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Detonation Charge Size versus Coda Magnitude Relations in California and Nevada

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Abstract Magnitude–charge size relations have important uses in forensic seismology and are used in Comprehensive Nuclear-Test-Ban Treaty monitoring. I derive empirical magnitude versus detonation-charge-size relationships for 322 detonations located by permanent seismic networks in California and Nevada. These detonations, used in 41 different seismic refraction or network calibration experiments, ranged in yield (charge size) between 25 and 10^6 kg; coda magnitudes reported for them ranged from 0.5 to 3.9. Almost all represent simultaneous (single-fired) detonations of one or more boreholes. Repeated detonations at the same shotpoint suggest that the reported coda magnitudes are repeatable, on average, to within 0.1 magnitude unit. An empirical linear regression for these 322 detonations yields $M = 0.31 + 0.50 \log_{10}(\text{weight [kg]})$. The detonations compiled here demonstrate that the Khalturin *et al.* (1998) relationship, developed mainly for data from large chemical explosions but which fits data from nuclear blasts, can be used to estimate the minimum charge size for coda magnitudes between 0.5 and 3.9. Drilling, loading, and shooting logs indicate that the explosive specification, loading method, and effectiveness of tamp are the primary factors determining the efficiency of a detonation. These records indicate that locating a detonation within the water table is neither a necessary nor sufficient condition for an efficient shot.

Refraction Detonation Database

Since 1976, the U.S. Geological Survey (USGS) and others have conducted numerous seismic refraction and network calibration experiments in California and Nevada using large chemical explosions. Detonations used in 41 of these experiments were located by a permanent seismic network (Fig. 1A; Table 1). Excluding 12 large quarry shots, the average charge weight for these detonations was 868 kg and their average reported magnitude was 1.72. Apart from these 12 quarry blasts, these shots represent simultaneous (single-fired) detonations of one or more boreholes. Detailed information for all 322 detonations is summarized in Table 2, including the shotpoint number; origin time; location, elevation, depth and number of boreholes; total charge size; reported magnitude; the residual magnitude after subtracting equation (1); and wetness of the borehole(s).

The detonation location (latitude, longitude), origin time, and charge size given in Table 2 are summarized in the publications cited in Table 1. The number of boreholes, the borehole depths, and the wetness of the boreholes for each detonation given in Table 2 have not been reported, but most were available from unpublished drilling and loading logs and, in some cases, from records of drilling contractors. For 16% of the detonations, highlighted in bold in Table 2, I calculated the borehole depth from the charge size assuming a tamp depth of 15.3 m and a linear charge density of 42 kg/m, which approximates a relation reported by Fuis *et al.* (2001).

The surface elevation of the detonations (Fig. 1D; Table 2) shows that most of these detonations occurred either along the Coast Range or in the Sierra Nevada. Because elevations for slightly more than half (52%) of these detonations have not been reported, North America Datum 1927 elevations for these were measured from digital topographic maps and have an estimated uncertainty of about 10 m.

USGS Shothole Procedures

The USGS experiments, which constitute 95% of the database (Table 1), generally used 20-cm-diameter boreholes tamped with either drill cuttings or sand and gravel. The total borehole depth was determined, assuming a cased hole, from a linear charge density of 42 kg/m of charge of Dyno-Nobel repumped emulsion and 34 kg/m of charge for bagged emulsion (T. R. Burdette, personal comm., 2003). (Uncased holes of this diameter load at a rate closer to 50 kg/m.) The average borehole depth was 40 m, reflecting the average charge size of 716 kg, allowing for 21 m of stemming. Casing was used as necessary to stabilize the boreholes for subsequent loading and to facilitate loading. The

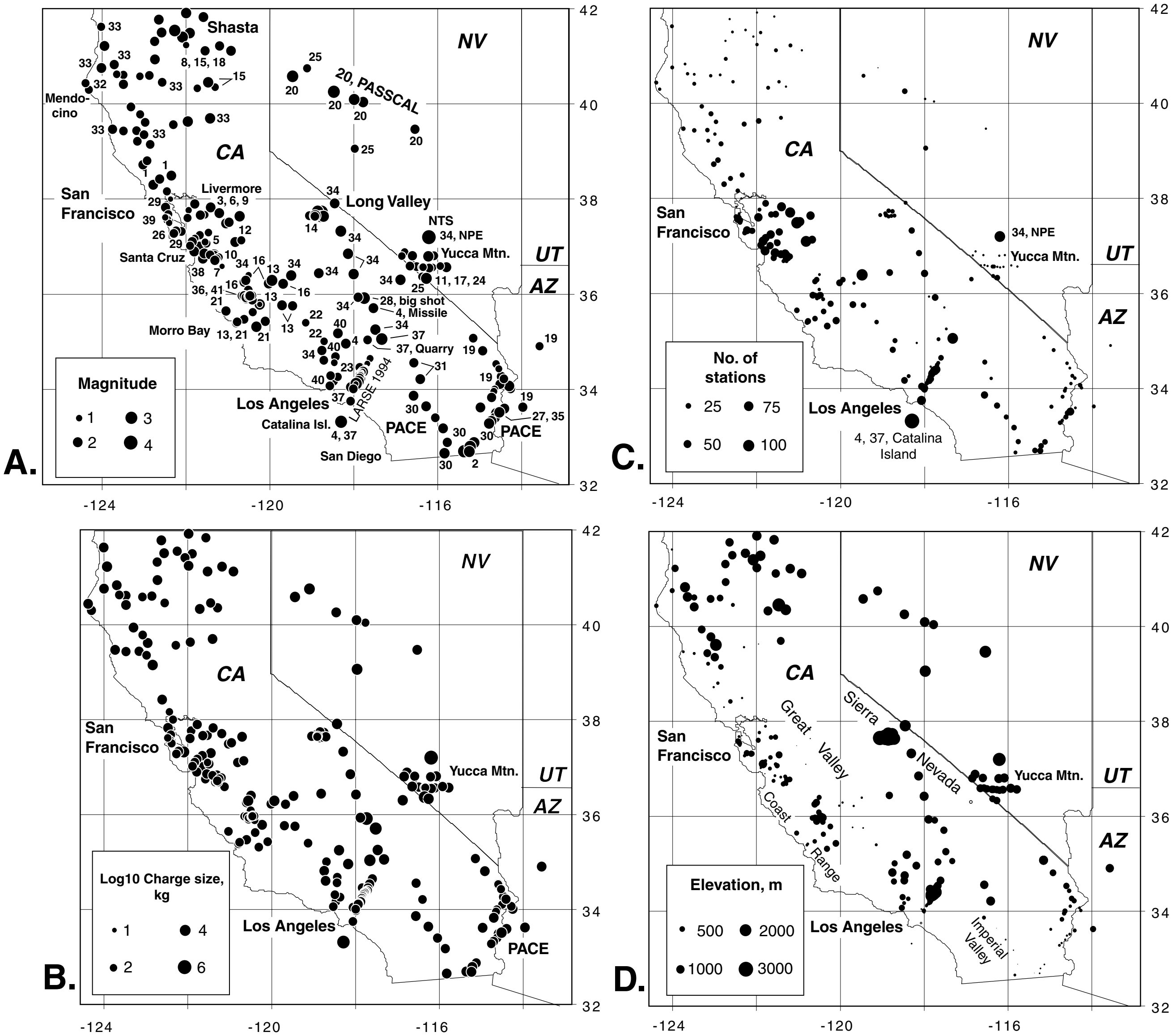

Figure 1. Maps of California and Nevada showing (A) reported coda magnitudes and (B) $\log_{10}$ charge weight (kg) for detonations located by the seismic networks. Individual experiments, numbered in (A) as in Table 1, can usually be identified as lines or clusters of detonations. (C) Number of stations used to locate each detonation. (D) Surface elevation, in meters, of the shot hole.

deep boreholes for small charges used in experiments 24 and 29 had a diameter of 10 cm (Brocher *et al.*, 1989; T. R. Burdette, personal comm., 2003).

Since about 1988, the USGS has used a repumped ammonium nitrate emulsion explosive containing high-pressure microballoons (an additive to prevent "dead pressing" of the explosive) to load the boreholes. Before 1988 (experiment 25), the USGS loaded the boreholes by hand using individual bags, or chubs, of ammonium nitrate emulsion containing high-pressure microballoons, normally Tovex Extra High Pressure (TVX 062). Detonations up to 120 kg in weight are still hand loaded. As discussed later, explosives lacking high-pressure microballoons loaded in holes deeper than 24 m may yield notably weaker detonations or might not detonate at all. The emulsion specifications (Dynoflo Plus 3, formerly RS) used by the USGS have been stable since 1990. Detonations used in experiment 24 in Amargosa Valley, Nevada, used 2.3-kg (5-lb) sticks of Austin Powder Company seismograph gelatin (60% high velocity) fired using two to five electrical blasting caps (Brocher *et al.*, 1989).

Generally, individual boreholes detonated by the USGS contain no more than 1360 kg (3000 lb) of chemical charge loaded to a depth of 50 m (Fig. 1B; Table 2). Larger detonations consist of multiple boreholes fired simultaneously. The 11 largest detonations compiled here (all heavier than 5385 kg) represent either surface detonations, quarry blasts,

Table 1
Summary of Seismic Experiments Providing Reported Detonations

Expt.	Experiment Location or Name	Reference	Year	No. Shots Located	Network
1	Geysers–San Pablo Bay	Warren (1981)	1976	5	NCSN
2	Imperial Valley	Kohler and Fuis (1988)	1979	2	SCSN
3	Livermore	Williams *et al.* (1999)	1980	5	NCSN
4	Western Mojave Desert	Harris *et al.* (1988)	1980	3	SCSN
5	Gilroy–Coyote Lake	Mooney and Luetgert (1982)	1980	4	NCSN
6	Livermore	W. D. Mooney (personal comm., 2001)	1981	2	NCSN
7	San Juan Bautista	Mooney and Colburn (1985)	1981	2	NCSN
8	Shasta II	Kohler *et al.* (1987)	1981	9	NCSN
9	Livermore	W. D. Mooney (personal comm., 2001); Murphy (1989)	1981	6	NCSN
10	Gilroy–Coyote Lake	Blumling *et al.* (1985)	1981	3	NCSN
11	Nevada Test Site 1980–1983	Hoffman and Mooney (1983); Rogers *et al.* (1987)	1982	1	SGBSN
12	Great Valley, Axial Lines	Murphy (1989)	1982	3	NCSN
13	Morro Bay to Coalinga	Murphy and Walter (1984)	1982	7	NCSN
14	Mono Craters–Long Valley	Meador *et al.* (1985)	1982	11	NCSN
15	Shasta III	Kohler *et al.* (1987),	1982	8	NCSN
16	Great Valley	Colburn and Walter (1984)	1983	4	NCSN
17	Nevada Test Site 1985, Nevada	Sutton (1985); Harmsen and Rogers (1987)	1985	13	SGBSN
18	Mendicine Lake–Shasta IV	Berge *et al.* (1986)	1985	5	NCSN
19	PACE 1985	Wilson and Fuis (1987)	1985	22	SCSN
20	PASSCAL Great Basin, Nevada	Whitman and Catchings (1987)	1986	6	NN, NCSN
21	PG&E Morro Bay	Sharpless and Walter (1988)	1986	5	NCSN
22	Tehachapi 1986	Ambos and Malin (1987)	1986	3	SCSN
23	Whittier Calibration Shot	J. M. Murphy (personal comm., 2001)	1987	1	SCSN
24	Amargosa Valley, NV	Brocher *et al.* (1989); Harmsen and Bufe (1991)	1988	4	NCSN
25	NOLIS/NRDC/USGS	J. M. Murphy (personal comm., 2001)	1988	3	SGBSN
26	Kaiser-Permanent Quarry	W. H. K. Lee (personal comm., 1989)	1988	10	NCSN
27	PACE 1989	McCarthy *et al.* (1994)	1989	1	SCSN
28	Big shot	F. Monastero (personal comm., 2001)	1990	1	NCSN
29	San Francisco Bay	Murphy *et el.* (1992); Kohler and Catchings (1994)	1991	15	NCSN
30	PACE 1992	T. R. Burdette (personal comm., 2001); Fliedner *et al.* (1996)	1992	13	SCSN
31	Landers Checkshot	Eberhart-Phillips and Mori (1994)	1992	2	SCSN
32	Mendocino checkshots	T. R. Burdette (written comm., 2001)	1992	3	NCSN
33	Mendocino experiment	Godfrey *et al.* (1995)	1993	22	NCSN
34	Southern Sierra	T. R. Burdette (personal comm., 2001)	1993	17	SCSN
35	Delta Force	Montana *et al.* (1994)	1994	2	NN, SCSN
36	Parkfield	Li *et al.* (1997); T. R. Burdette (personal comm., 2003)	1994	3	NCSN
37	LARSE 1994	Murphy *et al.* (1996)	1994	51	SCSN
38	Cienega Valley	Li *et al.* (1997); T. R. Burdette (personal comm., 2003)	1995	11	NCSN
39	San Francisco Peninsula	Parsons and Zoback (1997)	1995	7	NCSN
40	LARSE 1999	Fuis *et al.* (2001)	1999	13	SCSN
41	SAFOD, Parkfield	C. Thurber (personal comm., 2002); T. R. Burdette (personal comm., 2003)	2002	15	NCSN

NCSN, Northern California Seismic Network; NN, Nevada Network; SCSN, Southern California Seismic Network; SGBSN, Southern Great Basin Seismic Network.

or detonations in quarry adits, and none were detonated by the USGS. As a consequence, I do not know the type of explosive charge used for about half of these 11 largest detonations.

The USGS uses a series of cast 1-lb boosters ignited by a 50-grain reinforced detonating cord to detonate the main ammonium nitrate charge. Typically, boosters are looped through and taped along the detonating cord at linear intervals corresponding to 113 kg (250 lb) of main charge, and for the 20-cm-diameter boreholes, this corresponds to a separation of about 3 m. Thus, for 450- to 1360-kg detonations, 4–10 boosters are used. Shots smaller than 130 kg would typically use only two boosters. The string of detonating cord armed with boosters is hung in the well, and the pump hose is gently lowered to the bottom of the hole alongside it. The main charge is then pumped into the borehole from the bottom to the top.

Hand-loading procedures for bags of emulsion depend on the size of the charge to be loaded, depth to water in the borehole, size of the bag, and type and consistency of the emulsion (T. R. Burdette, personal comm., 2003). Regardless of the loading method, the loading begins by placing approximately 15 kg of explosive main charge at the bottom of the hole. A weighted detonation cord is then lowered

Table 2
Shotpoint Information and Reported Magnitude for Each Detonation

Expt.	Shotpoint No.	Date (UTC) (dd/mm/yy)	Shottime (UTC)	Latitude	Longitude	Elev. (m)	Hole Depth (m)	No. Holes	Yield (kg)	Mag	Equation (1) Residual Magnitude	Wet or Dry?
1	W-2	09/22/76	12:35:01	38.724670	− 123.02417	92	**37**	1	905	1.82	− 0.63	
1	W-3	09/22/76	13:05:01	38.302670	− 122.77667	61	**47**	1	1,357	2.06	− 0.52	
1	E-1	09/24/76	12:05:01	39.215830	− 123.15717	228	**47**	1	1,357	1.79	− 0.79	
1	E-2	09/24/76	12:35:01	38.809830	− 122.92650	193	**37**	1	905	1.79	− 0.66	
1	E-3	09/24/76	13:05:01	38.495170	− 122.35030	98	**47**	1	1,357	2.13	− 0.45	
2	1	11/17/79	9:00:01	32.884500	− 115.77233	12	**31**	1	653	2.43	0.08	D
2	1	11/17/79	11:00:01	32.884500	− 115.77233	12	**18**	1	109	1.81	0.03	D
3	1	02/02/80	9:00:00	37.670089	− 121.55303	402	37	1	977	1.84	− 0.63	W
3	1	03/21/80	8:00:00	37.670410	− 121.55325	402	37	1	434	1.28	− 0.94	W
3	3	03 /21/80	11:00:00	37.769806	− 121.93538	152	37	1	452	0.96	− 1.27	W
3	1	04/04/80	8:00:00	37.670250	− 121.55314	402	37	1	679	1.40	− 0.96	W
3	2	04/04/80	10:00:00	37.901500	− 121.78907	107	46	1	769	1.99	− 0.41	W
4	7	06/25/80	7:00:00	34.463570	− 117.86084	1073	**24**	1	381	1.60	− 0.58	
4	12	04/25/81	21:01:59	35.708667	− 117.53100	753	—	—	37,324	2.10	− 1.53	D
4	13	11/08/81	20:00:01	33.317178	− 118.30638	55	—	—	67,183	3.00	− 0.82	
5	3	01/28/81	0:00:56	36.751732	− 121.59503	214	**26**	1	452	2.01	− 0.22	W
5	6	02/14/81	10:00:00	37.298888	− 121.46145	655	**47**	1	1,357	1.49	− 1.09	W
6	6	02/11/81	10:00:00	37.298889	− 121.46146	655	**34**	2	1,584	1.64	− 0.99	W
7	6	02/26/81	7:00:00	37.298888	− 121.46146	655	**44**	1	1,222	1.37	− 1.17	W
7	1	06/12/81	7:00:00	37.069111	− 121.51089	355	45	1	700	1.55	− 0.82	
7	2	06/12/81	7:30:00	37.007027	− 121.68581	215	45	1	700	1.80	− 0.57	
8	3	06/12/81	8:00:00	36.900192	− 121.80032	20	45	1	700	2.12	− 0.25	
8	8105	06/30/81	7:30:00	41.548149	− 122.26693	1109	46	1	900	2.12	− 0.33	D
8	8102	07/09/81	7:00:00	41.322167	− 122.74750	1021	59	1	900	1.95	− 0.50	W
8	8105	07/09/81	7:45:00	41.548149	− 122.26693	1109	46	1	900	1.37	− 1.08	D
8	8112	08/13/81	7:30:02	41.122662	− 120.92475	1339	73	2	1,814	2.12	− 0.55	W
8	8105	08/13/81	7:45:00	41.548167	− 122.26700	1109	50	1	900	2.20	− 0.25	D
8	8103	08/16 /81	10:30:01	40.939500	− 122.73933	883	50	2	1,814	2.17	− 0.50	
8	8101	08/16/81	10:45:00	41.780121	− 122.64961	958	50	2	1814	2.14	− 0.53	
8	8105	08/16/81	11:15:00	41.548149	− 122.26693	1109	46	1	900	2.09	− 0.36	D
8	8105	08/20/81	7:30:00	41.548149	− 122.26693	1109	46	1	900	2.36	− 0.09	D
9	7	10/09/81	6:45:00	37.488110	− 121.04624	15	**43**	1	1,167	2.32	− 0.21	
9	9	10/09/81	7:15:00	37.640137	− 120.71895	33	**43**	1	1,167	2.26	− 0.27	W
9	10	10/16/81	6:30:00	37.097065	− 120.82956	28	40	1	923	2.19	− 0.27	W
9	7	10/16/81	6:45:00	37.488110	− 121.04624	15	40	1	923	2.10	− 0.36	
9	11	10/16/81	7:00:00	37.826695	− 121.41053	0	40	1	923	2.13	− 0.33	W
9	12	01/28/82	7:30:00	37.665390	− 121.65606	314	46	1	679	1.84	− 0.52	
10	7	11/04/81	7:30:00	36.840683	− 121.32491	156	40	1	923	2.16	− 0.30	
10	5	11/04/81	7:45:00	37.069112	− 121.51089	349	37	1	679	1.48	− 0.88	
10	4	11/05/81	8:00:00	37.246667	− 121.66972	303	40	1	679	1.60	− 0.76	
11	4	04/29/82	4:00:00	36.889084	− 116.78867	1122	43	1	1,127	1.40	− 1.12	W
12	14	06/25/82	6:00:00	37.707340	− 121.20484	0	40	1	900	2.02	− 0.43	
12	15	06/25/82	6:15:00	37.514942	− 120.97014	0	40	1	900	1.83	− 0.62	
12	16	06/25/82	6:30:00	37.137974	− 120.68145	0	40	1	900	1.45	− 1.00	
13	5	07/15/82	6:30:00	35.766353	− 119.70902	65	40	1	905	2.06	− 0.39	W
13	4	07/15/82	6:45:06	35.784607	− 120.24442	478	40	1	905	2.30	− 0.15	W
13	6	07/15/82	7:30:00	35.756706	− 119.46153	66	40	1	905	1.88	− 0.57	W
13	4	07/19/82	7:01:00	35.784607	− 120.24442	478	64	2	1,357	0.79	− 1.79	W
13	2	07/19/82	7:16:00	35.472916	− 120.61186	319	24	2	905	1.70	− 0.75	D
13	1	07/19/82	7:31:00	35.392952	− 120.80180	127	21	1	905	1.66	− 0.79	W
13	3	07/19/82	8:31:00	35.627075	− 120.40665	349	40	1	905	1.65	− 0.80	W
14	1	08/05/82	6:30:00	37.652805	− 118.92058	2236	61	1	905	2.06	− 0.39	
14	2	08/05/82	7:30:00	37.691597	− 118.93903	2317	61	1	905	1.64	− 0.81	
14	13	06/30/83	7:00:00	36.401428	− 120.50803	377	45	2	1,448	0.99	− 1.61	
14	18	07/28/83	7:00:00	37.733524	− 118.77125	2116	**37**	1	905	3.32	0.87	
14	1	07/28/83	7:15:00	37.652805	− 118.92058	2236	55	1	905	2.58	0.13	
14	16	07/31/83	7:15:00	37.742390	− 118.86207	2138	55	1	905	2.83	0.38	
14	15	07/31/83	7:30:00	37.622684	− 118.86182	2183	46	1	679	2.19	− 0.17	
14	12	08/03/83	7:15:00	37.634621	− 118.79745	2105	55	1	611	2.62	0.30	
14	11	08/03/83	8:00:00	37.654732	− 119.05913	2805	46	1	588	1.61	− 0.70	

(*continued*)

Table 2 (*Continued*)

Expt.	Shotpoint No.	Date (UTC) (dd/mm/yy)	Shottime (UTC)	Latitude	Longitude	Elev. (m)	Hole Depth (m)	No. Holes	Yield (kg)	Mag	Equation (1) Residual Magnitude	Wet or Dry?
14	13	08/03/83	9:00:00	37.638622	−118.72295	2081	46	1	679	2.63	0.27	
14	1	08/03/83	9:30:00	37.652805	−118.92058	2236	37	1	498	2.59	0.33	
14	17	08/18/83	7:00:00	37.638192	−118.92801	2287	30	1	226	1.62	−0.39	
15	8216	09/18/82	6:00:00	41.497101	−121.91250	1492	41	1	905	2.41	−0.04	
15	8205	09/18/82	8:00:00	41.547825	−122.26687	1113	41	1	905	1.66	−0.79	D
15	8217	09/22/82	8:30:00	41.832167	−121.58617	1291	41	1	905	2.12	−0.33	
15	8216	09/22/82	8:45:00	41.497101	−121.91250	1492	41	1	905	2.24	−0.21	
15	8203	10/08/82	6:30:00	40.355678	−121.30427	1525	41	1	905	1.28	−1.17	
15	8215	10/11/82	11:00:00	41.407715	−122.08233	1690	41	1	905	2.67	0.22	
15	8202	10/14/82	6:30:00	40.460087	−121.47334	2250	41	1	905	2.40	−0.05	
15	8205	10/19/82	11:00:00	41.547825	−122.26687	1113	41	1	905	2.72	0.27	D
16	12	05/18/83	6:45:00	36.255795	−120.61443	603	45	1	905	1.86	−0.59	
16	9	05/19/83	6:30:03	36.218826	−119.68684	67	45	1	905	2.16	−0.29	
16	10	05/19/83	6:45:01	36.228775	−120.02949	91	45	1	905	2.15	−0.30	
17	18	02/09/85	3:31:00	36.808203	−116.09281	1179	43	2	1,855	1.6	−1.08	
17	17	02/09/85	5:31:00	36.797949	−116.22306	1173	43	1	927	2.3	−0.16	
17	1	02/09/85	5:35:00	36.803967	−116.85558	1023	41	2	1,855	1.4	−1.28	D
17	4	02/09/85	5:39:00	36.810710	−116.60428	974	43	1	927	1.8	−0.66	D
17	20	02/13/85	3:31:00	36.598157	−116.57717	732	36	1	927	1.7	−0.76	
17	23	02/13/85	3:35:00	36.563717	−116.27288	774	36	1	927	1.5	−0.96	
17	25	02/13/85	3:37:00	36.561682	−116.12437	851	36	1	927	1.4	−1.06	
17	27	02/13/85	3:39:00	36.570780	−115.79401	1023	36	2	1,855	2.0	−0.68	
17	26	02/13/85	5:31:00	36.592216	−115.94037	1115	36	1	927	1.3	−1.16	
17	21	02/13/85	5:33:00	36.583142	−116.50544	736	36	1	927	1.6	−0.86	
17	22	02/13/85	5:35:00	36.570776	−116.35107	771	36	1	927	1.6	−0.86	
17	24	02/13/85	5:37:00	36.554045	−116.20260	765	36	1	927	1.6	−0.86	
17	29	02/13/85	5:39:00	36.590743	−116.65996	869	36	2	1,855	1.6	−1.08	
18	18	09/12/85	6:34:00	41.225525	−121.19686	1281	41	2	1,810	1.82	−0.85	D
18	6	09/12/85	6:36:00	41.916885	−121.99493	1292	53	1	1,360	2.27	−0.31	W
18	19	09/12/85	8:49:00	41.123393	−121.54688	1012	53	1	1,360	1.97	−0.61	W
18	8	09/12/85	8:51:00	41.243362	−121.99619	1085	41	2	1,810	1.00	−1.67	D/W
18	4	09/12/85	11:00:00	41.505212	−122.57905	963	53	1	1,360	2.02	−0.56	W
19	8	11/05/85	7:00:00	34.019858	−114.26789	155	**70**	1	1,357	1.9	−0.68	
19	11	11/05/85	7:02:01	35.077368	−115.15738	1146	**70**	2	1,810	1.9	−0.77	
19	13	11/05/85	7:04:01	33.625592	−113.97197	511	**70**	2	1810	1.9	−0.77	
19	9	11/05/85	7:06:01	34.532597	−114.61287	527	**70**	2	1,810	1.7	−0.97	
19	9′	11/05/85	7:30:00	34.532597	−114.61287	527	**45**	1	226	1.4	−0.61	
19	8X	11/05/85	9:00:00	34.073463	−114.29790	108	**50**	1	452	2.3	0.07	W
19	10	11/05/85	9:02:01	34.808565	−114.93256	640	**70**	1	1,357	1.8	−0.78	
19	4A	11/05/85	9:04:00	34.267855	−114.48411	463	**50**	1	905	1.9	−0.55	
19	9X′	11/05/85	9:30:00	34.430253	−114.54449	292	**45**	1	226	1.1	−0.91	D
19	12	11/08/85	6:00:00	34.909265	−113.57791	989	**70**	2	1,810	1.5	−1.17	
19	11	11/08/85	6:02:01	35.077368	−115.15738	1146	**50**	1	905	1.7	−0.75	
19	14	11/08/85	6:04:00	33.618272	−114.98434	108	**50**	1	950	2.2	−0.26	W
19	2	11/08/85	6:08:00	34.002965	−114.64592	352	**50**	1	452	1.3	−0.93	
19	3′	11/08/85	6:30:00	34.105447	−114.51908	190	**45**	1	226	1.8	−0.21	D
19	2′	11/08/85	6:34:00	34.002965	−114.64592	352	**45**	1	226	1.2	−0.81	
19	1	11/08/85	9:02:00	33.830427	−114.71946	280	**50**	1	905	1.7	−0.75	
19	4B	11/08/85	9:04:00	34.224305	−114.42589	351	**50**	1	905	1.5	−0.95	
19	1X	11/08/85	9:06:00	33.956408	−114.66668	268	**45**	1	226	1.2	−0.81	D
19	14	11/13/85	6:02:00	33.618272	−114.98434	108	**50**	2	1,448	2.2	−0.40	
19	11	11/13/85	6:06:02	35.077368	−115.15738	1146	**50**	1	905	1.7	−0.75	
19	1	11/13/85	9:02:01	33.830427	−114.71946	280	**70**	1	1,357	1.8	−0.78	
19	4B	11/13/85	9:04:00	34.224305	−114.42589	351	**50**	1	905	1.7	−0.75	
20	4	07/26/86	5:00:00	40.096228	−117.99101	1260	55	1	1,357	1.5	−1.08	W
20	7	07/30/86	5:00:00	39.470057	−116.54234	1938	55	1	1,357	1.9	−0.68	
20	14	07/30/86	5:04:00	40.040673	−117.77631	1069	18	1	226	2.4	0.39	
20	1	07/30/86	5:06:00	40.582707	−119.46028	1200	52	3	2,715	2.7	−0.10	W
20	4	07/30/86	7:00:00	40.096228	−117.99101	1260	55	1	1,357	2.5	−0.08	W
20	3	07/30/86	7:02:00	40.259335	−118.47411	1223	41	2	1,810	3.1	0.43	W
21	3	11/01/86	8:00:00	35.627075	−120.40664	351	26	1	452	1.54	−0.69	

(*continued*)

Table 2 (*Continued*)

Expt.	Shotpoint No.	Date (UTC) (dd/mm/yy)	Shottime (UTC)	Latitude	Longitude	Elev. (m)	Hole Depth (m)	No. Holes	Yield (kg)	Mag	Equation (1) Residual Magnitude	Wet or Dry?
21	1	11/01/86	11:00:00	35.419555	− 120.78110	120	**26**	1	452	1.76	− 0.47	
21	6	11/05/86	8:00:00	35.432916	− 120.11125	639	**26**	1	452	1.86	− 0.37	
21	5	11/05/86	10:00:00	35.320000	− 120.32458	549	**26**	1	452	2.25	0.02	
21	7	11/06/86	9:00:00	35.647416	− 121.04355	372	**26**	1	452	1.82	− 0.41	
22	1	11/11/86	13:49:01	35.402596	− 119.14860	110	**22**	1	272	1.3	− 0.77	
22	1	11/11/86	14:13:01	35.402596	− 119.14860	110	**22**	1	272	1.4	− 0.67	
22	2	11/11/86	15:35:01	35.007292	− 118.70674	527	**22**	1	272	1.4	− 0.67	
23	1	11/08/87	12:10:01	34.047400	− 118.06980	62	30	2	543	2.0	− 0.29	
24	1065	01/15/88	18:58:18	36.571667	− 116.38590	751	76	1	23	0.74	− 0.54	W?
24	1067	01/15/88	19:18:47	36.571667	− 116.38530	751	76	1	45	1.15	− 0.35	W
24	1069	01/15/88	19:28:16	36.571667	− 116.38470	751	76	1	90	1.13	− 0.59	W
24	1189	01/15/88	19:57:12	36.570667	− 116.35150	767	76	1	181	1.38	− 0.56	W
25	18	04/29/88	18:00:00	40.754191	− 119.11679	1196	49	5	9,050	1.50	− 1.68	
25	16	04/30/88	1:30:00	36.372437	− 116.37332	637	40	10	13,575	1.45	− 1.86	
25	17	04/30/88	19:00:00	39.064034	− 117.98136	1670	60	5	9,050	1.50	− 1.68	W
26	1	10/27/88	18:15:00	37.323967	− 122.10725	136	217	1	452	1.25	− 0.98	
26	2	10/27/88	18:30:16	37.321817	− 122.10890	327	10	14	3,167	1.49	− 1.36	
26	3	10/28/88	18:15:00	37.323967	− 122.10725	245	106	1	407	1.29	− 0.91	
26	4	10/28/88	18:30:00	37.323467	− 122.10748	339	10	4	860	1.08	− 1.35	
26	5	10/31/88	19:15:00	37.323967	− 122.10725	311	42	1	407	1.04	− 1.16	
26	6	10/31/88	19:30:00	37.319700	− 122.11252	326	10	1	290	0.84	− 1.25	
26	7	10/31/88	19:45:03	37.322133	− 122.13017	525	20	1	683	1.21	− 1.15	
26	8	10/31/88	19:46:00	37.323767	− 122.10752	341	10	1	154	0.92	− 0.97	
26	9	11/01/88	19:15:00	37.320450	− 122.11037	288	12	1	136	1.07	− 0.78	
26	10	11/01/88	19:30:01	37.324083	− 122.10752	352	10	23	5,385	1.70	− 1.32	
27	20	09/21/89	2:34:00	33.486010	− 114.59666	76	**44**	3	3,620	2.8	− 0.09	
28	Big	09/07/90	18:03:12	35.920500	− 117.75417	698	—	—	113,122	2.8	− 1.18	D
29	3	05/22/91	6:04:00	37.172819	− 121.79157	175	33	1	452	1.40	− 0.83	
29	5	05/24/91	7:00:00	37.085045	− 121.86142	530	54	1	1,357	1.31	− 1.27	
29	6	05/24/91	7:02:00	36.857161	− 121.56137	122	45	1	905	2.01	− 0.44	
29	2	05/24/91	7:04:00	37.105612	− 121.84721	1034	27	1	452	1.95	− 0.28	
29	1	05/24/91	8:04:00	37.021353	− 121.90279	79	38	1	452	1.57	− 0.66	
29	10	05/30/91	9:30:00	37.827884	− 122.49003	15	57	1	1,357	1.91	− 0.67	
29	5	05/26/93	8:00:00	36.792683	− 121.29377	299	43	1	1,357	1.65	− 0.93	
29	7	05/26/93	8:02:00	37.335630	− 122.23213	536	43	1	905	1.75	− 0.70	
29	6	05/26/93	8:08:00	37.540200	− 122.40602	340	43	1	905	1.79	− 0.66	
29	3	05/28/93	7:04:00	37.607670	− 121.96498	411	43	1	905	1.50	− 0.95	
29	8	05/28/93	7:08:01	38.167750	− 122.45167	2	21	1	90	1.44	− 0.28	
29	5	05/28/93	7:10:00	36.792683	− 121.29377	299	43	2	1,810	1.06	− 1.61	
29	1	05/28/93	7:12:01	38.423400	− 122.62912	280	43	2	1,810	1.89	− 0.78	
29	14	05/28/93	9:02:01	37.097580	− 121.54523	253	21	1	90	1.10	− 0.62	
29	9	05/28/93	9:08:00	38.003750	− 122.36446	21	61	1	136	0.67	− 1.18	
30	113	02/11/92	7:15:02	33.596820	− 114.41281	216	54	1	1,357	2.1	− 0.48	D
30	111	02/11/92	10:00:01	33.399762	− 114.63911	97	34	1	452	2.0	− 0.23	W
30	110	02/11/92	10:15:01	33.333349	− 114.72238	94	24	1	905	2.3	− 0.15	W
30	100	02/13/92	7:05:01	32.658810	− 115.84158	124	47	2	1,810	2.3	− 0.37	D
30	103	02/13/92	7:10:01	32.881261	− 115.13354	53	45	1	905	2.6	0.15	W
30	109	02/13/92	7:20:00	33.282943	− 114.77648	132	30	1	452	2.4	0.17	D
30	101	02/13/92	10:05:01	32.698583	− 115.37681	11	35	2	1,810	3.1	0.43	W
30	102	02/13/92	10:10:02	32.795872	− 115.22763	45	53	1	1,357	2.9	0.32	W
30	115	02/16/92	7:00:00	33.405096	− 116.06077	− 12	35	1	905	1.7	− 0.75	D
30	6	02/16/92	7:03:02	32.694754	− 115.25210	39	39	2	1,810	2.5	− 0.17	W
30	116	02/16/92	7:06:00	33.641106	− 116.27782	9	53	1	1,357	2.1	− 0.48	D
30	117	02/16/92	9:00:00	33.865179	− 116.57700	236	37	2	1,810	2.2	− 0.47	D
30	114	02/16/92	9:03:01	33.177433	− 115.87564	− 2	41	1	905	2.1	− 0.35	W
31	1	07/17/92	6:00:00	34.215000	− 116.41917	1150	**26**	1	452	2.0	− 0.23	D
31	2	07/17/92	6:03:00	34.559000	− 116.57217	1020	**37**	1	905	1.8	− 0.65	D
32	1	09/17/92	8:00:00	40.305000	− 124.31450	15	35	1	679	1.44	− 0.92	W
32	2	09/17/92	8:02:00	40.442500	− 124.39350	300	54	1	1,357	1.44	− 1.14	W
32	4	09/17/92	8:06:00	41.628167	− 124.02183	81	50	1	1,357	1.53	− 1.05	W
33	603	08/19/93	7:00:00	40.456730	− 122.56935	242	30	1	452	1.73	− 0.50	W

(*continued*)

Table 2 (*Continued*)

Expt.	Shotpoint No.	Date (UTC) (dd/mm/yy)	Shottime (UTC)	Latitude	Longitude	Elev. (m)	Hole Depth (m)	No. Holes	Yield (kg)	Mag	Equation (1) Residual Magnitude	Wet or Dry?
33	604	08/19/93	7:02:00	40.605450	−122.86928	652	44	1	905	1.68	−0.77	W
33	601	08/19/93	7:08:00	40.331140	−121.72925	1134	46	2	1,810	1.28	−1.39	W
33	606	08/19/93	7:46:00	40.615530	−123.48672	516	30	1	905	1.56	−0.89	W
33	605	08/19/93	10:02:00	40.585690	−123.09509	855	30	1	452	1.25	−0.98	W
33	608	08/19/93	10:04:00	40.758890	−124.01766	356	45	2	1,810	2.09	−0.58	W
33	107	08/23/93	7:00:00	39.432360	−123.49199	128	34	1	452	1.31	−0.92	D
33	102	08/23/93	7:02:00	39.635690	−121.95883	35	46	1	905	2.28	−0.17	W
33	101	08/23/93	7:04:00	39.701580	−121.42784	854	42	2	1,810	2.22	−0.45	W
33	108	08/23/93	7:10:00	39.469840	−123.74779	149	49	2	1,810	1.83	−0.84	W
33	106	08/23/93	10:00:00	39.440500	−123.17781	829	46	1	905	1.63	−0.82	D
33	103	08/23/93	10:02:00	39.567890	−122.30002	68	30	1	452	1.75	−0.48	D
33	901	08/27/93	7:00:00	39.151340	−122.85143	457	53	2	2,262	1.76	−0.98	W
33	903	08/27/93	7:02:00	39.614880	−122.97090	1932	45	2	1,810	1.72	−0.95	W
33	909	08/27/93	7:06:00	40.834040	−123.70785	1463	44	2	1,810	1.90	−0.77	W
33	905	08/27/93	7:08:00	39.938670	−123.31152	856	60	1	1,357	1.74	−0.84	W
33	911	08/27/93	7:12:00	41.225989	−123.94470	759	52	2	2,270	2.00	−0.74	W
33	902	08/27/93	10:00:00	39.355380	−122.99571	1005	34	1	452	1.74	−0.49	
33	904	08/27/93	10:02:00	39.782570	−123.09187	1164	30	1	452	1.44	−0.79	W
33	907	08/27/93	10:04:00	40.414400	−123.49127	1147	57	1	1,357	1.93	−0.65	W
33	908	08/27/93	10:06:00	40.628860	−123.64737	1322	33	1	452	1.30	−0.93	W
33	107	08/27/93	10:08:00	39.432360	−123.49199	128	34	1	679	1.65	−0.71	D
34	19	09/14/93	7:00:00	34.964970	−118.18758	849	48	3	3,620	2.14	−0.75	
34	18	09/14/93	7:02:00	35.259930	−117.48788	777	47	3	3,620	2.34	−0.55	D
34	4	09/14/93	7:04:00	36.444340	−118.83641	813	40	2	1,810	1.97	−0.70	
34	14	09/14/93	7:06:00	36.853450	−118.14043	1151	40	2	1,810	2.31	−0.36	
34	12	09/14/93	7:08:00	37.913550	−118.45771	1769	48	3	3,620	2.02	−0.87	
34	16	09/14/93	10:02:00	35.940270	−117.89657	1000	42	2	1,810	1.87	−0.80	D
34	3	09/14/93	10:04:00	36.394400	−119.49167	80	52	1	1,131	2.36	−0.16	
34	15	09/14/93	10:06:00	36.423230	−118.00461	1091	52	1	1,357	2.07	−0.51	
34	13	09/14/93	10:08:00	37.326990	−118.31154	1223	52	2	2,715	2.76	−0.04	
34	4	09/18/93	7:04:00	36.445130	−118.83765	813	40	2	1,810	2.19	−0.48	
34	9	09/18/93	7:08:00	36.303250	−116.89102	−74	49	2	2,715	2.24	−0.56	
34	1	09/18/93	7:12:00	36.292000	−120.57696	754	48	3	3,620	1.94	−0.95	
34	5	09/18/93	10:02:00	36.424310	−118.00534	1090	52	1	1,357	2.32	−0.26	
34	3	09/18/93	10:04:00	36.393670	−119.49202	80	52	1	1,131	2.32	−0.20	
34	13	09/18/93	10:10:00	37.326980	−118.31211	1223	52	2	1,810	2.63	−0.04	
34	2	09/18/93	10:12:00	36.295540	−119.94752	73	52	2	2,715	2.56	−0.24	
34	24	09/22/93	7:01:00	37.201940	−116.20985	2247	—	—	904,977	3.89	−0.75	
35	DVJ	05/19/94	7:03:00	36.331800	−116.26932	723	**37**	**3**	3,620	2.6	−0.29	
35	Blythe	05/19/94	7:09:00	33.514234	−114.52977	112	**37**	**3**	3,620	2.4	−0.49	
36	1	09/16/94	3:00:00	35.938330	−120.52361	606	60	1	317	1.3	−0.82	
36	2	09/16/94	5:00:00	35.963610	−120.50917	803	25	1	226	1.06	−0.95	
36	3	09/16/94	7:00:00	35.967220	−120.48278	577	30	1	226	1.07	−0.94	
37	8630	10/26/94	8:32:00	34.646019	−117.61397	827	48	1	907	1.1	−1.35	
37	8450	10/26/94	8:34:00	34.495945	−117.70397	1013	46	1	680	0.9	−1.46	D
37	8360	10/26/94	8:38:00	34.416153	−117.71704	1511	31	1	454	1.3	−0.93	W
37	8346	10/26/94	8:40:00	34.404720	−117.72503	1853	44	1	998	1.6	−0.88	W
37	8331	10/26/94	8:42:00	34.394367	−117.73026	1855	23	1	113	1.3	−0.49	W
37	8310	10/26/94	8:44:00	34.384659	−117.76129	2000	23	1	113	1.1	−0.69	W
37	9150	10/26/94	10:00:00	35.057013	−117.33096	590	43	3	2,722	2.9	0.10	D
37	8500	10/26/94	10:02:00	34.542076	−117.68095	916	46	1	907	0.8	−1.65	D
37	8400	10/26/94	10:04:00	34.455215	−117.71646	1221	41	1	680	0.5	−1.86	D
37	8351	10/26/94	10:08:00	34.411671	−117.71734	1548	23	1	227	1.1	−0.91	W
37	8344	10/26/94	10:10:00	34.401028	−117.72477	1866	27	1	408	1.1	−1.10	W
37	8330	10/26/94	10:11:59	34.393620	−117.74108	1862	21	1	113	0.9	−0.89	W
37	8302	10/26/94	10:14:00	34.379131	−117.76401	1803	44	1	907	1.5	−0.95	D
37	8350	10/26/94	11:38:00	34.409164	−117.71758	1587	23	1	227	0.9	−1.11	W
37	8320	10/26/94	11:42:00	34.392399	−117.75207	1917	23	1	113	0.8	−0.99	W
37	9990	10/26/94	22:04:00	35.040264	−117.67506	639		40	10,886	1.8	−1.44	D
37	8300	10/27/94	8:30:00	34.374699	−117.77277	2101	23	1	113	2.2	0.41	D
37	8270	10/27/94	8:32:00	34.358067	−117.79851	2323	23	1	113	1.2	−0.59	D

(*continued*)

Table 2 (*Continued*)

Expt.	Shotpoint No.	Date (UTC) (dd/mm/yy)	Shottime (UTC)	Latitude	Longitude	Elev. (m)	Hole Depth (m)	No. Holes	Yield (kg)	Mag	Equation (1) Residual Magnitude	Wet or Dry?
37	8240	10/27/94	8:34:00	34.334648	−117.82719	1986	26	1	113	1.8	0.01	D
37	8210	10/27/94	8:36:00	34.311920	−117.83444	1496	23	2	454	1.5	−0.73	W
37	8181	10/27/94	8:38:00	34.287594	−117.84238	975	18	1	113	2.2	0.41	D
37	8131	10/27/94	8:44:00	34.235634	−117.85053	427	26	1	227	0.6	−1.41	W
37	8100	10/27/94	8:46:00	34.212654	−117.86381	472	34	1	454	1.0	−1.23	D
37	8290	10/27/94	10:00:03	34.371483	−117.78187	2184	23	1	113	2.1	0.31	D
37	8260	10/27/94	10:02:00	34.351192	−117.80886	2285	34	1	318	1.4	−0.72	W
37	8230	10/27/94	10:04:00	34.331142	−117.83286	1824	23	1	181	1.0	−0.94	W
37	8180	10/27/94	10:08:00	34.283169	−117.84398	921	33	1	454	1.1	−1.13	D
37	8160	10/27/94	10:10:00	34.262657	−117.84593	673	18	1	113	0.9	−0.89	D
37	8141	10/27/94	10:12:00	34.248932	−117.86553	498	23	1	113	0.6	−1.19	D
37	8120	10/27/94	10:14:00	34.224739	−117.84897	431	19	1	113	2.3	0.51	D
37	8090	10/27/94	10:16:00	34.202263	−117.85693	330	26	1	227	1.1	−0.91	W
37	8280	10/27/94	11:30:00	34.365650	−117.78914	2248	23	1	113	1.0	−0.79	D
37	8250	10/27/94	11:32:00	34.345089	−117.82017	2202	23	1	113	0.6	−1.19	W
37	8220	10/27/94	11:34:00	34.322559	−117.83801	1685	25	1	113	1.0	−0.79	D
37	8190	10/27/94	11:36:00	34.293587	−117.84005	992	24	1	91	1.2	−0.52	W
37	8170	10/27/94	11:38:00	34.278965	−117.84438	791	24	1	227	1.3	−0.71	W
37	8150	10/27/94	11:40:00	34.260094	−117.85397	594	22	1	113	0.7	−1.09	D
37	8130	10/27/94	11:42:00	34.241005	−117.86491	463	32	1	454	1.6	−0.63	W
37	8110	10/27/94	11:44:00	34.216942	−117.85832	481	20	1	113	0.6	−1.19	W
37	8080	10/27/94	11:46:00	34.193722	−117.86566	350	23	1	113	0.9	−0.89	W
37	9991	10/27/94	22:01:44	35.040264	−117.67506	639		40	10,886	1.6	−1.64	D
37	8050	10/28/94	8:30:00	34.170002	−117.89051	234	32	1	544	2.5	0.21	W
37	9000	10/28/94	8:34:00	34.138920	−117.93504	145	23	1	408	1.3	−0.90	D
37	9023	10/28/94	8:36:01	34.128582	−117.94757	131	24	1	181	2.2	0.26	D
37	9010	10/28/94	10:04:01	34.133179	−117.93929	86	30	1	454	1.9	−0.33	D
37	9021	10/28/94	10:06:01	34.121777	−117.94725	118	30	1	340	2.8	0.66	D
37	9170	10/28/94	10:08:01	33.978897	−118.00550	142	23	1	272	1.4	−0.67	W
37	9450	10/28/94	10:10:04	33.752846	−118.08087	−31	34	1	408	1.6	−0.60	W
37	9030	10/28/94	10:12:01	34.114174	−117.94920	109	43	1	680	0.7	−1.66	D
37	9160	10/28/94	10:16:01	34.013092	−118.01123	283	30	1	399	1.6	−0.59	D
37	9992	5/23/95	19:00:04	33.312675	−117.30606	40			85,195	2.97	−0.89	
38	14	5/19/95	6:00:00	36.840167	−121.32033	212	27	1	362	1.14	−1.02	W
38	8	5/19/95	6:02:00	36.672700	−121.32130	635	24	1	181	1.12	−0.82	W
38	9	5/19/95	6:03:00	36.589500	−121.13980	671	27	1	362	0.79	−1.37	D
38	11	5/19/95	6:04:00	36.685167	−121.36767	387	20	1	136	0.78	−1.07	W
38	13	5/19/95	6:05:00	36.681333	−121.29167	240	20	1	136	1.30	−0.55	D
38	3	5/19/95	6:07:00	36.739833	−121.31500	189	20	1	136	1.70	−0.15	D
38	12	5/19/95	7:01:00	36.783000	−121.21083	424	27	1	362	1.35	−0.81	W
38	4	5/19/95	7:04:00	36.700167	−121.33833	291	20	1	113	1.03	−0.76	W
38	1	5/19/95	8:00:00	36.830700	−121.42600	111	27	1	362	1.71	−0.45	D
38	6	5/19/95	8:02:00	36.757000	−121.26670	306	27	1	362	1.41	−0.75	W
38	5	5/19/95	8:05:00	36.714300	−121.31230	323	27	1	362	1.83	−0.33	D
39	6	6/16/95	7:00:00	37.593900	−122.44290	359	24	1	339	1.58	−0.56	D
39	9	6/16/95	7:04:00	37.683100	−122.42120	145	30	1	452	1.45	−0.78	W
39	7	6/16/95	7:05:00	37.280000	−122.29000	162	30	1	452	1.74	−0.49	D
39	5	6/16/95	8:00:00	37.584000	−122.45080	352	20	1	113	1.63	−0.16	W
39	4	6/16/95	8:01:00	37.569800	−122.45020	330	32	1	452	1.52	−0.71	W
39	1	6/16/95	8:03:00	37.500600	−122.39840	150	26	1	226	1.06	−0.95	W
39	10	6/16/95	8:04:00	37.614200	−122.49280	31	21	1	113	0.94	−0.85	D
40	9350	10/20/99	8:34:01	34.615800	−118.74382	581	43	2	1818	1.97	−0.70	W
40	8570	10/20/99	8:35:00	34.544940	−118.49386	655	21	1	227	1.32	−0.69	W
40	8720	10/20/99	8:37:00	34.679200	−118.45747	923	16	1	23	1.91	0.66	W
40	9136	10/20/99	8:38:00	35.265130	−118.41124	1049	43	2	1818	2.11	−0.56	W
40	9360	10/20/99	8:39:00	34.818810	−118.76061	1020	40	2	1697	1.80	−0.85	W
40	8095	10/20/99	10:01:00	34.108100	−118.55900	614	52	1	1273	1.81	−0.75	W
40	8560	10/20/99	10:05:00	34.536340	−118.50337	644	31	1	455	1.38	−0.85	W
40	8331	10/20/99	11:33:01	34.328450	−118.54200	778	31	1	455	2.12	−0.11	D?
40	8590	10/21/99	8:35:00	34.559000	−118.48955	505	42	1	909	1.26	−1.19	D?
40	8620	10/22/99	8:32:00	34.593310	−118.49236	867	24	1	455	1.49	−0.74	D

(*continued*)

Table 2 (*Continued*)

Expt.	Shotpoint No.	Date (UTC) (dd/mm/yy)	Shottime (UTC)	Latitude	Longitude	Elev. (m)	Hole Depth (m)	No. Holes	Yield (kg)	Mag	Equation (1) Residual Magnitude	Wet or Dry?
40	8740	10/22/99	8:37:00	34.696540	−118.46050	1096	27	1	455	1.34	−0.89	W
40	9244	10/24/99	10:07:01	34.174470	−118.48437	212	30	1	294	1.71	−0.38	W
40	9212	10/24/99	11:39:01	34.264350	−118.38365	302	30	1	452	1.58	−0.65	W
41	DBLT	10/16/02	13:59:57	35.961132	−120.59178	629	20	1	45	1.90	0.40	D
41	LOMB	10/16/02	14:02:00	35.965866	−120.66497	432	26	1	181	1.65	−0.29	W
41	MATZ	10/16/02	14:04:01	36.089867	−120.51450	466	25	1	181	1.61	−0.33	D
41	CANS	10/16/02	14:05:59	35.900600	−120.56638	703	26	1	181	1.71	−0.23	D
41	COOK	10/16/02	14:08:00	35.882465	−120.42159	470	26	1	81	1.95	0.26	D
41	KEYS	10/16/02	15:00:00	35.974415	−120.60519	519	24	1	90	1.84	0.12	W
41	RCKY	10/16/02	15:02:00	35.965767	−120.61287	515	21	1	90	1.88	0.16	W
41	GLEN	10/17/02	2:00:00	35.933868	−120.56496	800	22	1	90	1.80	0.08	D
41	LCCB	10/17/02	2:02:00	35.980250	−120.51133	651	19	1	45	1.52	0.02	D
41	PRIS	10/17/02	2:03:58	35.975166	−120.48977	607	19	1	45	1.35	−0.15	W
41	PMM	10/17/02	2:06:00	35.957916	−120.50397	779	25	1	226	1.99	−0.02	W
41	CGAS	10/17/02	2:08:00	35.970383	−120.49920	604	19	1	45	1.26	−0.24	D
41	TIM7	10/17/02	13:59:59	35.993633	−120.47028	1028	21	1	90	1.49	−0.23	W
41	MUST	10/17/02	14:02:00	35.972332	−120.42548	1036	25	1	181	1.62	−0.32	W
41	LAKE	10/17/02	14:06:00	35.966499	−120.47500	642	23	1	226	1.91	−0.10	W

Borehole depths in bold are calculated from charge size assuming 15.3 m of tamp and 42 kg/m of linear charge. The number of boreholes used in experiment 35 is inferred from the charge size.

down the hole with one 1-lb booster attached at its bottom end. Loading is then accomplished (in holes with water not to the surface) by lowering individual bags of emulsion with a nylon line and a slipknot to release the bag when it reaches the bottom of the hole. In dry holes or holes with water to the surface, loading is performed by slitting bags and pouring emulsion into the boreholes, or in the case of a more firm emulsion, by cutting and dropping 2-kg chunks of doughy emulsion into the hole, or dropping entire small 2.5-kg bags into the borehole. In all cases 1-lb boosters are set along the detonation cord differently than with pump truck loading. Boosters are individually lowered down the detonation cord during the emulsion-bag loading to ensure their even distribution through the emulsion column. The boosters are lowered along the detonation cord at set poundage and/or emulsion column height intervals, depending on emulsion packaging and borehole conditions.

The shot hole is then carefully tamped to ensure that the tamp does not punch a hole through the charge, separating the boosters and primacord from the main charge. Generally a plastic bag filled with dirt is carefully placed on top of the charge to act as a stopper for the charge prior to placing tamp in the hole.

In all cases the detonating cord is ignited using an electrical blasting cap. Because the explosives are detonated electrically, the location and origin times of the detonations are known to within a few tens of meters and to a few milliseconds (e.g., Fuis *et al.*, 2001). The accuracy of the locations and origin times makes it possible to uniquely correlate the detonation with the computed locations and origin times of the explosions. The USGS normally detonates shotpoints in the late evening or early morning hours to minimize cultural noise (Table 2).

Reported Detonations

On average each detonation summarized in Table 2 was located using 23 stations (Fig. 1C). The nearest station used to locate the detonations was, on average, 15 km away. This information, as well as other aspects of the network recordings of the shots, such as the largest azimuthal gap between the stations used to locate the detonation, is available from the online Advanced National Seismic System catalog. For this reason they were not included in Table 2. There is a high density of detonations and reasonably complete geographic coverage of reported detonations in California; however, the geographic coverage of reported detonations in western Nevada is less complete (Fig. 1C). High station density in the San Francisco Bay Area and the Los Angeles region lead to large numbers of stations reporting detonations there (Fig. 1C).

Reported Magnitudes

I use the reported magnitudes and charge sizes for these 322 detonations (Table 2) to derive empirical relationships between charge size (yield) and magnitude (Fig. 2). These magnitudes are almost exclusively coda-duration magnitudes in California (Lee and Lahr, 1975; Eaton, 1992). For the 180 detonations in northern California, coda magnitudes were calculated from $M_c = 0.87 + 2.0 \log_{10}\tau + 0.0035\Delta$, where τ is the coda duration in seconds measured from the incident *P*-wave arrival time and Δ is the epicentral distance in kilometers (Eaton, 1992). For the 115 detonations in southern California, coda-duration magnitudes are calculated by fitting an decaying exponential envelope of the form $a(t) = a_0 t^{-q}$ over 2-sec-long averages of the *S*-wave coda amplitude (Johnson, 1979; Wald *et al.*, 1991). For 15 deto-

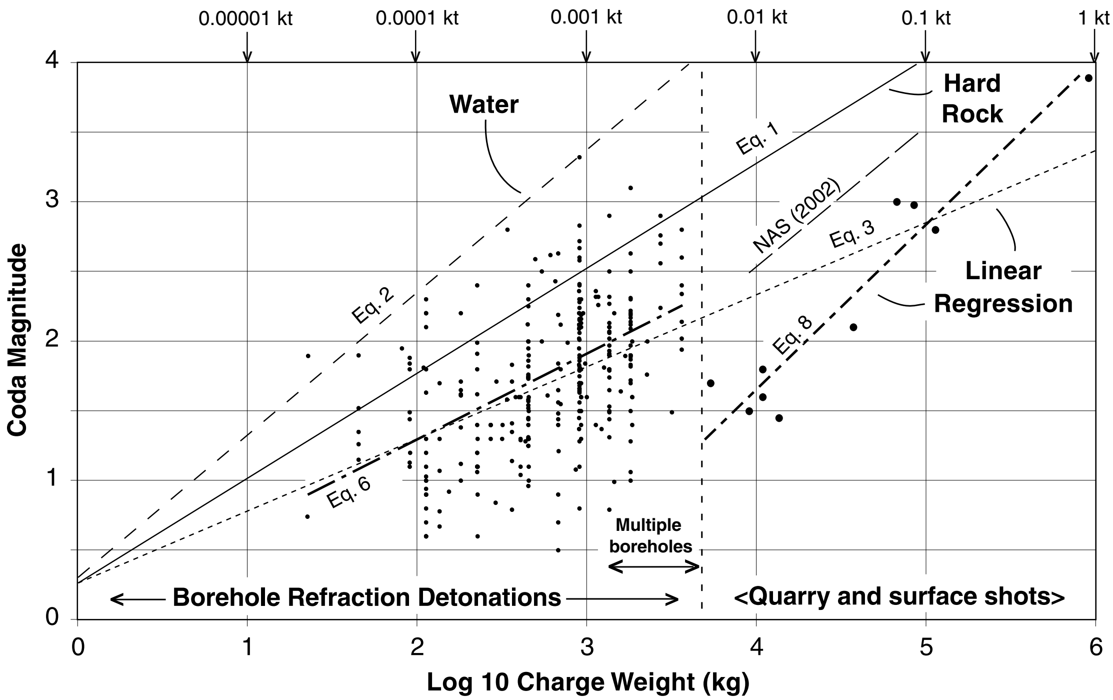

Figure 2. Reported magnitude for the detonations located by the networks versus the $\log_{10}$ charge size (in kg). Empirical relations between maximum magnitude and $\log_{10}$ charge size (kg) reported by Khalturin *et al.* (1999) for detonations in dry, hard rock (equation 1) (solid line) and by Gitterman and Shapira (2001) for water-fired detonations (equation 2) (dashed line) are shown for comparison. Three linear regressions for these observations (dotted and dashed lines) are also shown. The NAS (2002) curve represents an approximate relation for nuclear yields for tamped explosions in hard rock (National Academy of Sciences, 2002). Note that detonations in excess of 3600 kg (8000 lb) plotted as larger filled circles represent surface shots, quarry blasts, or blasts in adits, whereas detonations less than 3600 kg represent borehold refraction shots.

nations reported from experiment 17 near the Nevada Test Site in 1985, the coda-duration magnitude (M_D) is the weighted average of the duration magnitude and the coda amplitude magnitude (Rogers *et al.*, 1987). Magnitudes for four detonations in Amargosa Valley, Nevada (experiment 24) represent local magnitudes measured on the vertical component, or M_{Lv} (Harmsen and Bufe, 1992).

Yield versus Magnitude Relationships

The data show considerable scatter in event magnitude for a given charge size, reflecting variations in charge coupling and completeness of the detonation (Fig. 2). In general, the largest coda magnitudes for a given yield lie close to an empirical upper limit magnitude [$M = 2.45 + 0.73 \log_{10}$(weight [metric tons])], which I converted to

$$M_{\text{upper limit in hard rock}} = 0.26 + 0.73 \log_{10}(\text{weight [kg]}). \quad (1)$$

This empirical relation was derived mainly for chemical detonations in hard rock, but it also fits contained nuclear detonations (Khalturin *et al.*, 1998). Figure 3A plots, in map view, the residuals calculated by subtracting equation (1) from the reported coda magnitude for each detonation. As expected, the residuals are nearly all negative, although they are weakly positive for experiments near Long Valley, Shasta, and Los Angeles, along the southern boundary of California, and near Parkfield (Table 2, experiments 14, 15, 30, 37, and 41).

In Figure 2, I plot an empirical relationship between magnitude and charge size for detonations in large bodies of water (Gitterman and Shapira, 2001):

$$M_{\text{upper limit in water}} = 0.285 + \log_{10}(\text{weight [kg]}), \quad (2)$$

which, with its higher slope than equation (1), reflects the improved coupling of such detonations. Coda magnitudes for about 10% of the detonations lie between the curves for hard rock and open water detonations (Fig. 2).

I also show on Figure 2 the linear regression of the 322 observed charge-size magnitudes, subject to the constraint of an intercept of 0.26, for consistency with equation (1). The slope of this linear regression (equation 3) is lower than

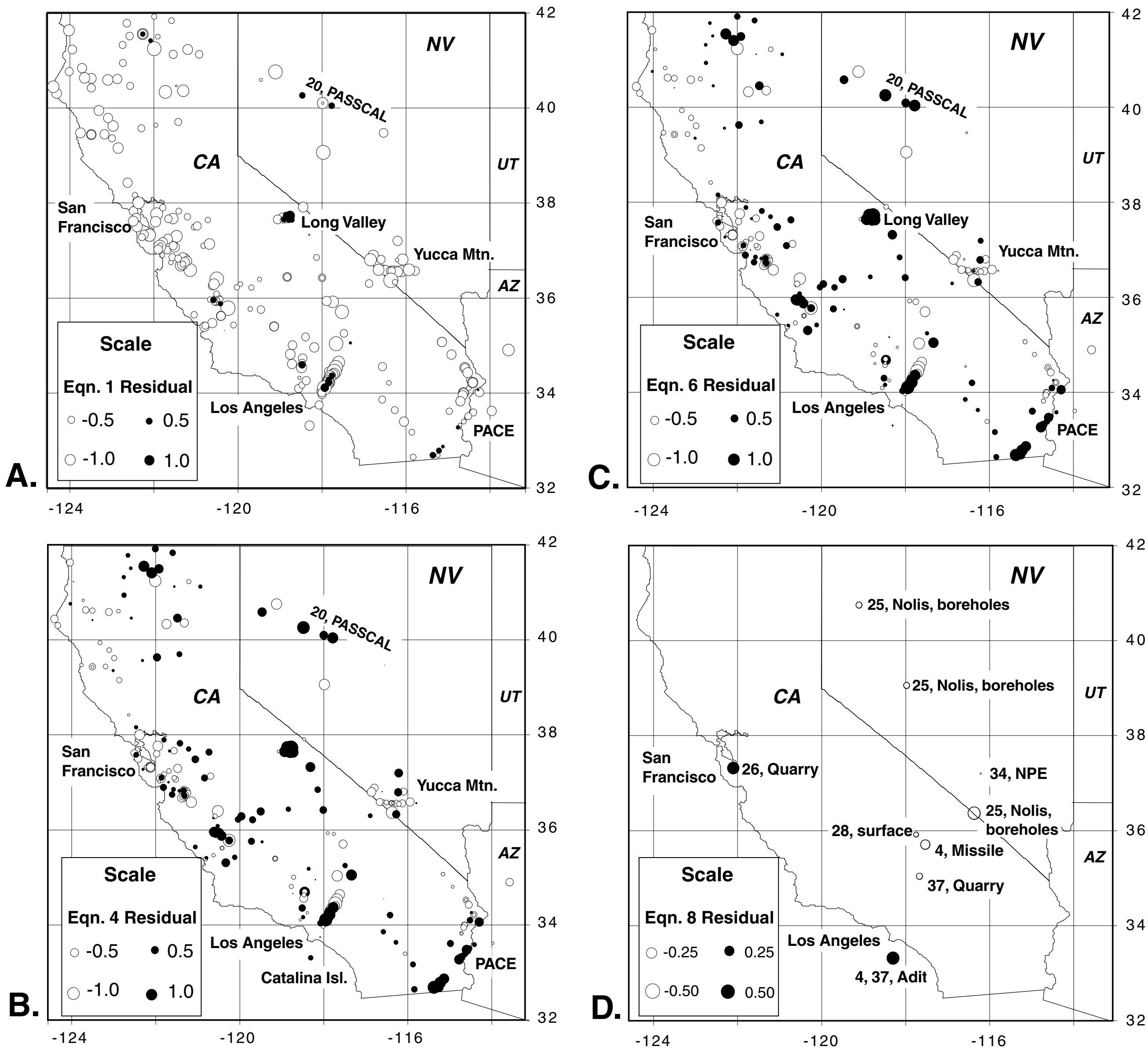

Figure 3. Map views of the magnitude residuals calculated for all detonations by subtracting (A) equation (1), (B) equation (4), and (C) equation (6) from the observed magnitudes. (D) Map view of the magnitude residuals calculated for the 11 largest detonations by subtracting equation (8) from the observed magnitudes. Individual experiments are numbered as in Table 1.

the slope of the line for hard rock (equation 1). This regression line fits the coda magnitudes with a standard deviation of 0.46.

$$M_{\text{linear regression, all detonations, fixed intercept}} = 0.26 + 0.52 \log_{10}(\text{weight [kg]}) \quad (3)$$

If the intercept is not fixed, the linear regression for all 322 detonations is

$$M_{\text{linear regression, all detonations, free intercept}} = 0.31 + 0.50 \log_{10}(\text{weight [kg]}). \quad (4)$$

Equations (3) and (4) are very similar and differ by less than 0.1 magnitude units for the range of charge weights studied here (23 to 905,000 kg). Figure 3B shows, in map view, the magnitude of residuals calculated by subtracting equation (4) from the reported magnitudes for each detonation. These residuals are strongly positive for experiments conducted near Long Valley, Parkfield, and Los Angeles, in northernmost and southernmost California, and in western Nevada (Table 1, Experiments 14, 15, 30, 37, and 41). Elsewhere positive residuals are randomly distributed.

If only 311 borehole detonations having yields less than or equal to 3620 kg are considered (Fig. 2), and the intercept is fixed, the linear regression becomes

$$M_{\text{linear regression, borehole shots, fixed intercept}} = 0.26 + 0.53 \log_{10}(\text{weight [kg]}). \quad (5)$$

Equation (5) does not differ substantially from equations (3) or (4). If these same detonations are considered (Fig. 2), but the intercept is not fixed, the linear regression becomes

$$M_{\text{linear regression, borehole shots, free intercept}} = 0.16 + 0.57 \log_{10}(\text{weight [kg]}). \quad (6)$$

Equation (6) differs more substantially from equation (3) than does equation (5) (Fig. 2). Figure 3C shows, in map view, the magnitude residuals calculated by subtracting equation (6) from the reported magnitude for each detonation. Figure 3C shows nearly identical geographic patterns as Figure 3B.

If only the 11 largest detonations having yields greater than 5385 kg are considered (Fig. 2), and the intercept is fixed at 0.26, the linear regression becomes

$$M_{\text{linear regression, large shots, fixed intercept}} = 0.26 + 0.45 \log_{10}(\text{weight [kg]}), \quad (7)$$

showing a lower slope than the regression for all detonations (equation 3) and that for the borehole detonations (equation 5). This regression line, however, fits the data very poorly. If these same largest 11 detonations are considered (Fig. 2), but the intercept is not fixed, the linear regression becomes

$$M_{\text{linear regression, large shots, free intercept}} = -3.07 + 1.18 \log_{10}(\text{weight [kg]}). \quad (8)$$

Equation (8) provides a close approximation to the observations (Fig. 2). Equations (7) and (8) differ substantially and are defined only for charges greater than 5385 kg and less than 10^6 kg. Figure 3D shows, in map view, the magnitude residuals calculated by subtracting equation (8) from the reported magnitude for every detonation larger than 5385 kg.

Yield Variability

In this section, I review some of the factors controlling the yield of the detonations compiled here. The number of boreholes, charge size in individual boreholes, and borehole depth are known for almost all of these detonations. Information on the borehole geology and degree of saturation of the borehole is available for about half of the detonations. Shooter's logs providing information pertinent to the quality and effectiveness of the tamping (noting the generation of fly rock, casing lifted up more than 3 m or blown completely out of the shot hole, and geysering) are available for about 35% of these detonations (for experiments 24, 30, 32, 33, and 36–41). Explicit knowledge of the completeness of the detonation is rare. As noted by Kohler and Fuis (1992), possible additional problems with shot-hole loading include (1) explosive charge being washed out of the hole by flowing groundwater, (2) loading an explosive too deeply for its specifications, so-called dead pressing, and (3) separation of explosive packets due to obstructions in the borehole (bridging). Explicit knowledge of the first and third of these problems is generally very limited.

Dead pressing causes very inefficient detonations that commonly fail to be reported by a permanent seismic network. It leads to the incomplete detonation of the chemical explosive charge. Fortunately, dead pressing is a well-known problem because records exist of the type of explosive used for nearly every experiment summarized here. Dead pressing in the deepest, largest detonations was recognized by the USGS in the summer of 1982; detonations after that date are not subject to this problem.

Adit, Quarry, and Surface Detonations

The 11 largest explosions used to define equations (7) and (8), shown in map view on Figure 3D and identified in Figure 4, represent adit, quarry, or surface blasts rather than borehole detonations. These explosions were not detonated by the USGS but were used to extend the subsurface coverage provided by these studies.

The largest detonation shown in Figure 3D was the Non-Proliferation Experiment, a 1-kt chemical blast detonated simultaneously in an adit on the Nevada Test Site in 1993 during the southern Sierra experiment (Table 2, experiment 34) (Fliedner *et al.*, 1996; Khalturin *et al.*, 1998). This detonation produced the largest magnitude, M_d 3.89, compiled here. The next largest detonation was an 113,112-kg surface detonation near China Lake, California, named Big Shot (Table 2, experiment 28; F. Monastero, personal comm., 2001). The third largest blast, 89,195 kg of ammonium nitrate/diesel-fuel mix detonated in a quarry adit on Catalina Island, yielded an M_L of 2.97 (Table 2, experiment 37) (Murphy *et al.*, 1996). The large detonations used during the Western Mojave Desert survey (Table 2, experiment 4) represent a 37,324-kg missile detonation at the surface and a simultaneous 67,183-kg blast in a quarry adit on Catalina Island (Given and Koesterer, 1983; Harris *et al.*, 1988). Los Angeles Region Seismic Experiment (LARSE) 1994 shots (Table 2, experiment 37) with charge sizes of 10,886 kg represent ripple-fired quarry blasts in a borate mine in the Mojave Desert (Murphy *et al.*, 1996). The 9050- and 13,575-kg detonations fired during the Nevada–Oregon Lithospheric Imaging Survey (NOLIS), a joint Soviet–U.S. nuclear calibration experiment (Table 2, experiment 25), employed 10–15 boreholes, each 40- to 60-m deep, spaced several meters apart, and fired simultaneously (J. Murphy, personal comm., 2001). The NOLIS shots used Tovan Extra 50/50 explosive, an even blend of emulsion and watergel.

Coda magnitudes of these largest blasts follows the lin-

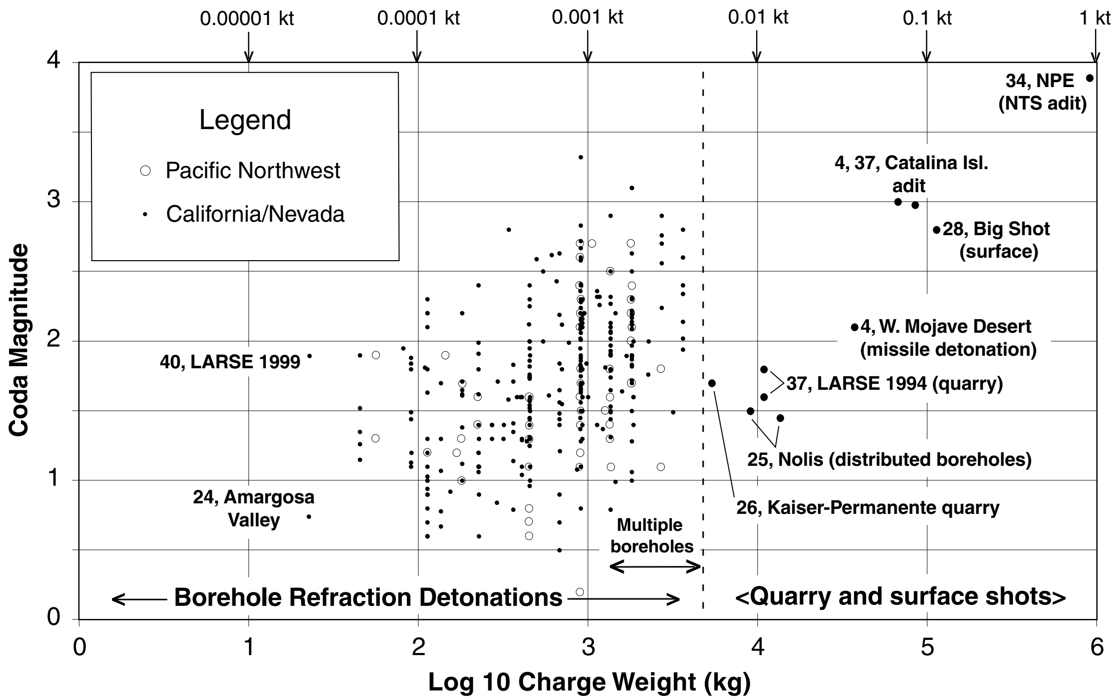

Figure 4. Comparison of reported magnitude for 322 detonations in California and Nevada versus those for 65 detonations in the Pacific Northwest (Washington and Oregon). Labels reference seismic refraction experiment numbers provided in Tables 1 and 2.

ear regression of the entire California and Nevada database reasonably well (equation 3) but fall well below the maximum magnitudes expected for detonations in hard rock (equation 1). In part, the lower magnitudes may reflect the fact that quarry detonations lose energy when breaking rock, in coupling sound waves to the atmosphere, and in using delayed firing patterns. Surface detonations are well known to be poorly coupled.

Seismic Refraction Detonations

Smaller borehole detonations used in the seismic refraction experiments are generally more efficient in generating radiated seismic waves than the larger surface and quarry blasts (Fig. 2; Khalturin *et al.*, 1998). In the following, I use the residual from equation (1), an empirical limit for detonations in hard rock, to estimate the efficiency of a detonation. For 10%, or 33, of the refraction borehole detonations, the computed magnitudes exceeded those given by equation (1), by an average of 0.32 magnitude units (Figs. 2 and 3A).

To investigate what made these shots more efficient than other borehole detonations, I compared shot-hole parameters for the 33 most efficient and the 33 least efficient detonations (the upper- and lowermost 10%). The average total charge size for the 33 most efficient explosions was 573 kg, and on average, they were detonated in 1.12 boreholes having a depth of 33.4 m (Table 3). Charge sizes in individual boreholes for these efficient detonations averaged 511 kg. If detonations larger than 4000 kg are excluded, the 33 least efficient detonations used an average of 1.30 boreholes and were 289 kg larger and 4.1 m deeper than their most efficient counterparts (Table 4). Charge sizes in individual boreholes for the least efficient shots were 662 kg, 151 kg more than their most efficient counterparts. The LARSE 1994 experiment in the Los Angeles region (experiment 37; Murphy *et al.*, 1996) produced the largest number of most and least efficient shots, 9 and 12, respectively (Tables 3 and 4).

Given these real but modest differences in shot-hole parameters between the most and least efficient detonations, other factors exert greater control on the detonation efficiency. Differences in explosive type are important: six of the most efficient detonations were associated with a Mono Craters–Long Valley study (experiment 14) that used ammonium nitrate explosive, whereas four of the least efficient shots were fired at Kaiser Permanente quarry (experiment 26) used Ammonium nitrate and fuel oil (ANFO) and Gas Well gelatin explosives (Figs. 1A and 3A; W. H. K. Lee, personal comm., 1989).

Explosive loading procedure is another primary factor determining detonation efficiency. About 75% of the most efficient shots were hand loaded, whereas 58% of the least efficient shots were loading by pump truck. The majority of the most efficient detonations produced by LARSE 1994 (experiment 37) were hand loaded (Table 3); in contrast, the majority of the least efficient detonations produced by the

Table 3
Shotpoint Information for the 33 Most Efficient Detonations

Expt.	Shotpoint No.	Yield Size (kg)	No. Holes	Hand or Pump?	Depth to Tamp (m)	Blowout?	Geyser?	Hole Depth (m)	Wet or Dry?	Geology
2	1	109	1	H				**18**		Dry lake bed
2	1	653	1	H				**31**		Dry lake bed
14	1	905	1	H				55	Wet?	Marsh
14	13	679	1	H				46	Wet?	Near spring, lake
14	12	611	1	H				55		
14	1	498	1	H				37		
14	16	905	1	H				55		Near stream
14	18	905	1	H				**37**		
15	8215	905	1	H				50		
15	8205	905	1	H				50	Dry	Hard Rock
19	8X	452	1	H				50	Wet	Alluvium
20	14	226	1	H				18		
20	3	1810	2	H				41	Wet	
30	103	905	1	P	9.1	N	Y	45	Wet	Water at 28′
30	109	452	1	P	15.2	Y	Y	30	Dry	
30	102	1357	1	P	3.0	N	Y	53	Wet	Water at 10′
30	101	1810	2	P	7.6	N	Y	35	Wet	Water at 15′
37	8240	113	1	H	7.9	N	N	26	Dry	Hard Rock
37	9150	2722	3	P	13.2	N	Y	43	Dry	Playa
37	8050	544	1	P		Y	Y	32	Wet	Hard Rock
37	9023	181	1	P	0.3	N	N	24	Dry	Alluvium
37	8290	113	1	H				23	Dry	Hard Rock
37	8300	113	1	H				23	Dry	Hard Rock
37	8181	113	1	H		N	N	18	Dry	Hard Rock
37	8120	113	1	H	1.5	—	N	19	Dry	Alluvium
37	9021	340	1	P	10.1	N	N	30	Dry	Alluvium
40	8720	23	1	H	0.0	N	N	16	Wet	Hard Rock
41	DBLT	45	1	H	0.9	N	Y	20	Dry	
41	COOK	81	1	H	0.0	N	N	26	Dry	
41	KEYS	90	1	H	3.0	N	N	24	Wet	Water at 67′
41	RCKY	90	1	H	0.3	N	N	21	Wet	Water at 49.5′
41	GLEN	90	1	H	0.3	N	Y	22	Dry	
41	LCCB	45	1	H	0.3	N	N	19	Dry	
Average		573	1.12		4.6			33		

same experiment were loaded by pump truck using the identical emulsion specification (Table 4). All six of the most efficient shots produced by the San Andreas Fault Observatory at Depth (SAFOD) (experiment 41) were hand loaded (Table 3). Slow loading by hand, especially in water-filled holes, minimizes bridging and partial detonation of the main charge.

Other, less well known factors may control shot-hole efficiency: these include the effectiveness of tamping in coupling the explosive energy into the ground and the completeness of the detonation (e.g., Kohler and Fuis, 1992). On average, the depth to the top of the tamp for the 33 most efficient detonations was 1.8 m shallower than for the 33 least efficient detonations (Tables 3 and 4), implying that more tamp was used for the most efficient detonations. Only 12% of the most efficient shots produced blowout (of either tamp or casing) (Table 3), whereas 38% of the least efficient shots produced blowouts (Table 4). Conversely, 44% of the most efficient shots produced geysering (Table 3), whereas only 30% of the least efficient shots produced geysering (Table 4). Observations of blowout thus appear to be a more reliable measure of shotpoint efficiency than observations of geysering.

All but two of the least efficient detonations for which the borehole geology is known were located in hard rock (Table 4). In contrast, nearly half of the most efficient detonations for which the borehole geology is known were located in dry alluvium or playa deposits (Table 3). This dependence on borehole geology is somewhat contrary to that noted by Fuis *et al.* (2001) in their compilation of LARSE 1994 (experiment 37) detonation data. They ranked in order of decreasing shotpoint efficiency: Mesozoic bedrock sites, wet alluvium sites, dry alluvium sites, and Tertiary sedimentary rock sites. They found that Mesozoic bedrock sites and wet alluvial sites produced nearly comparable upward ground velocities.

Coda duration magnitude is a measurement largely based on shear-wave arrivals, while single detonations primarily produce compressional waves. Detonations do produce shear-wave energy, however, and to some degree the

Table 4
Shotpoint Information for the 33 Least Efficient Detonations

Expt.	Shotpoint No.	Yield Size (kg)	No. Holes	Hand or Pump?	Depth to Tamp (m)	Blowout?	Geyser?	Hole Depth (m)	Wet or Dry?	Geology
3	3	452	1	H				37	Wet	
7	6	1222	1	H				**44**	Wet	
11	4	1127	1	H				**42**		
13	4	1357	2	H				64	Wet	
14	13	1448	2	H				45		Along creek
15	8203	905	1	H				50		Near stream
17	1	1855	2	H				36	Dry?	Rhyolite
17	26	927	1	H				36		
18	8	1810	2	H				41	Dry/Wet	
19	12	1810	2	H				70		Hard rock
26	4	860	4	P				10		Hard rock
26	6	290	1	P				10		Hard rock
26	5	407	1	P				42		Hard rock
26	7	683	1	P				20		Hard rock
29	5	1810	2	P				43		
29	5	1357	1	P				54		
29	9	136	1	H?				61		
32	2	1357	1	P	19			54	Wet	
33	601	1810	2	P	0	Y	N	46	Wet	Water at 100′
37	8400	680	1	P	0	N	N	41	Dry	Sandstone
37	9030	680	1	P	8	N	N	43	Dry	Alluvium
37	8500	907	1	P	12	N	N	46	Dry	Hard rock
37	8450	680	1	P	16	N	N	46	Dry	Hard rock
37	8131	227	1	P	9	—	N	26	Wet	Hard rock
37	8630	907	1	P		Y	Y	48	Dry	Playa
37	8100	454	1	P	0	Y	—	34	Dry	Hard rock
37	8141	113	1	H?				23	Dry	Hard rock
37	8250	113	1	H?	9	Y	Y	23	Wet	Hard rock
37	8110	113	1	H?	1	N	N	20	Wet	Hard rock
37	8180	454	1	P		N	N	33	Dry	Hard rock
37	8350	227	1	P		N	N	23	Wet	Hard rock
38	9	362	1	P	3	N	Y	27	Dry	
40	8590	909	1	P	0	Y	Y	42	Dry	Hard rock
Average		862	1.30		6.4			38		

variation in coda duration magnitude observed here may reflect variation in compressional to shear-wave conversion or in shear-wave generation.

Detonations in the Water Table

Detonations are widely believed to be more efficient if they are located within the water table. This belief seems consistent with the database as a whole, because for the entire database, the majority (114) of the boreholes were wet, whereas 77 were dry (Table 2). If this belief were to explain the most efficient shots, however, one might expect that a higher percentage of the most efficient shots to have been located within the water table than for the least efficient shots. The opposite, however, is observed. Drilling logs for the 33 most efficient detonations indicate that only 9 of 25 (36%) were detonated in wet holes (Table 3), whereas these logs for 22 boreholes of the least efficient detonations show that 45% were saturated (Table 4). Thus, detonation within the water table is neither a sufficient nor a required condition for an efficient detonation, a conclusion also reached by Fuis *et al.* (2001) on the basis of the LARSE 1994 (experiment 37) detonations.

Shotpoint Repeatability

Finally, I examined the variability in computed magnitude produced by 11 shotpoints in which explosions were repeated up to five times with charges of the same size. Thus, for these repeated detonations the recording station geometry and detonation geometry were identical. The average difference in computed magnitude between the first and subsequent detonations was 0.1. Thus, these sources are highly repeatable and demonstrate considerably less than the scatter shown in Figure 2. The scatter in magnitude shown in Figure 2 for charges having the same weight thus most likely reflects variations in charge coupling and completeness of detonation and not inaccuracies in the reported magnitudes.

Discussion and Summary

This study develops empirical relationships between magnitude and charge size in California and Nevada that apply chiefly to borehole explosions ranging in yield from 25 to 4000 kg (equations 5 and 6). Similar relationships are also derived for surface, adit, and quarry explosions ranging in yield from 5385 to 10^6 kg (equations 7 and 8). Magnitudes of adit explosions generally fall above equations (3) to (6), and magnitudes of surface explosions generally fall below these curves. The upper magnitude limit of the borehole explosions of this study (<4000 kg) falls near the empirical relationship of Khalturin *et al.* (1998) (equation 1) developed for generally much larger chemical shots and for the purpose of monitoring of the Comprehensive Nuclear-Test-Ban Treaty (e.g., National Academy of Sciences, 2002). The National Academy of Sciences (2002) report on masking nuclear tests through simultaneous mine detonations discussed yield versus magnitude relations between 0.1 and 0.01 kt (10^5 and 10^4 kg). Their approximate relationship in Table 2 falls in the range of the surface shots compiled here, but falls close to the upward projection of equation (6). Thus, the relationship developed here may be useful in extending the Khalturin *et al.* relationship to smaller charge sizes. Certainly, this study demonstrates that the Khalturin *et al.* relationship can be used to estimate the minimum charge size for magnitudes between 0.5 and 3.9.

This study may also have some value in forensic seismology, examples of which include Holzer *et al.* (1996) and Koper *et al.* (2001). Although terrorist and accidental explosions tend to be surface explosions, the relationship developed here can be of value in estimating the minimum charge size, as it provides an upper bound for the data from the limited surface explosions examined here (equation 1; Fig. 2). These limited data define a linear relation between charge size and magnitude for surface detonations between 5385 and 10^6 kg (equation 8).

A limited study of 10% of the most efficient detonations indicates that they typically represent small charges in relatively shallow boreholes (Table 3). These efficient detonations differ from less efficient detonations in the explosive specification used, the manner in which they were loaded, and in the efficiency of tamp in coupling the explosion to the ground (Tables 3 and 4). Surprisingly, a higher percentage of the most efficient shots were detonated in dry boreholes than less efficient shots (Tables 3 and 4). I infer that loading water-filled boreholes and washing of the charge out of the hole by flowing groundwater are larger problems than previously recognized. The former problem can be minimized by loading the borehole slowly, allowing the charge and the water to separate. The latter problem can be mitigated by detonating the hole as soon as possible after loading the hole.

The available data do not support any significant differential between the charge weight–magnitude dataset from California and Nevada and the dataset from the Pacific Northwest (Fig. 4; Brocher *et al.*, 2003). This lack of contrast most likely reflects the fact that the USGS detonation practices were identical in the two regions.

Data Availability

An electronic spreadsheet presenting information provided in the tables, as well as supplemental information for each detonation not reproduced here, is available from the author.

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