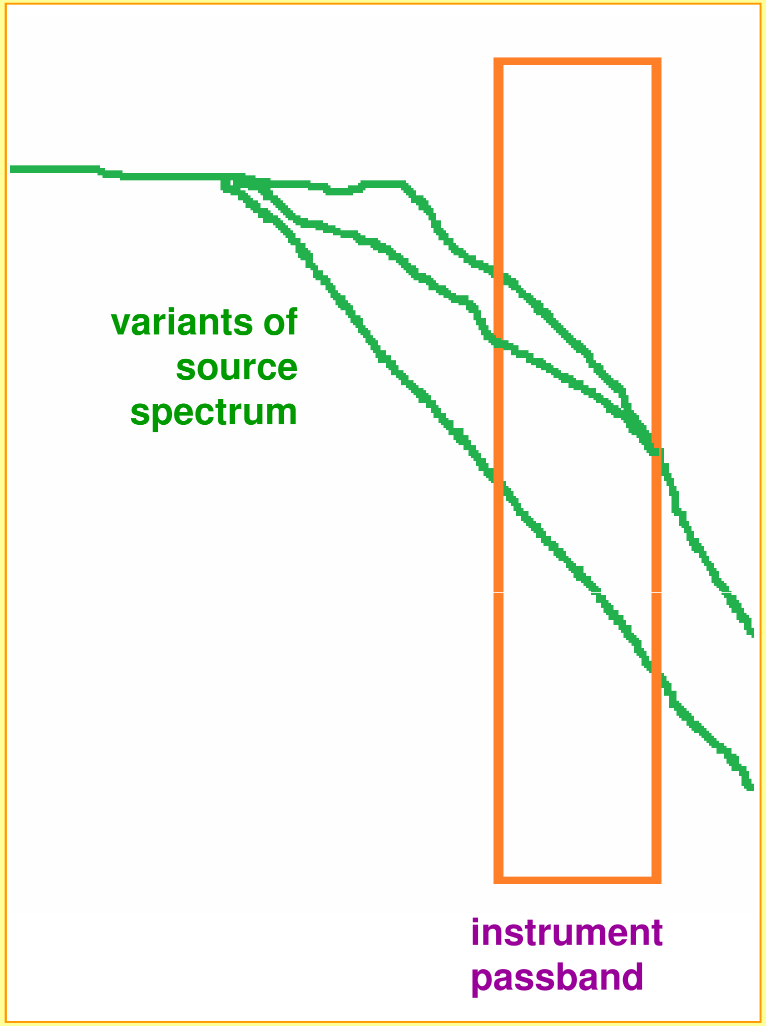


3.1. Proxy- Mw and quasi-Mw (continuation)

Case 2. Assume we wish to ascribe Mw to an event with Ms=8, or ML=7, or Mmacro=7. In such cases, the old magnitude refers to the part of the source spectrum on the right of corner frequency, not at the LF spectral plateau.

The converted *individual* Mw value will be based on the *average* Mw(Mold) relationship and thus may bear uncontrollable bias related e.g. to individual stress drop or stress parameter value.

For these cases of less relable conversion it seems preferable to use the denotation **"proxy-Mw", or pMw**.



3.2. From M-old to proxy-Mw or quasi-Mw: how or where to get a good conversion rule?

•***Theoretical.*** **Derive** the conversion rule on a theoretical basis. Gives invaluable general orientation but normally needs nonexistent input. Helps to discard implausible ways of data fitting

•***Empirical 1.*** **Construct** the conversion rule from scratch performing regression analysis over (Mold, Mw) pairs…
problems: scatter, insufficient data at high-M side, biases at low-M side, **unwarranted linearity assumption**

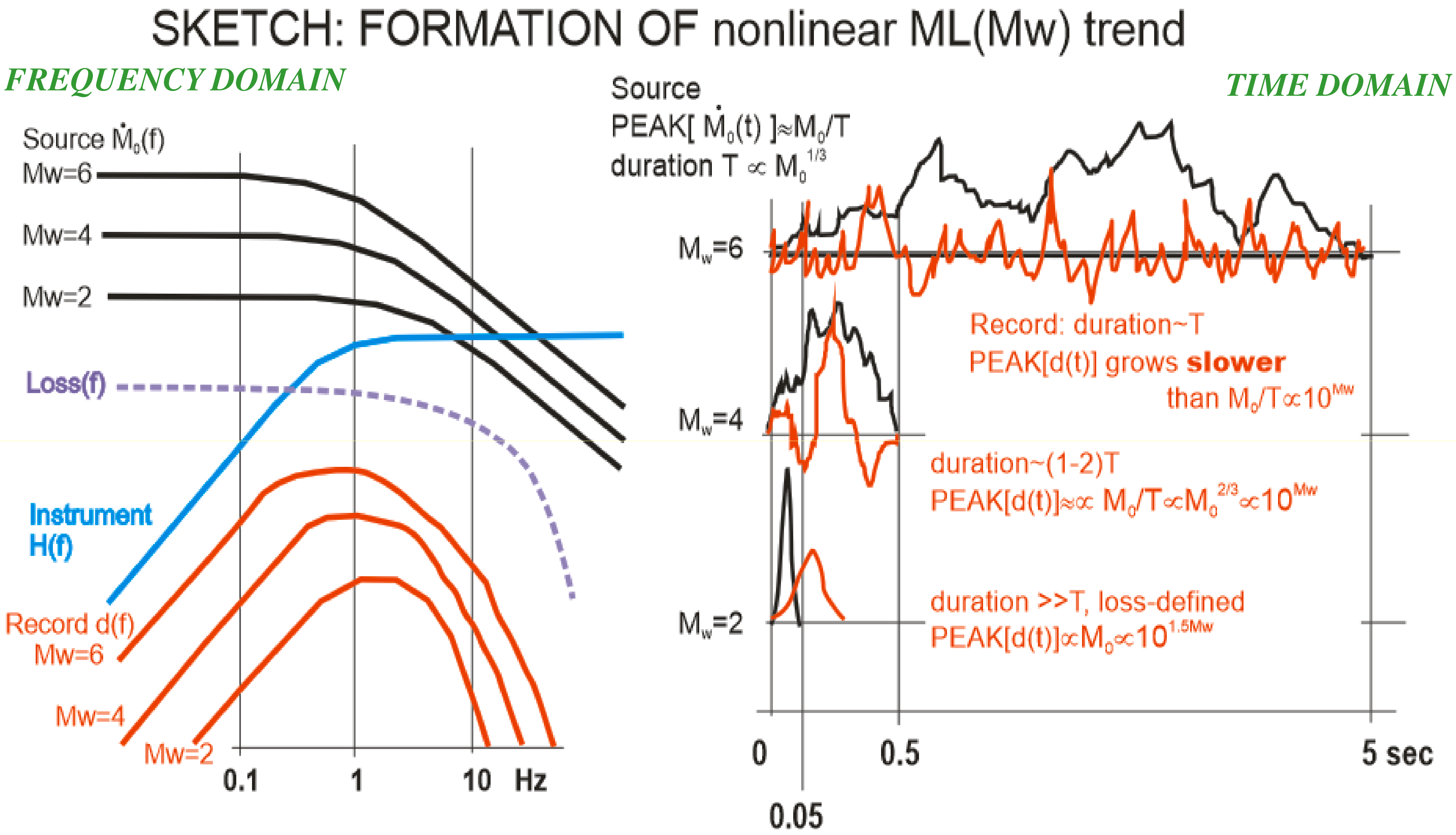
• ***Empirical 2.*** **Borrow** it from a **good(!)** global/alien fit:

2A: as is (*too crude a line*)

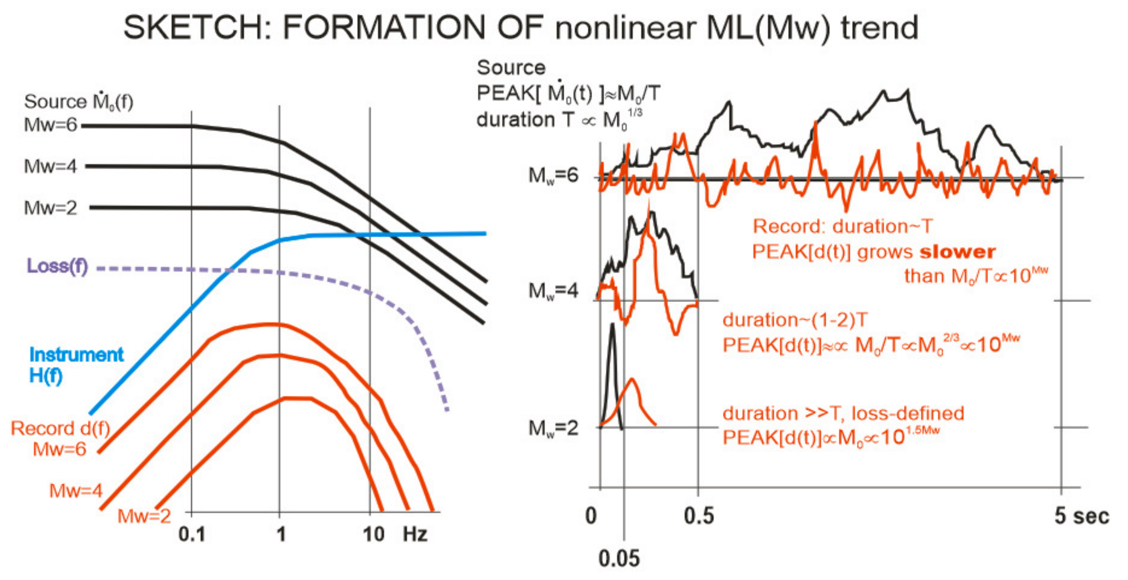
2B: keep the shape and adjust the level using local data (*often: near-optimal line*)

• ***Hybrid (semi-empirical).*** **Fit data** using/adjusting theoretical shapes. (*near-optimal but troublesome*)

3.3. Deriving a theoretical conversion rule: ML or mb vs. Mw



Deriving a theoretical conversion rule: ML or mb vs. Mw (2)



$M = \log(A_{peak})$+const

$\beta = d\log A_{peak}/d\log M_0 =$

$= dM/d\log M_0$

$10^M \propto A_{peak} \propto M_0^{\beta} \propto 10^{1.5\beta Mw}$

β monotonously decays with Mw

Ideal case (point source, uniform medium, no loss, no scattering):

duration = $\tau \propto M0^{1/3} \propto 10^{0.5Mw}$; $10^M \propto A_{peak} \propto M_0/\tau \propto M0^{2/3} \propto 10^{Mw}$ $\beta=2/3$

SP record:

at M=1-2: τ=const(loss+scattering); $A_{peak} \propto M0/\text{const} \propto M_0^1 \propto 10^{1.5Mw}$ $\beta=1$

at M=4-5: $\tau = T \propto M0^{1/3} \propto 10^{0.5Mw}$; $A_{peak} \propto M_0/T \propto M_0^{2/3} \propto 10^{Mw}$ $\beta=2/3$

at M=6-9: $\tau = T \propto M0^{1/3} \propto 10^{0.5Mw}$; $A_{peak} \propto M_0^{\beta} \propto 10^{(1.5\beta)Mw}$; $0.25<\beta<2/3$

at M=8-9; assuming ω^{-2} spectrum: $\beta \approx 0.20$; in fact $\beta \approx 0.23$;

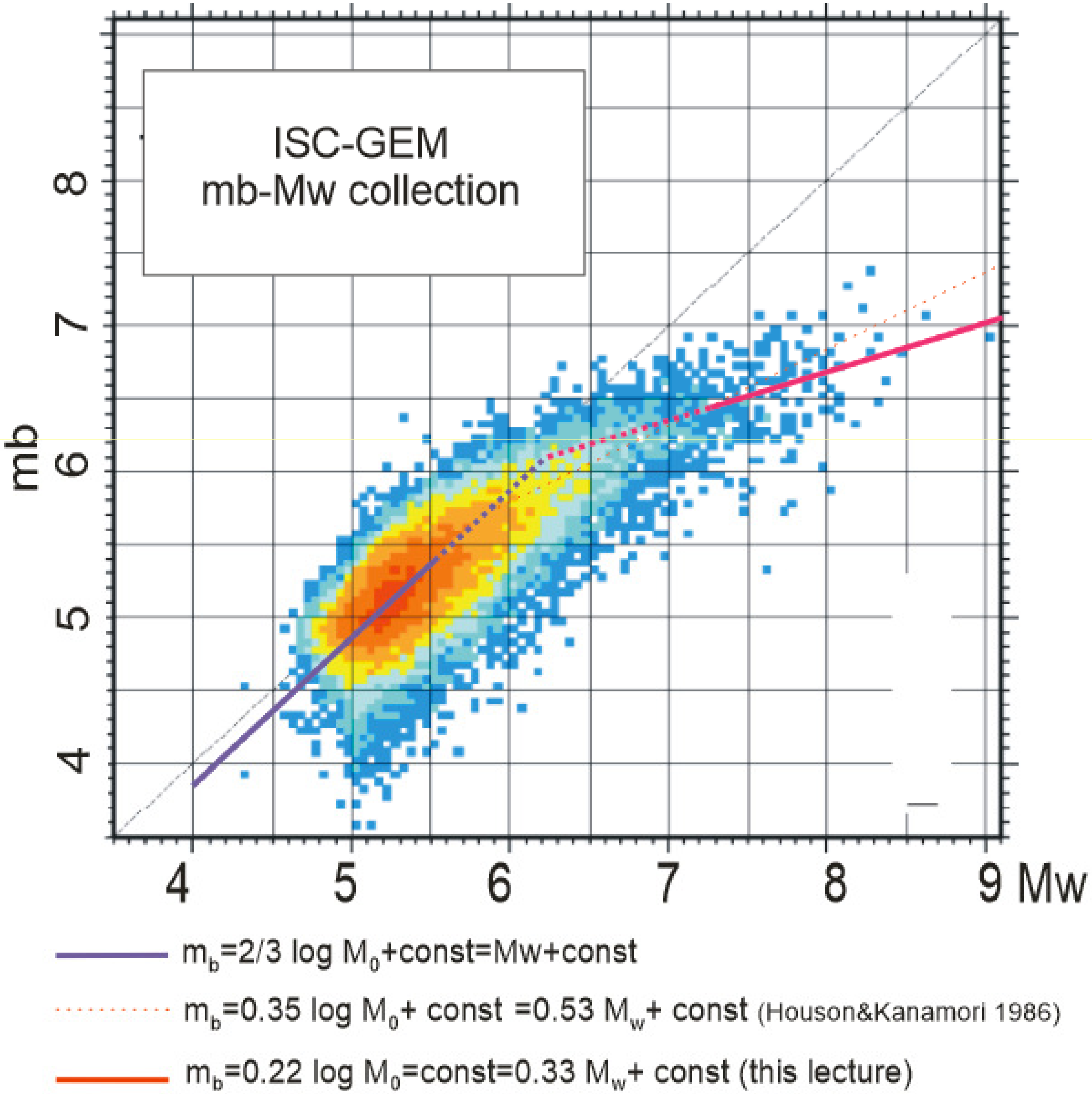
$A_{peak} \propto M_0^{0.23} \propto 10^{0.34Mw}$ (apprx)

Empirical vs. theoretical conversion rule: mb vs. Mw, cont.

1-s-instrument at M=4-5: duration = $T \propto M0^{1/3} \propto 10^{0.5Mw}$; $Apeak \propto M0/T \propto M0^{2/3} \propto 10^{Mw}$

at M=6-8: duration = $T \propto M0^{1/3} \propto 10^{0.5Mw}$; $Apeak \propto M0^{\beta} \propto 10^{(1.5\beta)Mw}$; $\beta=\beta(M)$; $\beta<2/3$

at M=8: assuming ω^{-2} spectrum: $\beta \approx 0.20$; in fact - $\beta \approx 0.22$;



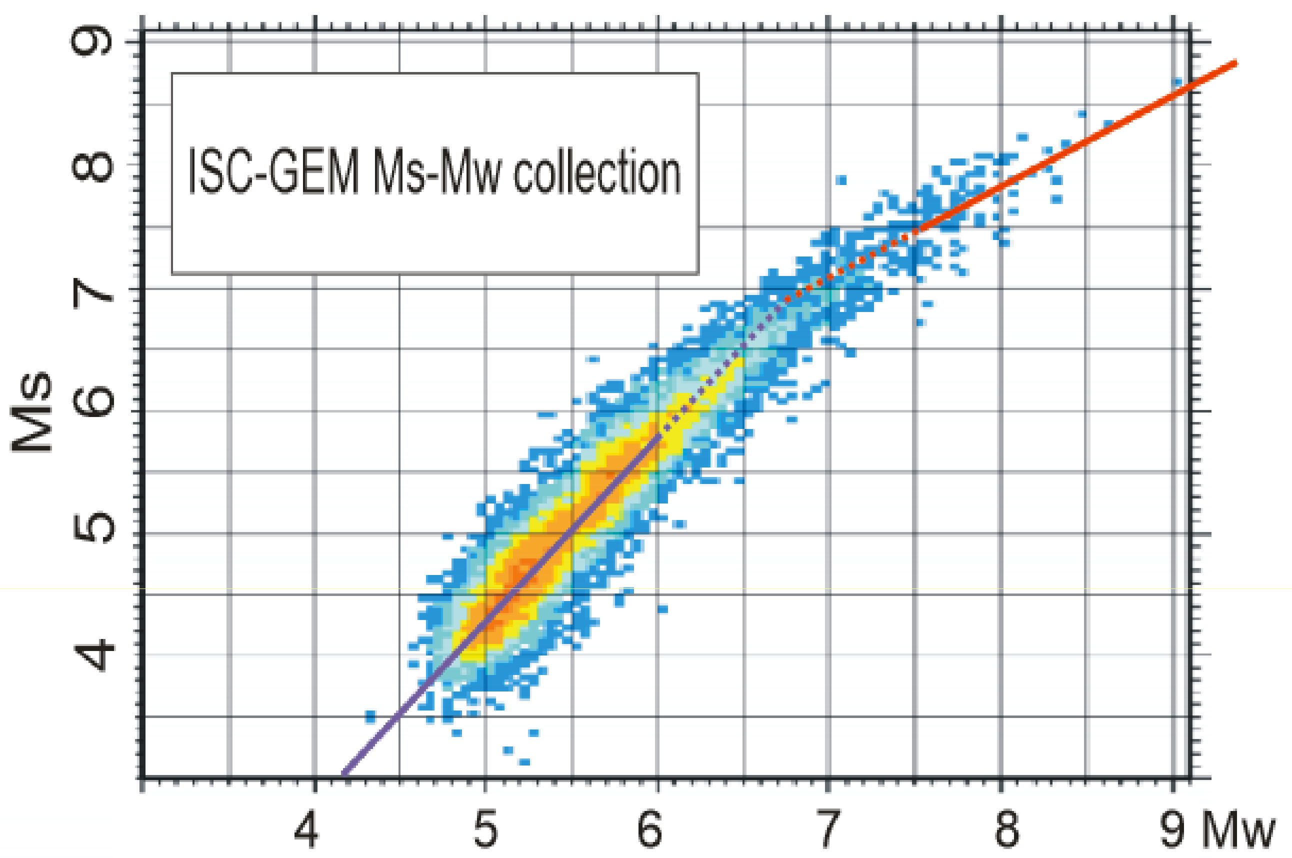
Key features of the true-mb vs. lgM0 trend:

(1) at low M0: aprx. straight-line

(2) at high M0: aprx. straight-line **no true saturation**

(3) general shape: **hyperbola-like**

Empirical vs. theoretical conversion rule: Ms vs. Mw



Key features of the Ms vs. lgM0 trend:

(1) at low M0: aprx. straight-line

(2) at high M0: aprx. straight-line no true saturation

(3) general shape hyperbola-like

at M=4-5: A(20s) $\propto M_0 \propto 10^{1.5Mw}$

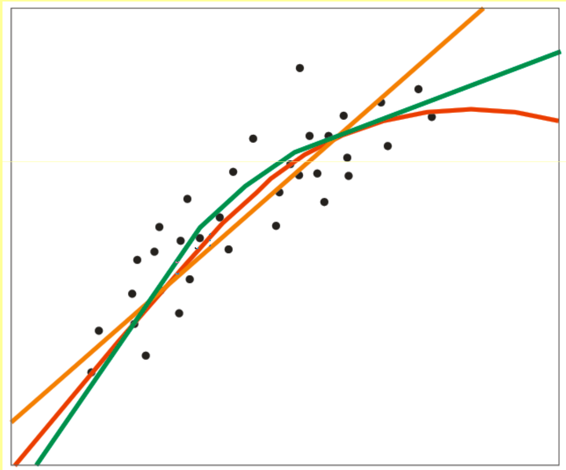
at M=8-9; : $\beta \approx 0.50$ fits $\omega^{-1.5}$ spectrum

3.4. Approximate ranges of non-moment magnitudes that may provide more adequate ("quasi") or less adequate ("proxy") estimate of Mw

kind of M	its basic *f* range	Apprx. thresold Mw	Mw range	H range	kind of result
ML, M-macro	0.5-10	**5.5**	2.5-5	all	quasi-Mw
			5.5+	all	*proxy*-Mw
mb, mSKM	0.7-1	**5**	3.5-4.5	all	quasi-Mw
			5+	all	*proxy*-Mw
Ms(20), or Ms(BB)	17-23 or 10-25	**6.5-7**	4-6.5	surface	quasi-Mw
			7+	surface	*proxy*-Mw
mB	3-10	**6-6.5**	4-6	all	quasi-Mw
			6.5+	all	*proxy*-Mw
M-tsunami	-	**-**	all	surface	quasi-Mw

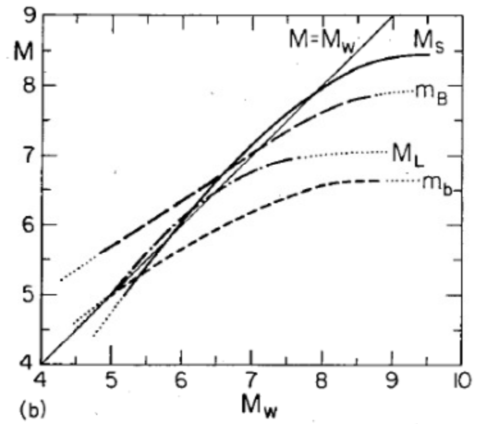
3.5. What to do and not to do when compiling M-Mw conversion rules

- **Do not** use **straight-line** approximations: they make poor predictions outside data span; often over-predict at high Mw.
- **Do not** use **quadratic** approximations: they make poor predictions above data span; often under-predict at high Mw, can predict negative slope at very high Mw.
- Expect **hyperbolic** (Mold:Mw) average trends.



On M-Mw conversion rules (2). The issue of "saturation"

SUPERCEDED by later work:



(1) Forget about **saturation of MS, mB, mb etc. at high Mw.**
Treat **(Kanamori 1983)**
as outdated (superseded by his own work).

(2)The case of **ML** is **very special**. Situation depends on the balance between **hypocentral distance, R, and source/fault size, L.**

At a high R/L ratio, situation is identical to that of the teleseismic case; ***saturation is nonexistent***, and the standard procedure of determination of ML is applicable. Typically, this is the case of **small Mw**.

At R/L<0.5-1 (at a close distance from a finite/extended fault) ***very real saturation* of amplitude** arises. Amplitudes at a band-limited instrument (real or emulated) do not increase with Mw, be it acceleration, velocity or HF displacement. **In this case, the standard procedure of determination of ML becomes invalid!!!** Typically, this is an infrequent case of **large Mw**.

EXAMPLE: Consider a local station at a fixed distance (say, 25 km) from a seismically active fault and a series of earthquake sources with increasing Mw on it. At Mw=7, L≈50. Thus, at Mw<<7, there is no saturation. At Mw>>7, amplitude (and the formal ML estimate) shall saturate at a value about 7. Note that Mw=9, the crossover distance can reach 250 km!!!

CONCLUSION: The standard ML determination procedure (based on M-independent calibration curve) becomes invalid for stations at distances at R<L/2; this fact causes biased, too low ML values. This case is rare, but may be misleading.

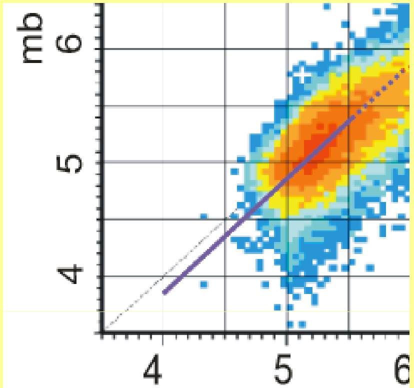
More recommendations on compiling M-Mw conversion rules

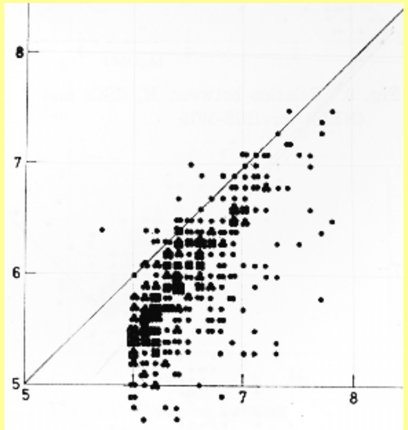
- Use orthogonal regression, but do not expect miracles.
- Prefer robust nonlinear orthogonal regression

Be careful at the low-M edge of data set:

- (A) Non-physical limits on data can radically distort your trends. Do not use orthogonal regression here; or sacrifice a part of data in order not to obtain an “accurate” but stupid result.
- (B) At the lower M limit of the network coverage, beware of (positive) bias from data produced by unusually sensitive stations. Use station corrections when possible

Examples of case A





4. Non-seismographic magnitudes

1. **Macroseismic magnitude**
(Kawasumi 1952; Rautian&Dotsev 1978).

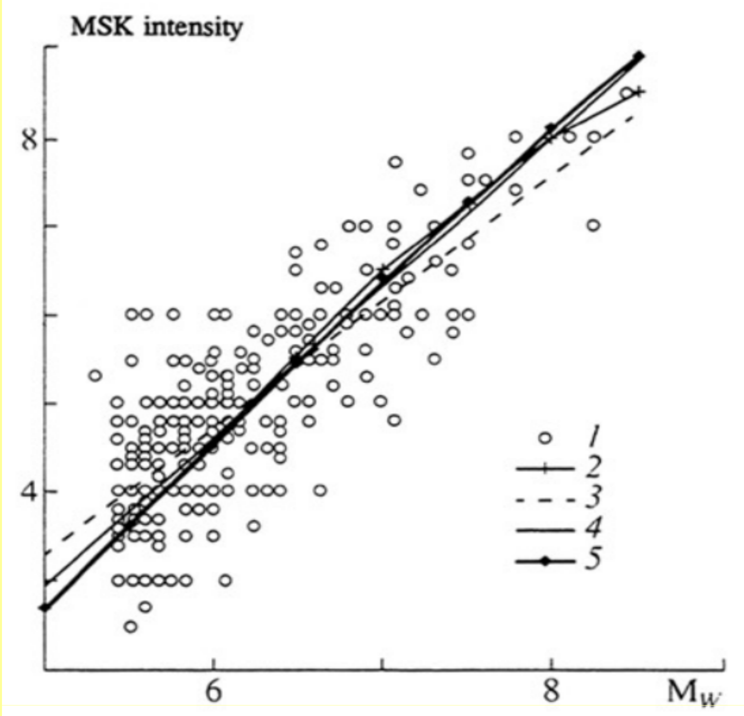
Based on macroseismic intensity *at a considerable distance*, typically 100 km, where near-fault saturation of amplitudes is absent or weak.

Another quite efficient but somewhat less accurate option is to use "**felt radius**"

M-macro is a powerful tool for analysis of historical data.

Qualitatively different parameter is macroseismic magnitude based on *epicentral* intensity.

It is more popular, but it cannot be recommended, because it must be strongly distorted by near-fault saturation of HF amplitudes.



Macroseismic intensity values reduced to r=100 km (≡Mmacro), vs. Mw for continental Northern Eurasia (fSU).

(Gusev&Shumilina 1999)

Non-seismographic magnitudes. (cont.)

2. **Tsunami magnitude** Mt is capable to estimate Mw for old earthquakes.

Proposed (Abe 1979) to estimate Mw of distant events from tsunami amplitudes.

Local tsunami data can also be used to judge about Mw, combining inundation heights and the extent of the flooded coast.

Paleo-tsunami data sometimes can be used to derive magnitudes of coastal earthquakes.

3. **Seismo-geological magnitude estimates**. Can be based on:

Paleo-dislocation data. M estimate is based on length of the structure and severity of long-living effects

Trenching data. M estimate is based on single-event slip and sometimes on rupture length when slips found in adjacent trenches across a seismogenic fault have the same date.

Turbidite/seismite data derived from disturbed layering of sediments at sea/lake bottom. M estimates may be uncertain.

Part 5. Magnitude section of a catalog aimed at hazard estimation.

5.1. Issues with homogeneity of magnitudes

- The catalog should be methodologically homogeneous, and based on uniform event size quantification (proxy-Mw). Rules used for between-magnitude conversion (ML=>Mw etc.) must be fixed and documented
- One can identify network calibration problems by checking up whether the lower magnitude threshold of the catalog varies in time.
- Expect biased M estimates at the low-M catalog edge from unusually sensitive stations. The cure is determination and use of station corrections
- Historical data may be quantified in M values of unspecified kind. No ready solution
- Network operators sometimes change the magnitude determination procedures without any published trace.

5.1. Homogeneity (continued)

Instabilities in magnitude determination procedures may be related to:

- the change/adjustment of calibration function/curve, or of the set of station corrections, often tacitly,
- the change from manual to automatic amplitude measurement procedure; or between automatic procedures
- the change of or within instrumentation. The change of damping that was not accounted for resulted in overestimation of M values in "Seismicity of Earth" by 0.3-0.5 for all events before 1912 (Abe and Noguchi 1984).
- when manually serviced stations in valleys are replaced by automatic/ telemetry instruments on mountain tops, this can introduce large site amplification, and severely distort network magnitudes values with no showing up. The cure is not to use station corrections anchored at network averge; ***station corrections must be anchored to a permanent station***.
- miscalibration of instruments; it can result from human error of from the lack of long-term stability of parts. Too large confidence can be put on producer's instrument calibration. It may be useful to systematically compare microseism or coda amplitude ratio between components of a station, and/or between adjacent stations.

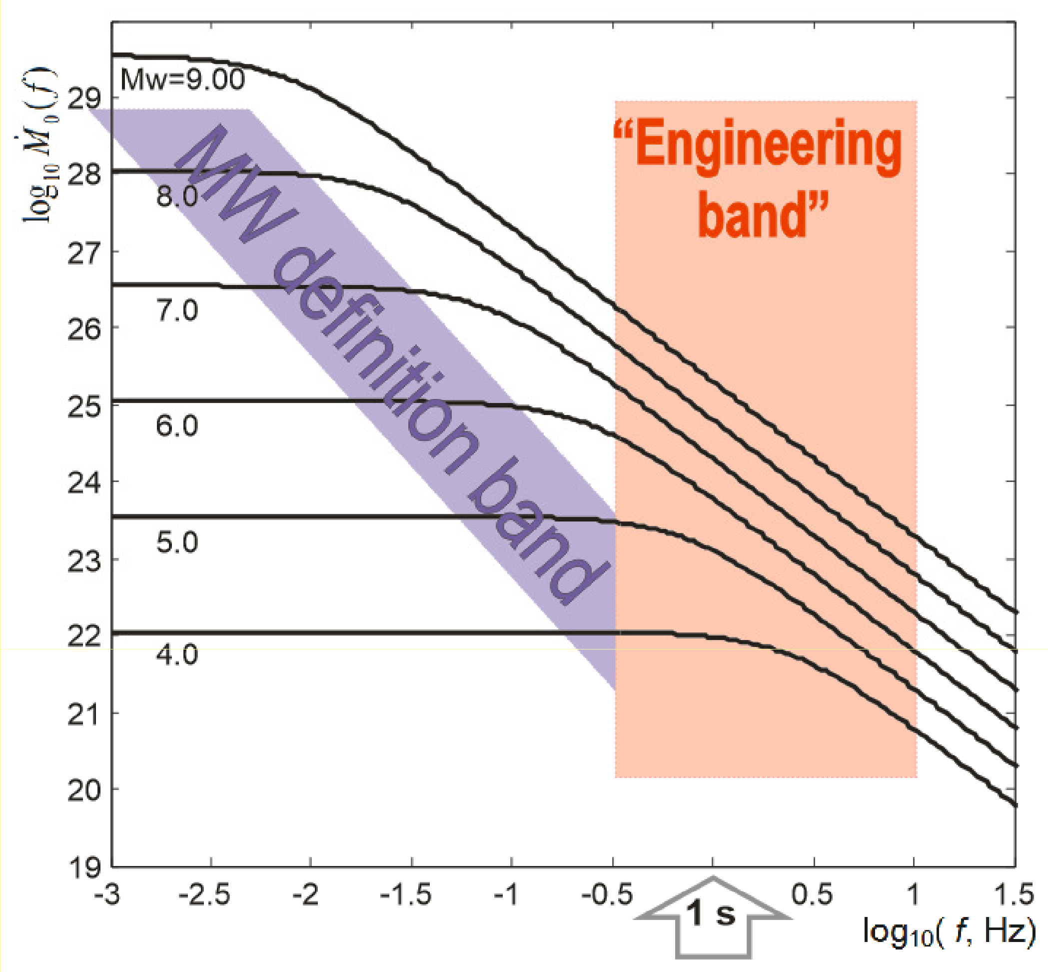
5.2. There is a methodological issue regarding use of old and new maginutudes for hazard studies

For large earthquakes:
macroseismic or ML-style data, and engineering effects, on one side,

and **Mw**, **on another side**,

are related to *separate parts of spectrum*.

The larger is M, the larger is separation.



For a large earthquake, engineering effects, and Mw are related to **separate part of spectrum**

Thus, Mw is hardly sufficient for use as a single size/scale parameter for prediction of engineering effects (load etc).

For this reason:

(1) For old data, the cautious policy is **to store M_{macro}, mb and ML, etc as a part of the hazard-oriented catalog.**

(2) Generally, for old and new data, it seems probable that future catalogs will store, in addition to Mw, some "**HF magnitude**".

There are a few ready options:

- **energy magnitude M_e** (***Choy and Boarwright***)
- m_1 (1-Hz log Fourier spectral level) (***Atkinson***)
- log***AHF*** (AHF is source acceleration spectrum plateau level) (***Dan, Irikura***)

A possible alternative is the cataloguing of the values of

(1) stress drop, AND (2) stress parameter

5.3. Miscellaneous

- keep all old M values (and proxy-Mw values derived from them) as additional obligatory entries in the catalog. Follow Engdahl&Villasenor who reserved eight slots in the event line to fill them with various magnitudes; each slot, when filled, includes both the code and the value of M-old.

- do not round off the proxy-Mw values; until making final list use the 9.99 number pattern, and keep the reserve digit despite its apparent redundancy

-before 1973, USCGS (now NEIC) did not supply Ms(20), so Ms(BB) of Obninsk (called MLH) is the only source of mass LF proxy-Mw estimates after the termination of Rothe's list.

-modern versions of Ms (Ms(20) and Ms(BB)) differ by ~0.2 from the Gutenberg's Ms scale of "Seismicity of Earth"

-until 1912, the M values of "Seismicity of Earth" are exaggerated, as found by Abe&Noguchi 1984.

Part 6. Example regional catalog with systematic use of proxy-Mw: the case of large Kamchatka earthquakes

(Gusev&Shumilina 2004)

Table 3. Catalog of Kamchatka earthquakes

Date	Epicentral coordinates		Depth H, km	Magnitudes									
				1	2	3	4	5	6	7	8	9	10
	deg N	deg E		M_{NC} (M_{LH})	M_{GR} (M_{Rothe})	M_S^{GR}	M_S^{US} (M_m)	m_B	M_W (M_S)	M_W (m_B)	M_W (M_0)	M_W (M_t)	M_W
October 17, 1737	50.5	158.0	(40)	8.3								9.2	9.2
November 4, 1737	55.5	163.0	(20)	7.8									(7.8+)
June 25, 1904, 14:00	52.0	159.0	(30)	7.7d	8.0	7.2		7.3	7.35	7.5			7.4
June 25, 1904, 21:00	52.0	159.0	(30)	7.7d	8.1	7.4		7.2	7.55	7.35			7.5
June 27, 1904	52.0	159.0	(30)	7.3d	7.9	7.2		7.0	7.35	7.15			7.3
July 24, 1904	52.0	159.0	(30)	6.9	7.5	(6.7)		7.1	(6.9)	7.25			7.0
September 15, 1905	53.0	164.0	(30)	7.0d	7.6	7.4		7.1	7.55	7.25			7.5
October 8, 1906	53.5	154.5	(200)	7.0	7.0			6.2		(6.2)			
March 4, 1922	53.1	158.3	220	7.4	7.0			7.1		7.25			7.3
February 2, 1923	52.5	160.5	(20)	7.0	7.25	7.2		7.3	7.35	7.5			7.4
February 3, 1923	53.0	161.0	(20)	8.5	8.3	8.3	(8.4)	7.7	8.7	8.2		8.8	8.5
February 24, 1923	55.0	162.4	(20)	7.7	7.4	7.3		7.4	7.45	7.7			7.5
April 13, 1923	55.4	162.8	(20)	7.3	7.25	7.2			7.35			8.2	8.2
August 19, 1925	54.4	168.6	(20)	6.9	7.2	7.0		7.3	7.2	7.5			7.2
November 4, 1952	52.3	161.0	(20)	8.5	8.25	8.2		7.9	8.6	8.7	9.0	9.0	9.0
November 29, 1952	52.8	159.2	40	7.3									

1. M(NC) of NovyyKatalog 1976. Before 1900: joint analysis of macroseismic and tsunami data expressed as (proxy) Ms; after 1900: Ms .

2. M=Ms(20) of "Seismicity of the Earth" (GR 1953) or Rothe(1962).

3. Same as (2) as corrected by Abe 1983 for instrument damping change in 1907-1912

4. Modern Ms(20); Mm of Okal is put into the same column

5. mB, after GR and Obninsk

6. proxy-Mw from Ms(20) and Ms(BB)

7. proxy-Mw from mB

8. Mw from Purcaru& Berkhammer (1983), or GCMT

9. quasi-Mw from Mt of Abe (1977)

10. summary Mw estimate

M-macro data had been already incorporated into M of Novyy Catalog 1976

Thank you

for your attention

Appendix follows

APPENDIX: MAGNITUDE: Q & A

1a-(Q.) How do we correct magnitude estimates for local attenuation variations?

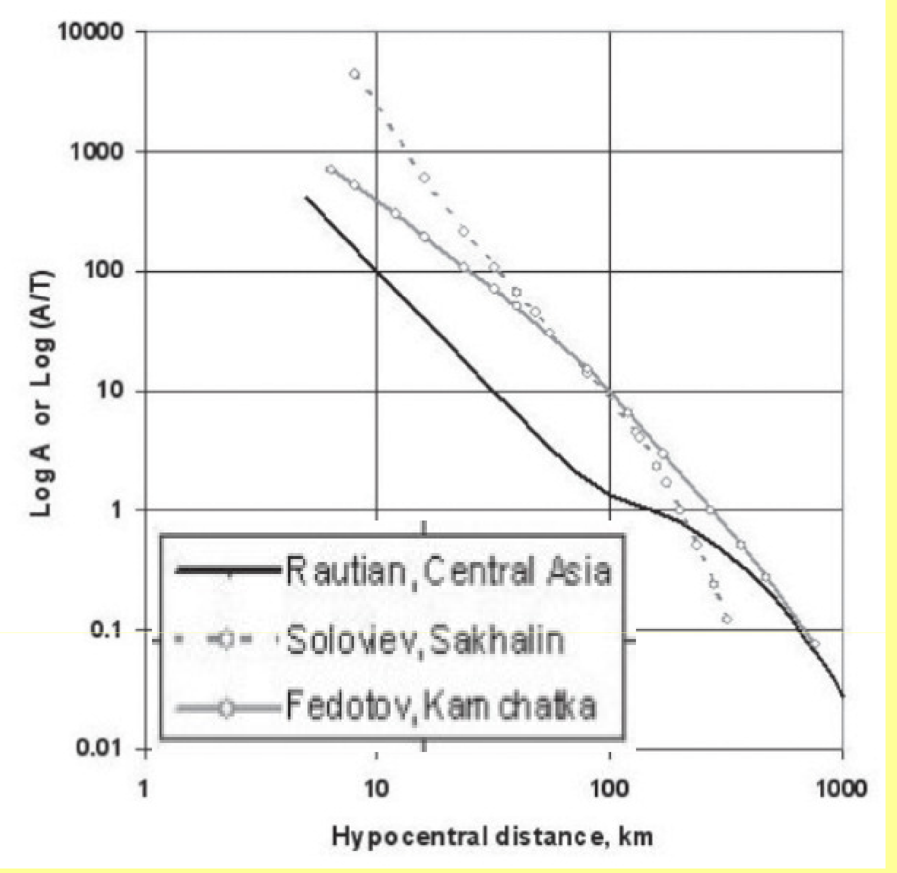
(A.) 1. Local attenuation variations (geometric spreading and loss) directly affect the shape of calibration curve; thus correction can well ne needed. Often it cannot be reduced to a constant shift, one may need to adjust entire calibration curve, and modify ML values station by station.

(A.) 2.The most prominent seems to be the difference between

• the continental case, where a calibration curve typically shows a flattening or bulge in the 70-120 km range (often manifesting Moho bounce) , and

• the subduction zone case where the Moho bounce is minor or absent.

Less prominent but quite significant differences do appear as well within each group



Example: calibration curves for 1-s-kind instuments, for: Central Asia (with flattening), Sakhalin-Kuriles, and Kamchatka (both with no flattening).

The difference between the last two curves seems to be produced mainly by the difference of instrumentation, with seismometer natural period of 0.6 s for Sakhalin-Kuriles, and 1.2 s for Kamchatka. (Rautian et al, 2007)

1a-(Q.) How do we correct magnitude estimates for local attenuation variations?(continued)

(A.) 3. The difference of levels of calibration curves is a minor issue as any difference may be compensated for through a constant correction term.

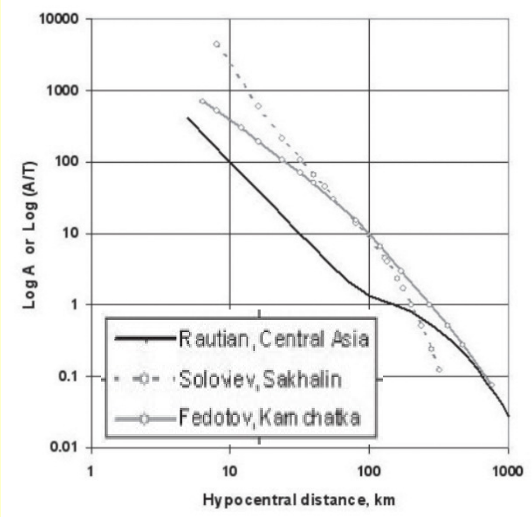
The shape of calibration curve (i.e. of amplitude attenuation function) may be a real issue. It depends on such factors as

- **given territory,**
- **instrument passband,**
- **source spectrum (M-dependent!)**

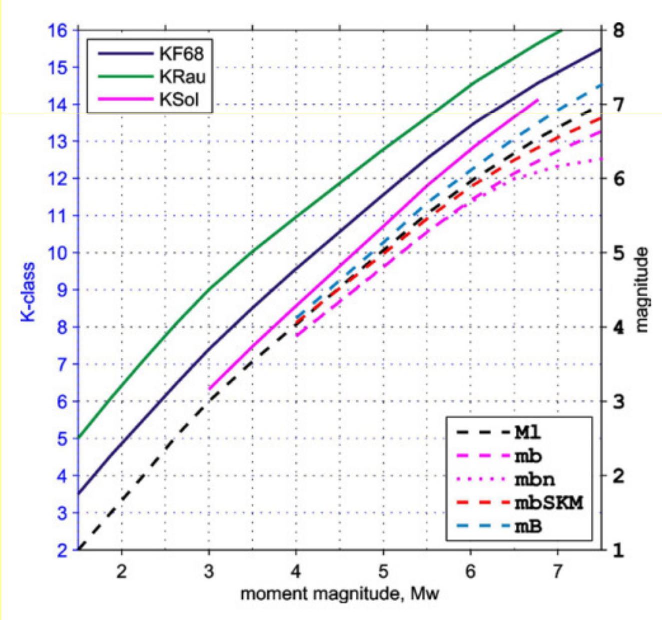
In the case of (relatively) narrow instrument passband, M dependence of calibration curve is often negligible.

In the case of broader instrument passband (like W-A), calibration curve is M-dependent.

Typically, this dependence is neglected



Plot 1. Fedotov's and Soloviev's calibration curves are for two networks with 0.6 s and 1.2 s instruments (Rautian et al 2007)



Plot 2. The difference of instruments (as explained above) results in non-identical slopes of ML(Mw) dependence:

Blue: Fedotov1968

Red: Soloviev

(Bormann et al 2012)

(the plotted curves are for

K-class= 2*ML+const)

1b-(Q.) How do we know whether our local corrections are valid?

(A.) It is difficult both to *define* and to *determine* "the true local magnitude" for a territory; thus the meaning of validity may be elusive.

The really important point is whether our observation/calibration system is intrinsically consistent. The following requirements must be fulfilled:

- **the network must be stably instrumented,**
- **the calibration curves in use must match**
  - **(a) to the area of study**
  - **(b) to the instrumentation/processing passband, and**
- **station corrections must be adequate.**

You can anchor your ML to mb, to Ms or to Mw, with anchor point around M=4.5-5. This choice is less significant. In the case of mb, chances are high that constant corrections/shifts occur sufficient for conversion; still, please verify.

1c-(Q.) Are local corrections needed for mb or Mw?

(A.)

The case of mb.

If you wish to convert global mb to your local ML or back, corrections may well be needed. Often, constant corrections may occur sufficient; still, please verify.

Also, mb to Mw average relationships (and thus such conversions) may be different for different event populations

The case of Mw.

Mw is a transformation of M0 in N·m and conceptually corrections has no sense in this case.

Still, a certain problem may well exist: Mw estimates of different networks and methods may show systematic differences among them (still, rarely in excess of 0.2).

In this case, one can select a preferable source and adjust data from other sources using constant corrections

2. (Q.) Are the limitations applied for ML, mb, MS, Mw and their variants, in ranges of distance, magnitude, ground motion frequency, etc., likely to be extended?

(A.)
For ML, mb, MS: hardly so, as the mentioned limits are based on large experience.

For Mw: no limits in principle, but the available data may not permit to estimate Mw (sufficiently dense station network is absent or impossible)

In my opinion, the fully consistent magnitude system should be

$$M_w(f),$$

i.e., the transformation of (entire source spectrum in N·m). The common Mw is Mw(f|f=0). All other magnitudes can be approximately converted to Mw(f) estimates for particular bands related to passbands of the instruments/ techniques used in the definitions of ML, mb, MS.

Even when S/N ratio is prohibitively low at low frequency, and Mw is unknown, one may manage to find $M_w(f)$ over some frequency band; otherwise the event cannot be observed at all.

The $M_w(f)$ magnitude system is an absolute one and therefore has no limitations of the listed kinds.

3. (Q.) If the magnitude data from the past ~100 years is to be useful, do we need to continue to compute values from current earthquakes using the original scales so that conversion relationships can be developed, and if so, for how long?

(A.) Indeed, ML, mb, MS of modern events are needed for constructing good conversion rules; these M should be continuously determined, may be for a few decades.

But this is not a complete story.

I doubt that the Mw scale is sufficient for seismological studies. Some high-frequency parameter is needed in addition, be it Me, or Mw(1Hz) or what else. Until this tradition establishes, some parameter like ML seems to be very useful.

An evident option (alternative or not) is to add the value of stress drop to a catalog. This is a conceptually reasonable option, but **TWO stress drops must be used in parallel**:

- **true Ds** with geological /dislocational underpinning, (on the order of μ*(slip)/(width)) and
- **"stress parameter"** of Boore and Atkinson, which is indispensable for prediction of strong motion in hazard studies, and related to dynamics/statistics of rupture

These two parameters should never be confused.

Still, for small earthquakes, their estimates may occur to be identical

4. (Q.1.) Where does the 1.5 (or 3/2) often used in the conversion from moment to Mw come from?

(A.)

(1) Historical factors, which in fact have a solid foundation

(2) For unbounded elastic medium, assuming similarity of sources, and relating M to wave displacement amplitude

Duration $\propto M_0^{1/3}$

(Peak displacement amplitude) $\propto M_0$ / Duration $\propto M_0^{2/3}$

M=log(Peak displacement amplitude)+C=2/3 log M_0+C

(Q.2.) Does this affect the applicability or comparability of Mw values?.

(A.2.) No

5.(Q.) Does the use of Mww, Mwp, Mwb, Mwc, etc, simplify the magnitude problem, or further complicate it?

(A.)

Mww is a “good” Mw, only determined by a specific technique; no complications arise.

Mwp (and its modifications) is, conceptually, no more than “dirty” or proxy Mw invented specially for tsunami warning use; need not be catalogued if better estimates are present.

Still, in a modified form (Abubakirov 2016) Mwp occurred to have rather high accuracy, representing a “quasi-Mw”.

6 (Q.) If ML, mb and MS are based on ground motion displacement, and Mw is based on earthquake source moment, is there any reason to expect them to have a simple relationship?

(A.) **Of course there is no such reason!.**

For each M-Mw pair, there is a global-average relationship, always nonlinear, approximately hyperbolic, that can be adjusted for each earthquake population. Typically, adjustments may represent constant shifts, but no guarantee.

Here "population" denotes a region, a subregion, a local spot, and a depth range in each case. The particular choice depends. For a subduction environment, land/ocean separation and 2-3 depth ranges seems to be a must.

Note an important distinction between "quasi-Mw" and "proxy-Mw" in the main body of this lecture. In other words, even accurate average Mw(M) conversion rule will be of different accuracy for lower and higher M.

7. (Q.1.) Is it possible to describe the 'size' of an earthquake by a single simple scalar number called magnitude?

(A.1.) Definitely no

(Q.2.) If not, how many numbers do we need?

(A.2.) For point source representation, Mw(f) (=source spectrum) sampled each 2/3 octave (5 points per decade) looks as a possible balance between sufficient details and not too big amount of figures. Over the 10s-30 Hz range, this is 12 numbers. I shall show at the meeting a raw version of how this can be done. As an alternative, the combination of stress drop and stress parameter may work.

Finite-source description needs much more.

(Q.3.) Will these be the same for geologists (rupture size, fault slip) and hazard studies (frequency content, stress drop)?

(A.3.) Neither geologists nor hazard people will probably be satisfied with point source representation. They additionally need finite rupture parameters. Here is my minimal list of parameters which must be added to source spectrum, for geologists (G), earthquake hazard people(EH) and tsunami hazard people (TH)

- **length, width (G, EH, TH) ,**
- **slip (G, EH, TH),**
- **duration (EH, TH) ,**
- **rupture velocity (EH, TH) ,**
- **degree of asymmetry of rupture [uni/bi-laterality] (EH, TH)**

Also, hazard studies also require statistical parameters (distribution law, its parameters, correlation properties in space and time) for wave amplitudes, slip, rupture velocity. Nether peak nor average values are sufficient.

8. (Q.)Do earthquakes smaller than ML, mb, MS, Mw = 5 provide a significant hazard?

(A.) South Africa, Poland and many other locations are known for rockbursts

Recently, hydrofrac–generated shocks become famous, but this sort is known for long.

With no active underground interference, bad luck can happen. The center of Tashkent was destroyed by M5.3 event. Was this significant?...