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Education matters

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It is a sad truth that in the present era of compressed undergraduate courses few students of geophysics get to study seismology.

Last year, during a collaboration between Deakin, Melbourne and Monash Universities on using seismometers for the unlikely task of detection of megafaunal bone beds, I asked Gary Gibson to clarify for me the meaning of the many measures of earthquake magnitudes and, with tongue somewhat in cheek, I also asked for his comment on our 2016 ASEG conference logo. Gary is a Principal Research Fellow at Melbourne University, and one of Australia's most senior seismologists.

25th ASEG-PESA-AIG conference logo.

Gary's discussion of quake magnitudes, ranging from rumbles we barely feel to those which notionally split the earth, appear in the article below.

Emma Brand, Chair of the ASEG Education Committee, also brings us a review of the role of the Committee and advance notice of two forthcoming OzStep courses in our continuing professional education programme; with one seismic and one EM-inversion course, there is something for each of us to enjoy as we sharpen our skills.

Earthquake magnitude 12?

Gary Gibson
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We hear about very large earthquakes with magnitudes 10 or 12, especially from fiction writers and Hollywood, but just how large can an earthquake be?

Earthquakes vary widely in scale. The largest earthquake recorded (Chile, 22 May 1960, (energy) moment magnitude Mw 9.5) released about 106 times as much energy as Australia's most damaging earthquake of recent decades (Newcastle 1989, ML 5.6). Extending the scale, the Chilean Mw 9.5 quake released 1012 times as much energy as a very small earthquake that is only felt within a couple of kilometres (ML 1.5) – such as minor movements in the Sydney basin. More on the different units Mw and ML is given below.

An earthquake is the motion produced when stress within the earth exceeds the strength of a fault, which then fails, with one side of the fault moving (slipping) relative to the other giving a permanent displacement. The point on the fault where the rupture starts is called the earthquake hypocentre or focus, and the point on the earth's surface vertically above it is called the earthquake epicentre.

Once started, a rupture can propagate predominantly in one direction from the hypocentre, so that the hypocentre may be at one end of the rupture (e.g. Nepal, 2015, Mw 7.9). Alternatively, it can propagate in all directions so that the hypocentre may be near the centre of the final rupture (e.g. Chile, 2010, Mw 8.8).

Much energy is required to maintain the propagation, with most being converted to heat and some to seismic wave energy. The fuel maintaining the rupture is the available stored tectonic strain energy in the volume surrounding the fault. If the fault ruptures into an area without high stress (i.e. with low tectonic strain energy density), the rupture will slow and/or stop.

As the tectonic deformation continues the strain, strain energy density and stress rebuild, and the weakest point on the fault is the likely location of the initial rupture for future earthquakes. After each earthquake the total slip between the two blocks increases and the fault dimensions (length, width, area) may increase slightly, so the fault may be capable of a slightly larger earthquake next time. The fault may eventually become the dominant fault within the locality, and will be the mechanism for most of the strain energy release within the vicinity.

Earthquake size can be measured in many ways, such as energy release, fault rupture length, duration of motion, radius of perceptibility, and especially the level of ground motion recorded at a seismograph some distance from the earthquake.

Energy release is difficult to measure because the proportion of energy released as heat and seismic ground motion varies, the seismic wave radiation pattern varies with direction depending on the orientation of the fault, and the absorption of seismic wave energy with distance varies with geology, leading to uncertainties in attenuation of ground motion with distance, especially for the higher frequency motion experienced from smaller earthquakes.

Earthquake magnitude scales are defined to characterise the size of an earthquake using one of these measures, most commonly a measure of earthquake ground motion.

These can include measures of motion that are permanent, such as the area, length, width or the slip that occurs during the earthquake. They can also be measures of the transitory seismic wave motion as recorded on seismographs, with the wave motion measured as displacement, velocity or acceleration, usually recorded as a function of time in three orthogonal directions (east, north and up). This motion can be simplified by using parameters such as peak ground displacement (PGD), velocity (PGV) or acceleration (PGA), or alternatively using parameters relating to the spectral content (also using displacement, velocity or acceleration, and three components).

Unfortunately, the ground motion measurements possible vary greatly from small to large earthquakes, and from near to distant earthquakes. This has resulted in a range of different magnitude scales from ground motion measurements that are each applicable for certain magnitude ranges, and distance ranges.

For example, the original Richter magnitude, ML, is used for small earthquakes recorded within 600 kilometres. This takes the logarithm to base 10 of the peak body wave (P or S) horizontal ground displacement and applies a simple empirically determined correction for attenuation that varies with distance. This depends on the properties of local rock types, with unconsolidated sediments giving rapid attenuation with distance, while hard crystalline rocks (e.g. Australian Shield) give relatively little attenuation with distance beyond inverse square geometric spreading.

The body wave magnitude, mb, is used for moderate magnitude earthquakes beyond 2000 km, also uses ground displacement and has a tabular distance correction that corresponds to the less variable attenuation of waves through the mantle compared with the dominance of crustal motion as used with ML.

A range of moment magnitudes Mw, Mww, Mwp, Mwc, etc are determined from long-period frequency spectra used for moderate to large earthquakes. The variation in spectral attenuation in crustal rocks limits the use of this method for nearby earthquakes, especially smaller earthquakes with dominant high frequency motion.

In addition, there are magnitude scales based on the duration of motion, MD, and radius or area of perceptibility, MP, used mainly for determining magnitudes of historical earthquakes.

All scales were defined to conform as closely to the Richter magnitude ML as possible, but since each uses a different measurement, the relationships are non-linear, and conversion plots or functions and range limits for magnitude and distance are needed. Since these are different depending on local geology, local differences in methodology and practice have developed.

It might seem reasonable that to reduce confusion, the magnitude should be converted to a single defined value. Modern conventions include the GSHAP method where magnitude M is based on ML, mb and Mw, over different magnitude ranges (ML or mb depending on distance for events below Mw 5.0, and Mw for those events larger than Mw 5.0), giving a scale that retains all past values.

An alternative is a trend to converting all magnitudes to Mw, although it is not easy to measure Mw values smaller than Mw 5.0, and certainly not less than Mw 4.0. This method also results in the need to re-compute millions of earthquake magnitudes (mainly ML and mb) using empirical conversion functions that will not be universally applicable.

Most earthquake hazard studies consider only earthquakes above Mw 5.0, as damage from smaller events is rare, so a conversion, if used, has little impact on hazard estimates. At this stage giving the magnitude type and value as measured, without a conversion, is probably the best we can do.

If an earthquake is very shallow it may rupture the surface. For some earthquakes, the surface rupture gives the total length of the fault, while for others the rupture may extend further at depth, so the surface rupture length is only a fraction of the total length. However, most earthquakes do not rupture the surface at all.

A better way of establishing the fault length and width is to install a high-resolution seismograph network that will allow determination of precise locations of aftershocks to an accuracy of one kilometre or less in longitude, latitude and depth. For this reason groups such as Geoscience Australia and University of Melbourne maintain boxed sets of seismographs ready for immediate shipping and deployment when a significant quake occurs on the continent, such as the Petermann Ranges (west of Uluru) earthquake of magnitude Mw 6.1 on 20 May 2016 (the largest earthquake within Australia for 19 years).

Aftershocks are often on the original rupture or around the edge of the rupture, thus delineating the rupture and allowing estimates of area, length and width. However, many aftershocks may be on smaller related faults and delineate the surrounding volume that has experienced stress change in the earthquake, rather than the main rupture itself. Although relatively few earthquake ruptures can be delineated, and these are mainly only for larger earthquakes, they are used to determine relationships between magnitude and fault rupture parameters.

The following table shows approximate empirical relationships between magnitude and several parameters such as rupture area, fault length and width, fault slip and rupture duration. Earthquakes vary from simple one fault ruptures to very complex ruptures, some have simple geometry (e.g. approximating a circular plane rupture or a rectangular plane as often used in theory) while most have varying rupture outline shape or varying slip across the rupture. The aspect ratio of a fault rupture can vary from length = width, to length = 10 times width or more, especially for large crustal faults.

The values of area, length, width, slip or duration will usually be within the range from half to double the quoted value, depending on the stress drop from the earthquake, with a higher stress drop giving smaller ruptures.

The slip value depends on fault strength, and gives an indication of the deformation needed to trigger the earthquake. The rupture duration depends on fault properties that determine the rate at which the rupture propagates across the fault plane, usually at about three kilometres per second.

The actual slip motion between the two sides of the fault at any point along the fault is much slower, and is usually up to a couple of metres per second. At such a point the time between the start of slip movement until the slip has ground to a halt will be measured in seconds for larger earthquakes, and fractions of a second for smaller earthquakes. This is a much shorter period than the total rupture duration along the fault as a whole, as described above. For larger earthquakes, by the time the slip finishes at one point on the fault, slip movement may have initiated kilometres away, further along the fault.

The table was empirically determined using earthquakes in the range from Mw = 4 to Mw = 8. Because of the

Table 1. Approximate fault parameter values as a function of magnitude. Extrapolation to magnitudes higher than about Mw 9.5 requires faults larger than are currently available

Moment magnitude Mw	Rupture area (km^2)	Typical rupture size Length × width (km × km)	Fault slip Length/20 000 (metres)	Rupture duration Length/3 (seconds)	Average number, World (per year)
4	1	1 × 1	0.05	0.3	20 000
5	10	3 × 3	0.15	1	2000
6	100	10 × 10	0.50	3	200
7	1000	30 × 30 50 × 20	1.5	10	20
8	10 000	100 × 100 200 × 50	5	33	1
9	100 000	500 × 200 1000 × 100	25	170	0.05
10	1 000 000	1000 × 1000 5000 × 200	50	333	0
11	10 000 000	3000 × 3000 30 000 × 300	150	1000	0
12	100 000 000	10 000 × 10 000 300 000 × 300	500	3000	0

arbitrary definition of the original Richter magnitude, it is probably just a coincidence that a magnitude Mw = 4 gives a 1 square kilometre rupture, and that there is a factor of 10 in rupture area for each unit change in magnitude.

For intraplate earthquakes within continents, where the seismogenic zone extends down to just tens of kilometres, usually just 20 to 30 kilometres, and faults are rarely much longer than 100 kilometres, the typical maximum credible earthquake is usually less than about Mw 7.5.

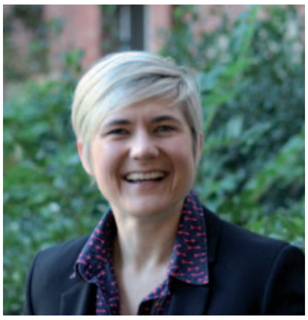
Large subduction interface earthquakes may reach a little over Mw 9.5, but require very long subduction zones (over 1000 km), and deep subduction that can give a rupture width extending down to about 300 km. The largest subduction zones are along the west coast of South America, the Tonga-Kermadec Trench south of Fiji, the Sunda Trench south of Indonesia, and the large trenches in the north-west Pacific (Aleutian, Kuril, Japan and Mariana Trenches). All known earthquakes larger than Mw 9.0 have occurred on these subduction zones.

For plate boundary earthquakes, large strike-slip earthquakes may rarely exceed Mw 8.5, because of length limitations along existing boundaries and especially because of rupture width limitations imposed by the shallow seismogenic depths available.

The table can be extrapolated down to smaller earthquakes, below magnitude 0.0 and will give reasonable estimates (within half to double depending on stress drop). If we extrapolate to magnitude 12, then the values for magnitude 9 seem reasonable, but for magnitudes 10 to 12 the fault lengths and/or widths available at plate boundaries are not enough to provide the tectonic strain energy needed. An Mw 12 quake implies a 10 000 km × 10 000 km displacement, comparable with the Earth's diameter of 12 742 km.

Perhaps the impact of a large object from space may give such an event. Or, returning to the question Michael Asten asked me last year, a truly earth-shattering ASEG conference might just do it!

The ASEG Education Committee: what can we do for you?



Emma Brand
ASEG Education Committee Chair
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2016 was a tough year, once again, for geophysicists. If you weren't personally affected by the cuts across the industry, I'm sure you will know plenty of friends and colleagues that were. It's not news to state that geophysics is a highly specialised profession. We are deep technical experts. In boom times our profession is in high demand and we are very well compensated for our skills. During down times the first cuts are to the exploration budget, which means our once highly prized, well compensated skill set is no longer valued by our industry. This leaves many of us in the unenviable position of having to fight it out against more and more candidates in a smaller pool of roles, waiting for the industry to pick back up.

The question that I posed to myself during the uncertainty of the last several years was: what happens if my role is made redundant? In an industry with very few new roles and an uncertain future, how do I 'future proof' myself? How do I ensure that I have a skill set that is mobile and flexible and, more importantly, if worst came to worst, understood outside of my industry?

As I took up the role of chair of the ASEG Education Committee late last year, stepping into the huge shoes left by Wendy Watkins, I began to think further about what it means to be a practicing geophysicist. Throughout my ten year career in the oil and gas industry I've interpreted seismic data and undertaken quantitative analysis, I've planned and drilled wells, I've worked on exploration prospects and on oil fields that have been producing for 50 years, I've planned and executed seismic surveys, I've managed people, I've managed projects, I've collaborated in multi-disciplinary teams.

How many times have you been to a dinner party and had to explain what it is that a geophysicist actually does? My typical line is that we work out what is in the ground without having to dig a dirty big hole. That might be all well and good over a cocktail but, if you had to, how would you translate your deep, specialised skill set and incredible range of experiences into something that is recognisable outside of our industry?

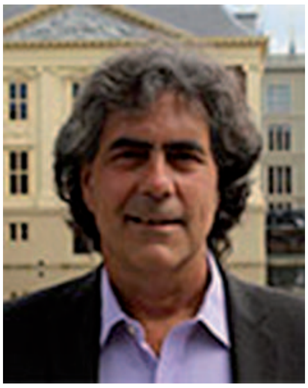
This year the Committee, consisting of the wonderful, thoughtful and experienced crew of Jarrod Dunne, Megan Nightingale, Chris Wijns and Tim Dean will tackle the broad question of how the ASEG Education Committee should respond to our current resource industry landscape in order to benefit our Members. For instance, how do we determine topics for OzStep? How can we provide the support needed to our Members to translate their skill sets outside of our industry? Should the Education Committee 'push' OzStep topics, or 'pull' topics that are requested by Members or is needed by the industry? Can we do more to address upskilling recent graduates into the industry? And more importantly, what else might our Members be interested in?

So, I throw this question out into the ether and solicit your responses: what would you be interested in seeing the ASEG Education Committee organise in 2017?

Upcoming OzStep courses: 'Reservoir Geophysics – Applications', a one-day course by Bill Abriel will be held at various locations in May. Doug Oldenburg will also be giving a course on EM-inversion. Stay tuned for more information.

SEG Distinguished Lecturer 2017: Paul Hatchell

Getting more for less: frequent low-cost seismic monitoring solutions for offshore fields



Paul Hatchell

Summary

Time-lapse seismic reservoir surveillance is a proven technology for offshore environments. In the past two decades, we have seen this technology move from novel to necessary and enable us to monitor injection wells, water influx, compaction, undrained fault blocks, and bypassed reserves. Value is generated by influencing the management of our field operations and optimising wells to reduce cost, accelerate production, and increase ultimate recovery.

Significant advances in technology are improving the quality of our data. Errors in acquisition repeats are nearly eliminated using permanently installed systems or dedicated ocean- bottom nodes. We now routinely obtain surveys with such a high signal-to-noise ratio that we can observe production-induced changes in the reservoir after months instead of years. This creates a demand for frequent seismic monitoring to better understand the dynamic behaviour of our fields. Increasing the frequency of seismic monitoring will have a proportionate cost implication, and a challenge is how to design a monitoring program that maximises the overall benefit to the field.

Reducing individual survey costs is important to enable frequent monitoring. Several techniques are considered for lowering these costs such as:

- Reducing the number of shots and/or receivers to minimise offshore vessel time. This includes shooting targeted (i4D-style) surveys on a frequent basis in between full-field surveys that are acquired infrequently.
- Use of smaller source arrays towed by less-expensive vessels.
- Semi-permanent ocean-bottom nodes that can be left on the seafloor for multiple on-demand surveys.
- Time-lapse VSPs that use permanent distributed acoustic sensors (DAS) in well bores.
- High-resolution 4D surveys that monitor shallow reservoirs cost effectively using low-cost vessels towing arrays of short-streamer cables (e.g. P-cable).

There is no single solution that works for every field, and we need to understand the pros/cons of the various technologies to select the best option for a specific field. Some results of applying these techniques to offshore fields will be discussed.

Biography

Paul Hatchell joined Shell in 1989 after receiving his PhD in theoretical physics from the University of Wisconsin. He began his career at Shell's Technology Center in Houston and worked on a variety of research topics including shear-wave logging, quantitative seismic amplitude analysis, and 3D AVO applications. Following a four-year oil and gas exploration assignment in Shell's New Orleans office, Paul returned to Shell's technology centres in Rijswijk and Houston where he is currently a member of the Areal Field Monitoring team and Shell's principal technical expert for 4D reservoir surveillance. His current activities include developing improved 4D seismic acquisition and interpretation techniques, seafloor deformation monitoring, and training the next generation of geoscientists.

Australian schedule:

3 April 2017	Perth	University of Western Australia
3 April 2017	Perth	ASEG WA Branch meeting