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The relationship between local seismic magnitude ML and charge weight for UK explosions

Earth Hazards Programme

Open Report OR/09/062

BRITISH GEOLOGICAL SURVEY

EARTH HAZARDS PROGRAMME

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D C Booth

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British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA
Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Forde House, Park Five Business Centre, Harrier Way, Sowton EX2 7HU
Tel 01392 445271 Fax 01392 445371

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF
Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

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Summary

Measurements of seismic local magnitude of explosions of stated charge weight on land and underwater in the UK region in the years 1987 to 2009, recorded at BGS seismological network stations, have been added to similar BGS data for earlier years. The results are presented and discussed as a guide to the estimation of the charge weight for explosions recorded in the UK.

1 Introduction

The British Geological Survey (BGS) provides objective information on seismic events occurring within the UK, to the government, media, the public, and academic, national and international research agencies. Information on large global earthquakes is also provided. BGS has monitored the seismicity of the UK since the late 1960s, using a seismograph network which has expanded over the years to cover the whole of the UK. In the 1990s, the network comprised up to 146 stations with an average station spacing of 70km and a detection threshold of 2.5 ML for onshore seismic events. With improved technology in the form of broadband instruments with better frequency response and dynamic range, emphasis has switched to providing fewer, better seismographs and the network is currently converting to a broadband network of about 50 stations.

The seismographs mainly record earthquakes and explosions, as well as other distinctive seismic events such as sonic booms, mine collapses, aircraft crashes and even rock concerts. The recorded explosions are mostly generated by mining and quarrying; others arise from exercises involving the military services, including mine and bomb disposal operations. Only one accidental explosion of estimable magnitude (the Buncefield oil depot explosion) has occurred which was well recorded by the BGS network (Ottemoller and Evers, 2008). Explosions caused by terrorist activity in the past few decades were not detected by the network, mainly due to their considerably smaller size, their location relative to the nearest BGS seismograph station, and poor coupling to the ground.

Most onshore explosions can be attributed by location and seismogram characteristics to known mines and quarries. Every year, BGS detects a variable number of seismic events offshore which generate seismograms consistent with an explosive origin, showing large, ground-up P-wave onsets with relatively little shear-wave energy. While many can be identified by information provided by mine disposal teams, coastguards, foreign monitoring agencies, etc., there are always some which remain unidentified. Some are probably spontaneous explosions of old munitions; for example, there is known to be a munitions dump in the Beaufort's Dyke area of the North Channel where occasional small magnitude explosions (< 2 ML) have been detected (Ford et al., 2005).

This report focuses on the explosive events occurring in the UK area, recorded by the BGS network. The object of the report is to present the measurements of recorded seismic magnitude of these explosive events and their charge weight or 'yield', as measured in pounds of chemical explosive, and discuss the factors which govern the relationship between them. It is not possible to estimate the yield for an explosion for a given seismic magnitude, with reasonable error bounds, without considering many contributory factors.

2 Data

The explosion data has been taken from the BGS catalogue of UK seismicity, and from a previous BGS report on seismic magnitudes determined on the first BGS seismic network in the Scottish lowlands (LOWNET) which was subsequently expanded to form the UK network (Jacob & Neilson, 1977). Jacob & Neilson (1977) provide tables of underwater explosions and quarry blasts. Most of the quarry blast data comes from their tables; an approach made to Scottish quarry operators during the author's study produced data from only two quarries, Hillhouse (Ayrshire) and Glensanda (Morvern) quarries, which are included. Data from a surface explosion on a munitions testing range at Spadeadam, Dumfriesshire, and the vapour cloud explosion which occurred at the Buncefield oil depot near Hemel Hempstead in December 2005, are also included.

BGS has detected and catalogued many more underwater explosions since the publication of the Jacob & Neilson report. Explosions in river estuaries and at sea have occurred due to mine or bomb disposal, structural demolition, or seismic experiments for research or surveying purposes. While BGS detects many underwater explosions in UK waters and in the English Channel and North Sea, in many cases it has not been possible to obtain an estimate of the charge size. Military agencies will not report charge sizes used during tests and naval exercises, only in cases of mine and bomb disposal where there is no strategic value. Seismic surveys offshore using significant quantities of explosives are not conducted now for environmental reasons, hence the current lack of accurate data provided by such experiments. The updated data for this study are tabulated in Appendix 1 for underwater explosions, and Appendix 2 for explosions on land.

The seismic magnitudes supplied here are local magnitudes ML, as derived by BGS and used in the BGS catalogue of UK seismicity. This scale is the same as that defined by Hutton & Boore (1987), following earlier work by Richter (1935), which uses the maximum trace amplitudes recorded on standard Wood-Anderson horizontal seismometers. The BGS has used Willmore Mk3 seismometers, and more recently, Guralp broadband seismometers rather than Wood-Anderson seismometers, but using the responses of the two instruments, amplitudes are measured from equivalent Wood-Anderson seismograms. This is done by a process of deconvolving the Willmore response from the Fourier transform of the seismogram and convolving the result with the Wood-Anderson response, then taking the inverse Fourier transform to give the Wood-Anderson seismogram.

Hutton and Boore (1987) published a correction for distance which is based on observations in California, and the BGS has applied this correction when estimating local magnitude using amplitude measurements from its UK seismic monitoring network stations. The BGS recognised that seismic wave attenuation characteristics may differ between California and the UK, so that application of the Hutton and Boore correction for the effect of attenuation of amplitude with distance would result in calculated local magnitudes being biased in some way with respect to those determined by independent global magnitude scales. Booth (2008) used UK data to produce local distance and station corrections for estimation of an *ML* which is consistent with the original Richter definition of *ML*. This *ML* has a standard deviation which is smaller than that produced by the Hutton and Boore (1987) correction, which is defined according to attenuation in Southern California. The reduction in standard deviation is mainly due to the incorporation of station terms to correct for station effects, since it turns out that the observed variations and the Hutton and Boore (1987) variations of attenuation with distance are similar. Except where stated, the magnitudes for the post-1985 events reported here have not been updated for the new corrections, since there is a requirement for consistency between the MLs derived by Jacob & Neilson (1977) and those derived more recently.

The relation between log charge weight W, where W is the charge weight in pounds, and the recorded local seismic magnitude ML is shown in Figure 1, for both underwater and land explosions. In Figure 2, the underwater explosions are separated into those catalogued by Jacob & Neilson, both at optimum depth and at unrecorded depth, and those catalogued since then, all at unrecorded depth. In Figure 3, land explosions are separated into quarries and air blasts, and records for different quarries are shown separately, where multiple records are available for the same quarry. The distribution of these observations, and the scatter which they display, are discussed in the following section.

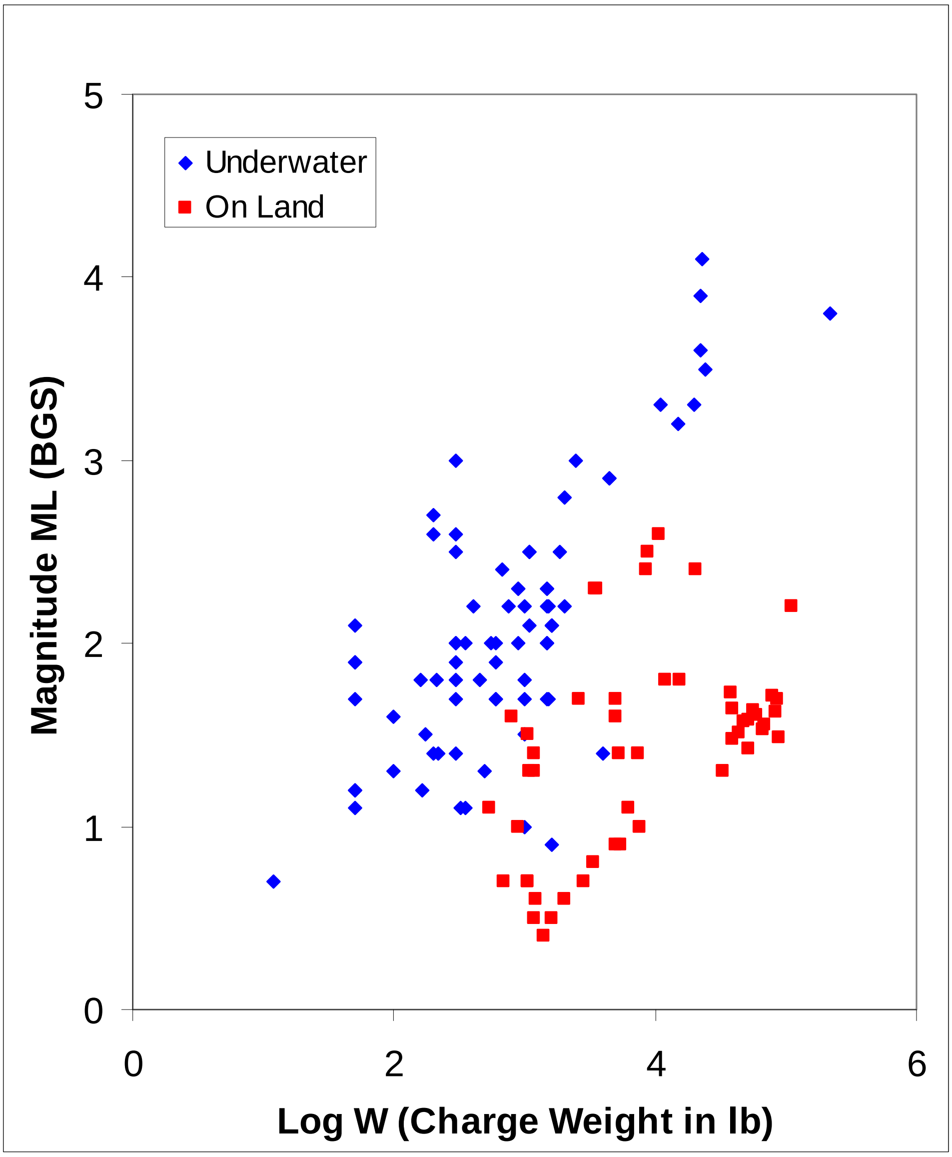

Figure 1. BGS local magnitudes ML for chemical explosions of different charge weights (W) in pounds, both underwater (blue diamonds) and on land (red squares).

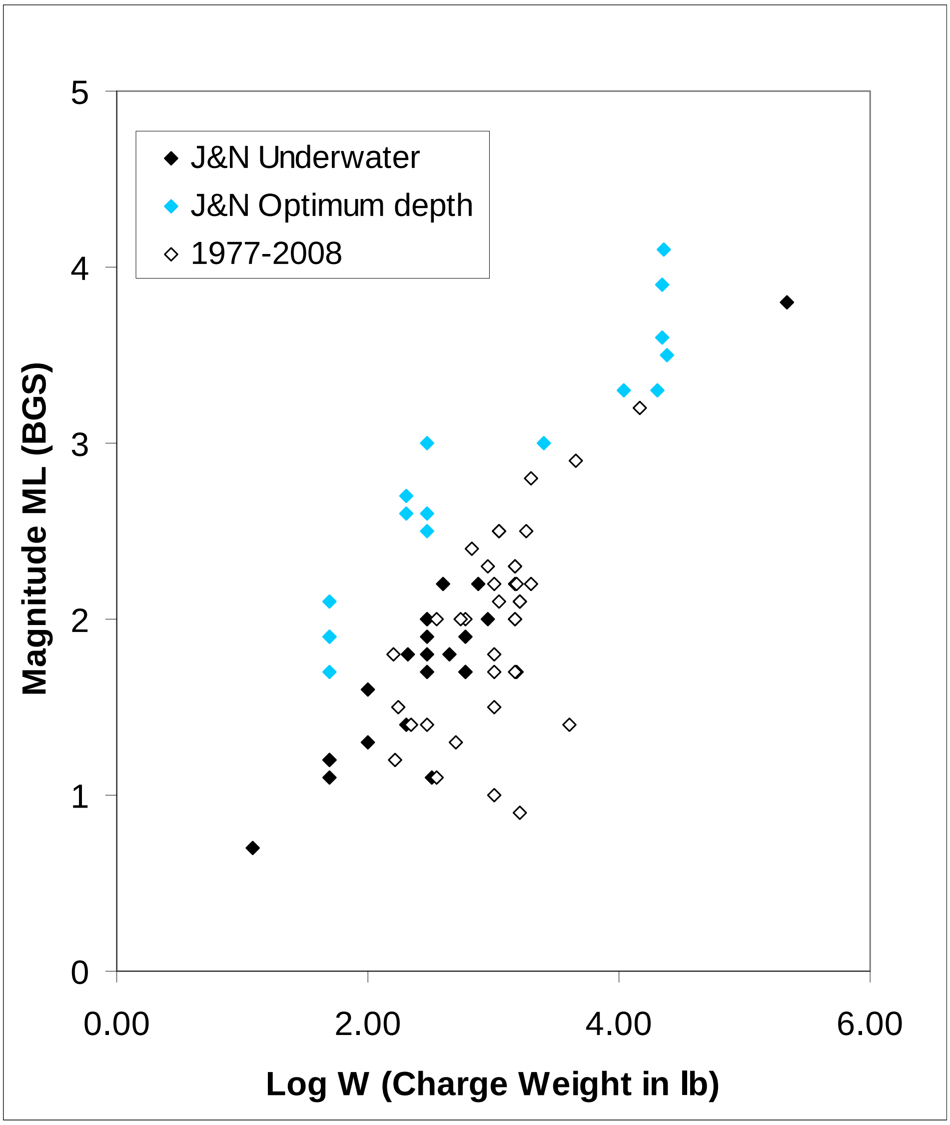

Figure 2. BGS local magnitudes ML for underwater chemical explosions of different charge weights (W). Solid diamonds represent the data of Jacob & Neilson (1977) for explosions fired at optimum depth for seismic energy release (blue) and other depths (black). Open diamonds represent data obtained since 1977 at depths which are unknown and unlikely to be optimum depths.

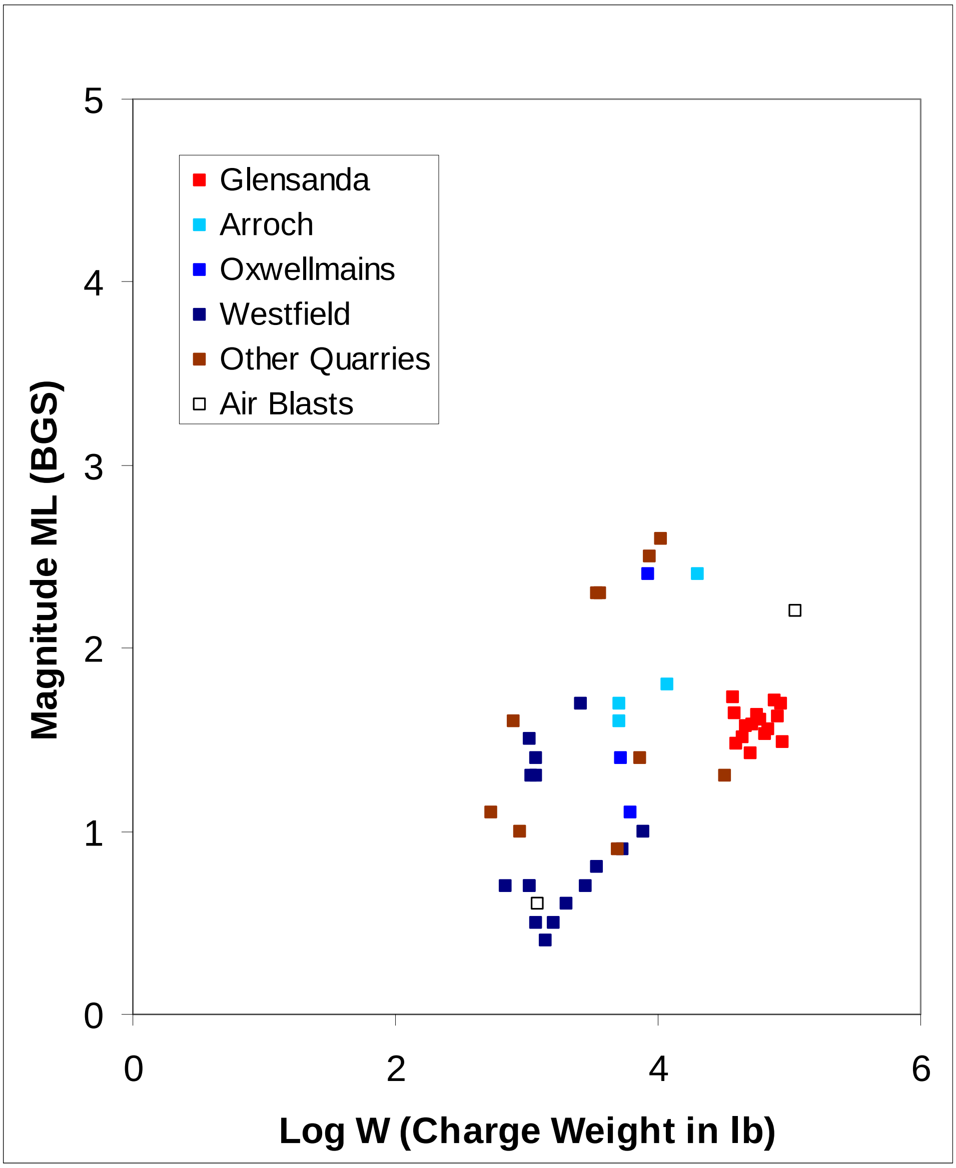

Figure 3. BGS local magnitudes ML for chemical explosions of different charge weights (W) fired on land, mostly in quarries. Explosions fired above ground (air blasts) are shown as open squares.

3 Relationship between magnitude and charge weight

In general, the observations in Figure 1 show that the local magnitude of a recorded explosion increases with charge weight, as might be expected. The distribution shows considerable scatter, and the reasons for this should be understood before any attempt is made to estimate the equivalent yield for an explosion, given its seismic local magnitude.

When an explosion is detonated underwater at a depth which is sufficient to prevent immediate venting of the gas bubble at the surface, the energy of the explosion is well-coupled to the surrounding transmitting medium and through surface reflection most of it is directed downward so that there is efficient generation of seismic waves. The situation on land is generally quite different: most explosions are quarry blasts, which are designed to move and shatter rock for quarrying purposes, and the seismic disturbance is minimised for social and environmental reasons. A greater proportion of the energy is converted to vertical and lateral displacement of the surrounding rock. Therefore, for a given charge size, explosions at sea generally produce larger seismic waves than explosions on land, and this is clearly seen in the distribution of magnitude with charge weight for different explosions in Figure 1. In general, the seismic efficiency of underwater explosions is about ten times that of explosions in hard rock.

3.1 UNDERWATER EXPLOSIONS

Data from underwater explosions has come from explosions fired at sea; the author is not aware of explosions in inland lakes or lochs in the UK which have generated recorded seismic waves. While explosions at sea generally produce larger seismic waves than explosions on land for the charge sizes examined here, there are significant variations within each distribution, as seen in Figure 2. For underwater explosions, these variations are mainly due to inaccuracy in evaluating charge weight and variations in the depth of firing.

3.1.1 Uncertainty of charge weight

The charge weight reported here is as reported by the agency responsible for detonating the device, often relayed by the coastguard. While the charge size is usually known for controlled explosions used for seismic experiments or demolition of structures, the charge size for mine or bomb disposal can only be a best estimate based on the identification of the type of device, and the explosive charge used to detonate it. For example, a report of a 1000 lb mine may or may not refer to the charge weight, which will be less than the actual weight of the mine. Also, it will not be known whether all the charge was detonated, or whether it detonated efficiently, as the chemicals in old WWI or WWII mines will have degraded with age.

3.1.2 Depth of explosion

A chemical explosion instantaneously releases gas and heat, producing a high pressure shockwave travelling at very high speed. In a shallow explosion at sea, most of the pressure is vented upwards, moving gas and water into the air. If the depth of firing is sufficient to prevent the gas bubble produced by the explosion immediately breaking at the surface, the bubble contracts and expands in a series of pulses, generating a regular series of seismic pulses of decreasing amplitude. These bubble pulses are detectable in the frequency spectrum of the recorded seismogram, as in Figure 3 of Ford et al. (2004), and are a useful means of identifying an underwater explosion. For example, the observation of bubble pulses in spectra of seismograms of the submarine ‘Kursk’ explosion was crucial in proving the disaster was due to an explosion rather than a collision (Koper and Wallace, 2001). Most of the energy is then contained within the water and converted into compressional seismic waves, which propagate through the water and into the earth at the seabed. Compressional waves travelling upwards from the source will be reflected at the sea surface, adding to the seismic energy directed downwards into the Earth.

Jacob (1975) noted that there was an optimum depth for explosions underwater, where the bubble pulse and the first surface reflection are in phase, so maximising the propagation of seismic energy, and demonstrated the advantages of using optimum depth dispersed charges for lithospheric studies. The optimum depth technique was previously used to generate teleseismic signals from ten-ton shots (Jacob & Willmore 1972), and was also used for the LISPB experiment (Bamford et al., 1978) and other refraction studies. Optimum depth shots are designed for seismic efficiency and it is seen in Figure 2 that they show the largest magnitudes for a given charge weight.

For underwater explosions not at optimum depth, O’Brien (1967) found that the seismic amplitude is proportional to W^n , where W is charge size and n is about two-thirds. Muller et al. (1962) presented results from explosions in lakes which provided a value for n of 0.65±0.013. O’Brien (1967) notes that charges detonated on the water bottom produce a large amount of shear wave energy, due to the asymmetry at the source location, and sometimes the primary shear-wave amplitude can be greater than that of the primary P-wave. Thus the seismic amplitude of the recorded wavetrain can significantly vary for a given charge weight, depending on the depth of firing.

3.2 EXPLOSIONS ON LAND

The source conditions for explosions on land can also vary considerably. Variations are mainly due to the firing pattern, and the depth of firing. Large charge weights are rarely detonated in a single explosion. When a large total weight of explosive is used, the explosive is generally dispersed between many shot holes.

Depth of firing is again significant, since at greater depths coupling is improved and the explosive is surrounded by stronger rock; the size and time delay of the surface reflection also varies with the depth of explosion. Quarry blasts are usually detonated in a predetermined time sequence with millisecond time delays between successive shots. The shot pattern is designed to maximise fracturing and minimise the seismic effects of the blast, through destructive interference of the seismic waves which are generated. This practice commonly occurs in production mining, for example on open cast sites. Non-seismic energy is expended in deforming and moving the rock, as well as in heat and sound. The firing pattern can cause the recorded magnitude to vary considerably. In Figure 3 there is no clear linearity in the relationship between magnitude and Log(charge weight), even at individual quarries. This is quite common for chemical explosions carried out on land, even when the explosions are restricted to a particular mining region (Khalturin et al. 1998).

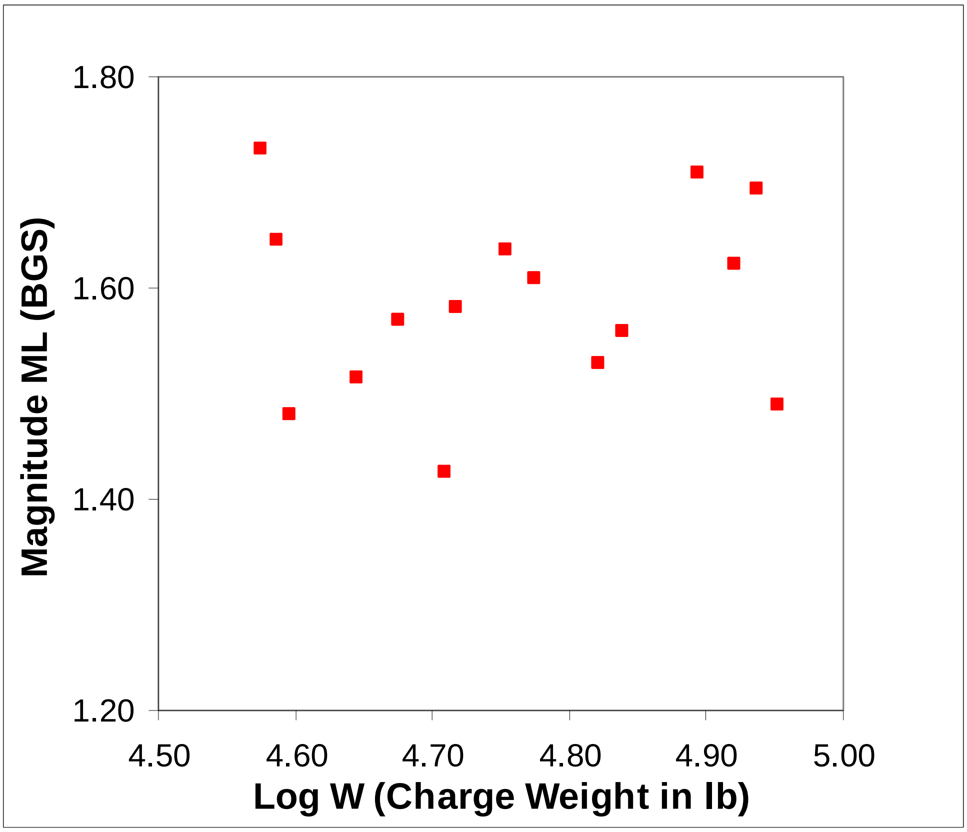

Figure 4. BGS local magnitudes ML for different charge weights (W) fired at Glensanda quarry and recorded at two or more BGS stations.

Figure 4 shows the distribution of magnitude against charge weight for 15 explosions at a single quarry (Glensanda) in 2007, recorded at two or more BGS stations. Details of the charges used were kindly provided by the quarry operator. The explosions were located in different parts of the quarry, and different firing patterns were used. There is considerable scatter in the distribution. While there is a general trend for magnitude to increase with charge weight, the largest charge weight produced a relatively small recorded magnitude, and the smallest charge weight produced the largest magnitude. This demonstrates the high variability in seismic energy according to firing pattern. The seismic signature of the blasts, as recorded at nearby BGS seismic stations, varied in character as well as amplitude, although the explosions only varied in position by 1.5 km or much less. Further analysis of the Glensanda data is presented and discussed in Appendix 3.

Occasionally, an explosion on land can generate as much seismic energy as an explosion at sea, as shown by a few of the Jacob & Neilson (1977) observations. These were likely to have been single shots, well-tamped in a deep hole, or shots fired in a sequence which generated constructive interference of seismic waves. Recently, seismic waves from two explosions of known or estimable charge weight, detonated as air blasts on the surface, were detected with signal to noise sufficient to allow a magnitude to be calculated (see Fig.3). These were a surface explosion on the testing range at Spadeadam, Dumfriesshire, and the vapour cloud explosion which occurred at the Buncefield oil depot near Hemel Hempstead in December 2005. Since the coupling to ground is relatively poor, it is not surprising that they both show low seismic efficiency for their charge weight.

4 Conclusions

Underwater explosions are more seismically efficient than explosions on land in generating seismic energy for a given charge weight. The magnitude recorded for a given charge weight on land or underwater can vary by at least one unit according to the efficiency of coupling to the transmitting medium; variations in charge depth and tamping have the greatest effect on the seismic efficiency of the explosion.

It follows that an estimate of charge weight from a given seismic local magnitude using the distribution can be in error by an order of magnitude unless some of the source conditions are known. For a reasonably confined estimate it is essential to obtain answers to the following questions:

1) Was the explosion underwater, or on land? Explosions underwater are better coupled to the transmitting medium and generate higher amplitude seismic waves than those detonated on land.

2) If underwater, was it at shallow depth, or deep enough to be contained underwater? If the explosion is deep, the created gas bubble rapidly expands and contracts, generating high energy compressional waves which are transmitted through the earth when they reach the sea/lake bottom. At shallow depth, the gas bubble is likely to vent into the atmosphere, throwing water into the air, and considerably reducing the seismic energy transmitted downwards by expansion and contraction of the bubble.

3) If underwater and contained, could it have been at optimum depth (maximum seismic efficiency) or at the water bottom (with relatively large shear-waves for an explosion)? Explosions fired at optimum depth, which varies with charge size, give the highest seismic energy for a given charge weight.

4) If on land, is the location near a known quarry, likely to use delayed shot firing to minimise seismic vibrations generated by the blast? Modern quarry blasts are designed to move as much rock as possible with as little environmental disturbance as possible, and generate relatively small amplitude seismic waves for a given charge size.

5) If on land, was the explosive fired on the surface, or well tamped down a hole? Explosions on the surface are very poorly coupled to the Earth, whereas well-tamped explosions in a deep hole

are well-coupled to the Earth. The amplitude of the generated seismic waves is strongly and directly proportional to the efficiency of coupling.

If at least some of these questions can be answered, then the observations presented in this report can be used to estimate an approximate charge weight for a chemical explosion in the UK, given a given recorded local magnitude.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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Appendix 1. Underwater explosions

The source data for underwater explosions which is used in this report is provided below. The earliest data is obtained from a table in Jacob & Neilson (1977) (denoted by J&N 1977). Explosions fired at optimum depth are indicated by an asterisk in the 'Location' column.

Date	ML (BGS)	Charge Wt (lb)	Log Ch.Wt	Location	Source
	1.2	50	1.70	Blackness, Forth	J&N 1977
	1.3	100	2.00	Society Bank, Forth	J&N 1977
	2.0	300	2.48	Society Bank, Forth	J&N 1977
	1.9	300	2.48	Society Bank, Forth	J&N 1977
	1.8	300	2.48	Dalgety Bay	J&N 1977
	1.7	600	2.78	Dalgety Bay	J&N 1977
	2.0	300	2.48	Pittenweem	J&N 1977
	2.2	1500	3.18	off W Hartlepool	J&N 1977
	1.7	600	2.78	Gosford sands	J&N 1977
	0.7	12	1.08	Fife Ness	J&N 1977
	1.1	50	1.70	Blackness, Forth	J&N 1977
	1.6	100	2.00	Blackness, Forth	J&N 1977
	1.1	328	2.52	Gosford sands	J&N 1977
	2.2	400	2.60	Dalgety Bay	J&N 1977
	1.2	50	1.70	off.W Ireland	J&N 1977
	1.8	210	2.32	Kirkcaldy Bay	J&N 1977
	2.2	750	2.88	Dalgety Bay	J&N 1977
	1.7	300	2.48	Dalgety Bay	J&N 1977
	1.8	450	2.65	Dalgety Bay	J&N 1977
	1.9	600	2.78	Dalgety Bay	J&N 1977
	2.0	900	2.95	Dalgety Bay	J&N 1977
	3.8	220000	5.34	St Bridget off Wolf Rock	J&N 1977
	1.4	200	2.30	May Island	J&N 1977
	1.9	50	1.70	North Sea (Camb.proj.)	J&N 1977
	1.9	50	1.70	North Sea (Camb.proj.)	J&N 1977
	1.7	50	1.70	North Sea (Camb.proj.)	J&N 1977
	2.1	50	1.70	North Sea (Camb.proj.)	J&N 1977
	2.7	200	2.30	North Sea (Camb.proj.)	J&N 1977
	2.6	200	2.30	North Sea (Camb.proj.)	J&N 1977
	2.6	300	2.48	Minch, HMSP*	J&N 1977
	3.0	300	2.48	Minch, HMSP*	J&N 1977
	2.5	300	2.48	SOSP II, W Scot.*	J&N 1977
	3.6	22000	4.34	TenTon 1*	J&N 1977
	4.1	22600	4.35	TenTon 2*	J&N 1977
	3.9	22000	4.34	TenTon 3*	J&N 1977
	3.0	2500	3.40	LISPB N11*	J&N 1977
	3.3	11000	4.04	LISPB N21*	J&N 1977
	3.3	20000	4.30	LISPB N24*	J&N 1977
	3.5	24000	4.38	LISPB N25*	J&N 1977

Appendix 1. Underwater explosions (contd.)

Date	ML (BGS)	Charge Wt (lb)	Log Ch.Wt	Location	Source
19870927	2.9	4490	3.65	North Sea	(Burton et al 1989 BGS Rep WL/89/7)
19870927	2.3	898	2.95	North Sea	(Burton et al 1989 BGS Rep WL/89/7)
19890328	3.2	14775	4.17	Piper Alpha demolition	
19911112	1.4	220	2.34	off Hartlepool	BGS
19931105	1.0	1000	3.00	off Fraserburgh	BGS
19940525	0.9	1600	3.20	Thames Estuary	BGS
19951018	2.1	1600	3.20	Thames Estuary	BGS
19951019	2.1	1600	3.20	off Folkestone	BGS
19970303	2.2	1000	3.00	off Dungeness	BGS
19970305	2.2	1535	3.19	off Amble	BGS
19970309	1.7	1535	3.19	off Port Seton	BGS
19970611	1.5	1000	3.00	Minch	BGS
19970611	1.7	1000	3.00	Minch	BGS
19970617	1.8	1000	3.00	Minch	BGS
19971006	2.4	672	2.83	Humber	BGS (Mine was 672lb, charge may be greater)
19980323	2.1	1600	3.20	Lyme Regis	BGS
20000830	1.4	300	2.48	Largo Bay	BGS UK Eq. Mon. Report 2000/01)
20020417	2.0	600	2.78	off Margate	BGS & Thames Coastguards
20020707	2.0	350	2.54	North Minch	BGS (2 charges simultaneously, 160.4 kg total)
20030612	2.0	550	2.74	Kyles of Bute	BGS
20050414	2.8	2000	3.30	S North Sea	BGS
20050608	1.5	176	2.25	Minch	BGS
20051207	2.1	1100	3.04	Rame Head, Devon	BGS
20051220	2.2	2000	3.30	Blacktail Spit	Port of London News Nov/Dec 2005: British WWII mine 'L'Mk3, charge wt 2000lb
20060209	1.1	350	2.54	off Pittenweem	BGS
20060516	1.2	165	2.22	Liverpool Bay	timesonline;http://www.warbirdsresourcegroup.org/LRG/pc500.htm (PC500 bomb, 75kg charge wt.)
20060607	2.0	1500	3.18	Thames Estuary	BGS
20061028	1.4	4000	3.60	Swansea bay	http://hitlernews.cloudworth.com/bomb-threats.php (1800kg mine: 'heard across Bay': vented, only partly discharged?)
20070128	2.0	1500	3.18	Isle of Wight	
20070703	2.5	1100	3.04	S North Sea	
20071012	2.3	1500	3.18	off Margate	Navy News December 2006
20071103	2.3	1500	3.18	off Margate	Navy News December 2007
20080222	1.8	160	2.20	Isle of Bute	BGS
20080315	2.5	1850	3.27	Dover Straits	French Marine Ops (J P Santoire,CEA, LDG)
20080327	2.5	1100	3.04	S North Sea	Controlled explosion by Dutch minesweeper Schiedam, confirmed by J P Santoire,CEA, LDG
20080412	1.7	1500	3.18	Bristol Channel	http://www.burnham-on-sea.com/coastguard/bomb-explosion-12-04-08.shtml
20080726	1.3	500	2.70	Cumbrae	http://www.sundaymail.co.uk/news/scottish-news/2008/07/27/exclusive-prawn-fisherman-nets-500lb-bomb-near-great-cumbrae-78057-20672376/

Appendix 2. Explosions on Land

The source data for explosions which is used in this report is provided below. The earliest data is obtained from a table in Jacob & Neilson (1977) (denoted by J&N 1977). Except for the air blast explosions denoted with an asterisk, the explosions are quarry blasts at named quarries. Data for blasts at Glensanda quarry are provided separately in Table 1 in Appendix 3.

Date	ML (BGS)	Charge Wt (lb)	Log Ch.Wt.	Location	Source
	0.7	1050	3.02	Westfield	J&N 1977
	1.0	7700	3.89	Westfield	J&N 1977
	0.9	5400	3.73	Westfield	J&N 1977
	0.8	3400	3.53	Westfield	J&N 1977
	0.5	1600	3.20	Westfield	J&N 1977
	0.5	1200	3.08	Westfield	J&N 1977
	0.6	2000	3.30	Westfield	J&N 1977
	0.4	1400	3.15	Westfield	J&N 1977
	1.5	1060	3.03	Westfield	J&N 1977
	1.3	1200	3.08	Westfield	J&N 1977
	1.7	2600	3.41	Westfield	J&N 1977
	0.7	2800	3.45	Westfield	J&N 1977
	0.7	700	2.85	Westfield	J&N 1977
	1.4	1200	3.08	Westfield	J&N 1977
	1.3	1100	3.04	Westfield	J&N 1977
	0.7	1050	3.02	Westfield	J&N 1977
	1.6	5050	3.70	Arroch	J&N 1977
	1.7	5050	3.70	Arroch	J&N 1977
	2.4	20400	4.31	Arroch	J&N 1977
	1.8	12000	4.08	Arroch	J&N 1977
	2.4	8408	3.92	Oxwellmains	J&N 1977
	1.1	6256	3.80	Oxwellmains	J&N 1977
	1.4	5270	3.72	Oxwellmains	J&N 1977
	1.8	15350	4.19	Oxwellmains	J&N 1977
	1.1	535	2.73	Clatchard	J&N 1977
	1.6	800	2.90	Clatchard	J&N 1977
	1.4	7320	3.86	Craigpark	J&N 1977
	0.9	4970	3.70	Craigpark	J&N 1977
	2.6	10600	4.03	Goat	J&N 1977
	2.3	3600	3.56	Cunmont	J&N 1977
	2.5	8750	3.94	Cairngryffe	J&N 1977
	1.0	900	2.95	Hazelbank	J&N 1977
20070919	1.3	32967	4.52	Hillhouse	(Quarry Manager 19Sept2007 HandiBulk Expl)
20050120	2.3	3476	3.54	Caldon	BGS
20051211	2.2	112200	5.05	Buncefield*	Ceranna et al GJI *177* 491-508 give 51tonne
20020823	0.6	1210	3.08	Spadeadam*	BGS; BGS staff attended blast

Appendix 3. Explosions at Glensanda Quarry

Seismic data acquired from 15 explosions at Glensanda Quarry recorded at two or more BGS seismometer stations has been analysed. Details of charge sizes for these explosions were provided by the quarry operators, together with the location and firing pattern for a subset of them. Glensanda quarry is the largest granite quarry in Europe and occupies an area of approximately 2.5 km^2 on the high ground NW of Loch Linnhe in west Scotland. The BGS seismometer network frequently records seismic waves due to blasting at the quarry. Figure 5 shows its location relative to the nearest 3-component BGS seismometer stations at which the local magnitude of the explosions is estimated using the resulting shear waves.

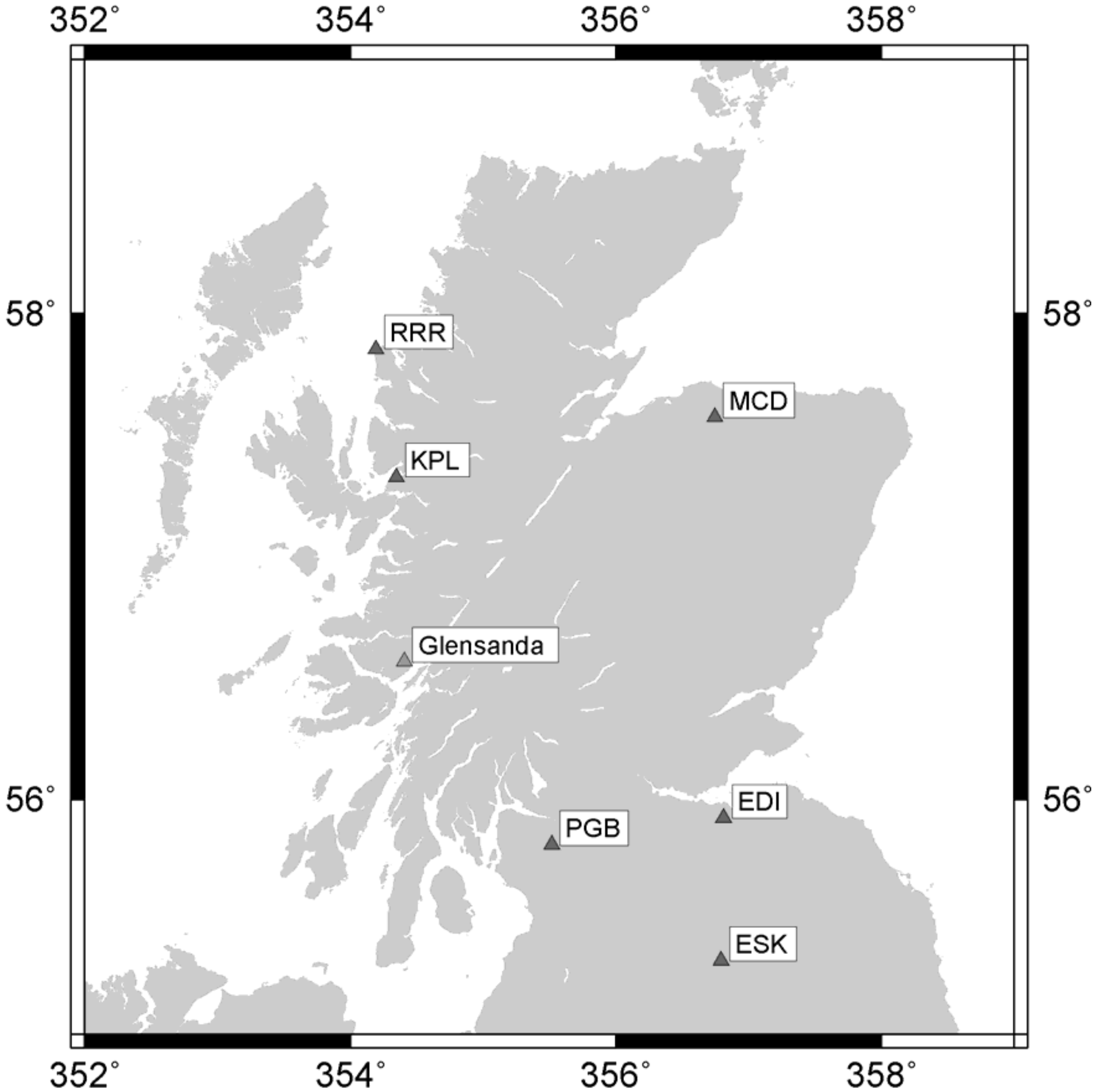

Figure 5. Location of Glensanda quarry and the nearest BGS 3-component seismometer stations.

Local magnitude ML calculated by applying the BGS method to amplitudes measured at nearby 3-component stations (see Figure 5) and taking the average ML will be denoted by ML(BGS); the BGS magnitude for the nearest station (KPL) only will be denoted by ML(KPL). The average magnitude calculated by applying the Booth (2008) station and distance corrections to the amplitudes measured at the nearby 3-component stations will be denoted by ML(Booth). Figure 6 shows seismic waves generated by the 15 explosions as recorded by the nearest station (KPL), and the source data for the explosions is given in Table 1.

Table 1. Source data for explosions at Glensanda quarry. The charge weight W and the blast ratio (Tonnes extracted per kg of charge) were provided by the quarry operators. Magnitudes ML(BGS), ML(KPL) and ML(Booth) are described in the text.

Date	Time (UTC)	W (kg)	Log(Wt in lb)	Blast Ratio (T/kg)	ML(BGS)	ML(KPL)	ML(Booth)
20070125	1337	31319	4.84	4.73	1.52	1.92	1.70
20070216	1339	17559	4.59	3.71	1.70	2.06	1.79
20070302	1339	37820	4.92	4.90	1.62	1.83	1.70
20070329	1240	27052	4.77	4.65	1.61	1.90	1.71
20070404	1237	17090	4.58	3.78	1.73	1.96	1.79
20070412	1239	21525	4.68	4.79	1.57	1.73	1.63
20070503	1236	40739	4.95	4.62	1.49	1.91	1.72
20070517	1230	30114	4.82	3.58	1.53	n/r	1.66
20070606	1235	35557	4.89	4.61	1.71	1.89	1.78
20070614	1239	20058	4.64	3.49	1.52	1.74	1.67
20070621	1238	39274	4.94	4.94	1.69	n/r	1.54
20070703	1242	23276	4.71	4.92	1.43	1.82	1.57
20070713	1240	23717	4.72	3.71	1.58	1.79	1.64
20070821	1241	25783	4.75	4.20	1.64	n/r	1.62
20070831	1245	17915	4.60	5.13	1.48	1.76	1.66

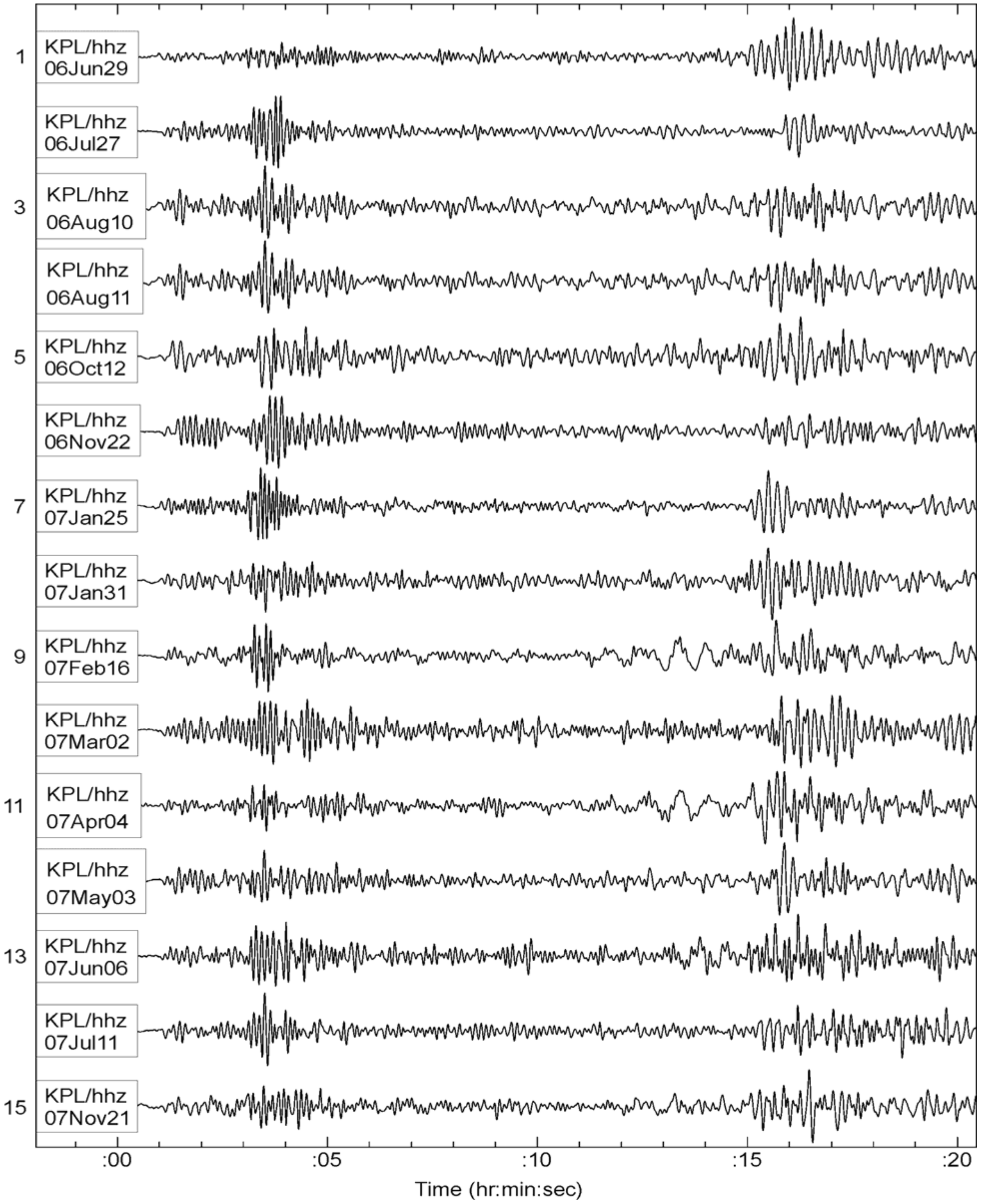

Figure 6(a). Seismograms of explosions at Glensanda quarry recorded on the vertical component seismometer at KPL

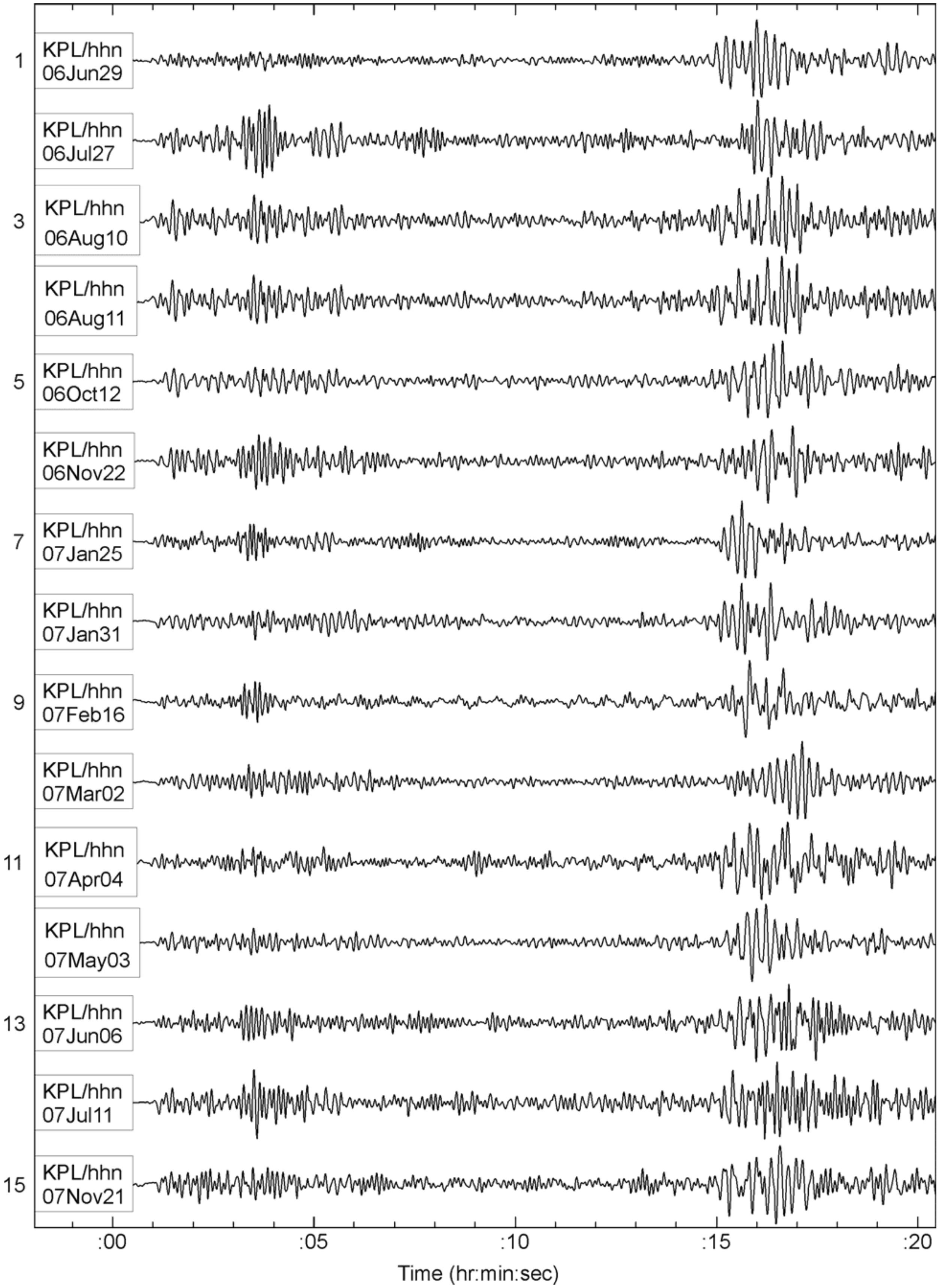

Figure 6(b). Seismograms of explosions at Glensanda quarry recorded on the N-S horizontal component seismometer at KPL

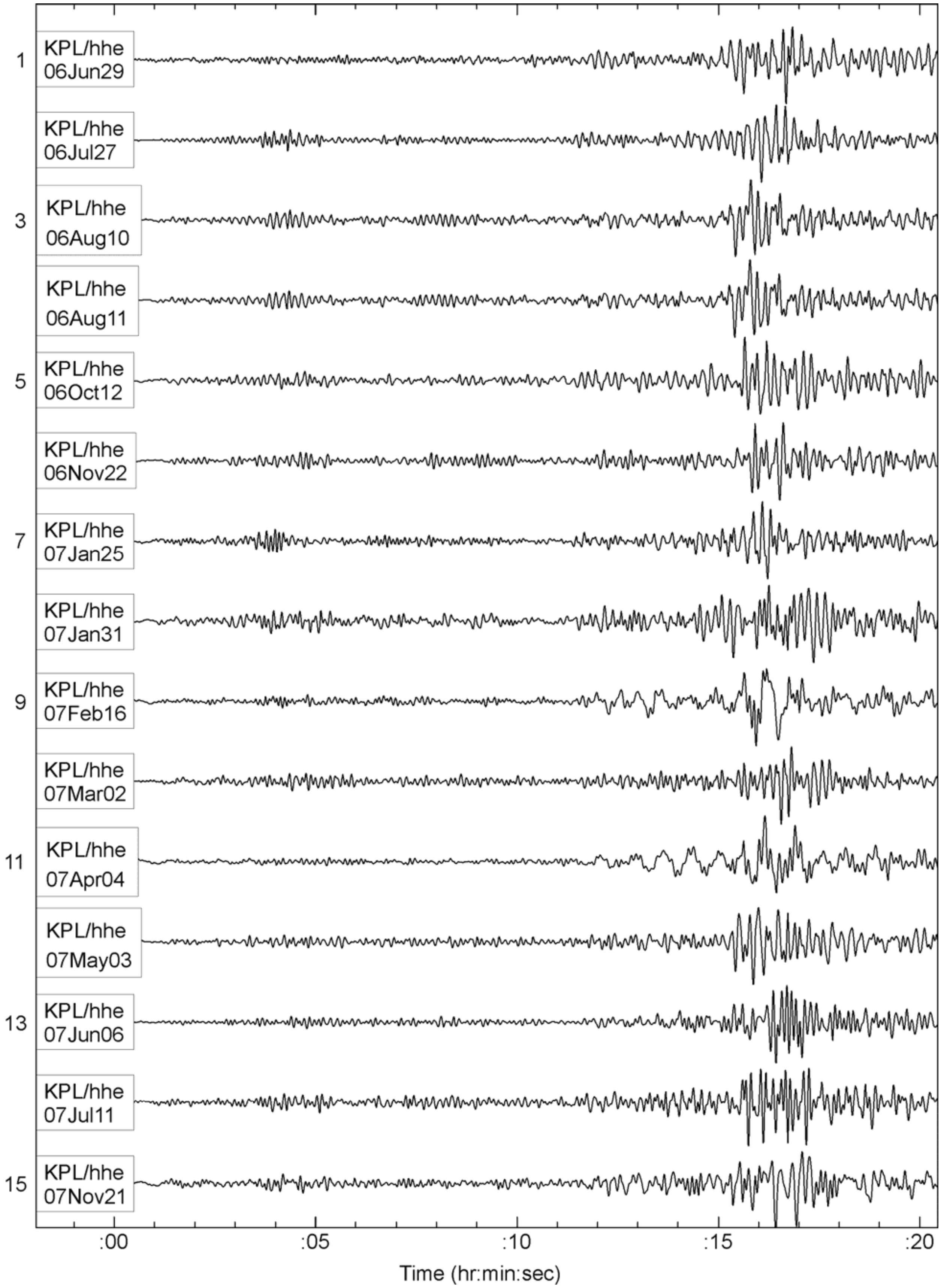

Figure 6(c). Seismograms of explosions at Glensanda quarry recorded on the E-W horizontal component seismometer at KPL.

While the explosions vary in location by 1.5 km or less, there is considerable variation in their waveforms. The explosions occurring on 6 June and 11 July 2007 occurred close together, along parallel 380m faces separated by 30m, and with similar but not identical firing patterns. However, the corresponding seismograms are distinctly different. Conversely, two explosions on 16 February and 4 April 2007 show similar long period energy in the S-wave coda, but the rockwalls being shattered differ in orientation by nearly 90° and are well separated, being 1.5 km apart. The firing patterns for these explosions are quite different.

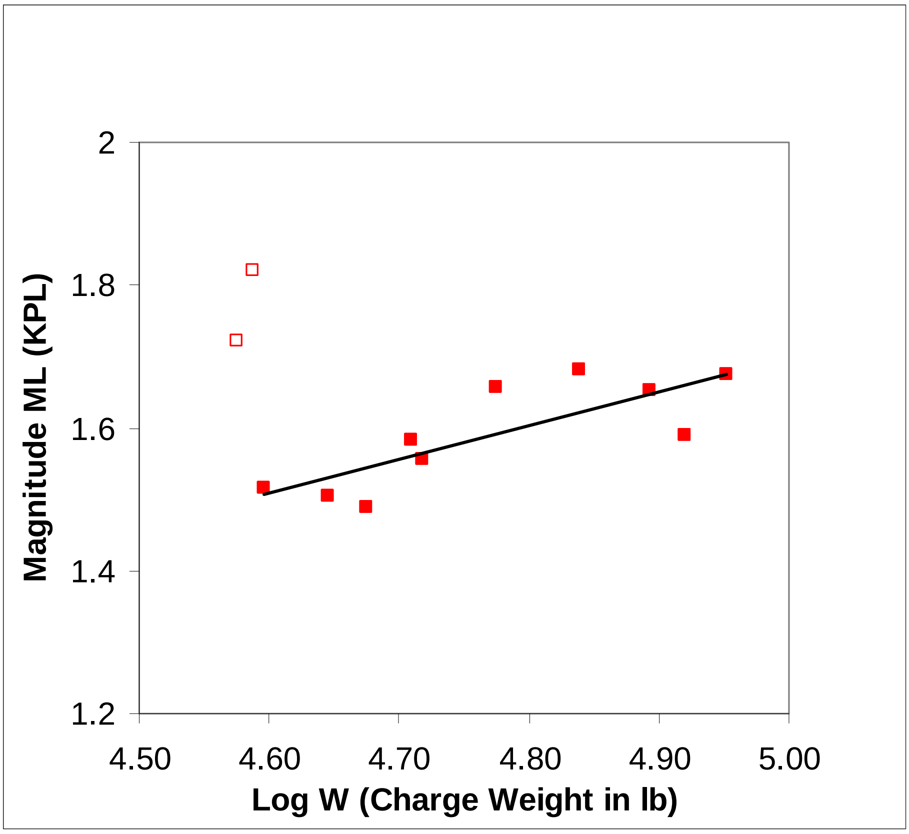

Figure 7. BGS local magnitudes ML measured at KPL for different charge weights (W) fired at Glensanda quarry, as listed in Table 1. Outliers are indicated by open squares.

The variation of local magnitude ML for the corresponding charge weight shows a lot of scatter, as was shown in Figure 4. The scatter is reduced slightly by using ML calculated for the nearest station (KPL), or ML calculated using the Booth (2007) station and distance corrections. The corresponding variations are displayed in Figures 7 and 8 respectively and show a general trend for magnitude to increase with charge weight, apart from two or three outliers to the general trend which appear in each of these figures, as well as in Figure 4. If the outliers are ignored and a best fitting straight line is drawn through the remaining points, the relationship between ML and charge weight for explosions at Glensanda is given by

$$ML\ (KPL) = 0.47 \log W - 0.67$$

for ML measured at the KPL station, and

$$ML\ (Booth) = 0.31 \log W + 0.21$$

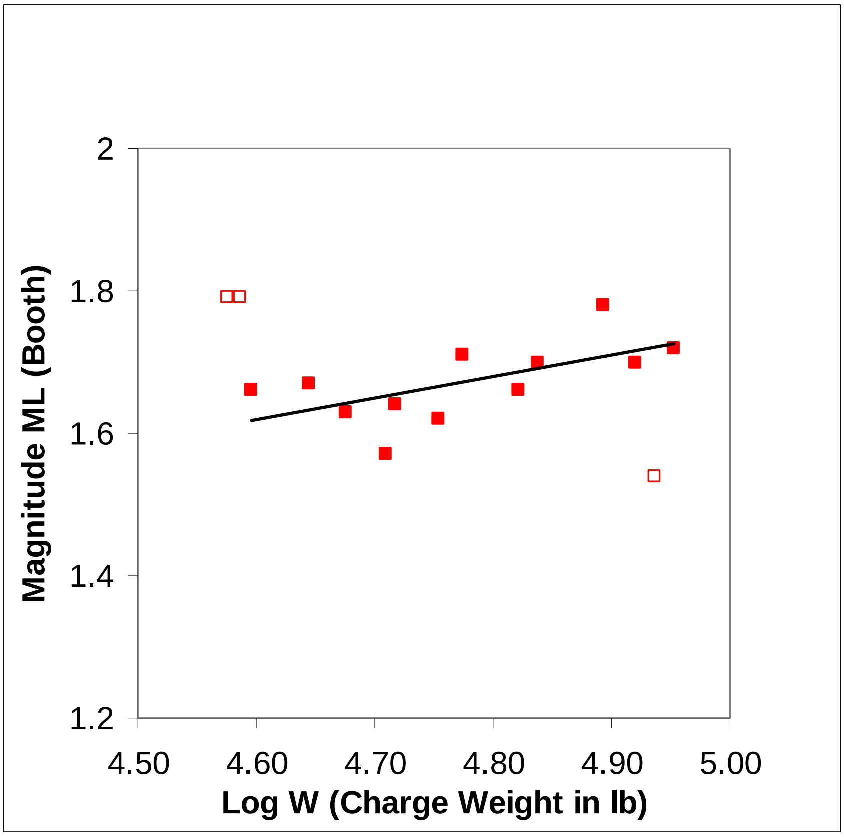

Figure 8. Local magnitudes ML calculated using the Booth (2007) station and distance corrections for different charge weights (W) fired at Glensanda quarry, as listed in Table 1. Outliers are indicated by open squares.

for ML measured using the Booth (2007) station and distance corrections. These relations are comparable with the results of O'Brien (1967), who observed that for charge weights greater than a few hundred pounds, seismic amplitude of the first arrival increases as $W^{1/3}$, where W is the charge weight in pounds for a charge fired on land in a single hole.