An Updated Scaling Relationship Between Energy and Crater Diameter for Surface and Subsurface Explosions

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Abstract

We provide an updated scaling relationship between explosion energy and the diameter of the resultant crater for single-burst explosions, as follows:

$$\log D = 0.29 \log E - 1.79,$$

where E and D are the explosion energy and crater diameter, respectively. This relationship was applied to two recent explosion incidents (Tianjin and Beirut) to estimate their explosion energy. The energy estimated for these events were consistent with those determined from seismological, infrasonic, and remote sensing observations. This demonstrates that our updated scaling relationship can be applied to evaluate the energy of both man-made explosions and those of volcanic origin.

Key words: Explosion experiment, Explosion energy, Crater diameter, Scaling relationship

1. Introduction

Explosion phenomena affect the geological environment by leaving a crater in the ground [1),2)]. The characteristics of the crater are controlled by the physical conditions of the explosion. There exists an approximately cube-root scaling relationship between explosion energy and the diameter of the resulting crater, provided for explosions in a single burst [1)-4)]. Sato and Taniguchi (1997) [3)] compiled observations of explosion energy and crater diameter from chemical and nuclear explosion experiments, and from volcanic events, and proposed that the cube-root scaling relationship is valid across a range of 15 orders of magnitude in explosion energy (10^3–10^{18} J). On the other hand, crater diameter depends not only on the explosion energy but also on the source depth of the explosion.[4)-9)]. The effects of explosion energy and source depth can be combined into a single parameter as the scaled depth (d_{sc}), such that $d_{sc} = d\ E^{-1/3}$, where E and d are the energy and source depth of the explosion, respectively. The scaled diameter ($D_{sc} = D\ E^{-1/3}$) of the crater reaches a maximum value at a scaled depth of $d_{sc} \sim 0.004$ m $J^{-1/3}$ [4),9)].

The energy of explosion phenomena can be inferred from the diameter of the resultant crater using these scaling relationships, even if the explosion occurred in the past. For example, previous studies have estimated the energy of volcanic explosions from the crater diameter [10)-12)]. However, there has not been much progress after the work of Goto *et al.* (2001). To better evaluate the energy of an explosion, it is necessary to update the scaling relationship between explosion energy and the diameter of the resultant crater. Here, we update the relationship by considering the results of recent explosion experiments, and the updated scaling relationship is applied to two recent explosion incidents. The results indicate that the updated scaling relationship gives reliable estimates of the energy of explosions in the past, based on the diameter of the resultant crater.

2. Updating the scaling relationship

The explosion experiments considered in this study are listed in **Table A1** [1)-4),6),8),9),13)-18)]. We focus on experiments with single-burst explosions because multiple bursts lead to more complex results that are unsuitable for constructing a simple scaling relationship [9),19)]. We also summarize the results of explosion experiments located at the surface and in the subsurface, for which our scaling relationship is

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confirmed.

The energy of an explosion is measured in Joules, based on the amount of TNT (trinitrotoluene) required to generate an equivalent explosion, and we consider explosions with energy of 300 J to 1.2 × 10^{15} J. The crater diameters cover five orders of magnitude, from 0.07 to 501 m. The depths are <193 m, and the scaled depths are from 0 to 0.021 m $J^{-1/3}$. The scaled diameters are therefore estimated to be 0.00038–0.02500 m $J^{-1/3}$. Most experiments were performed in soil or granular materials, except for that of Bjelovuk *et al.* (2015) [18] who conducted their explosion experiment on an asphalt surface.

We determine an updated scaling relationship based on the data listed in **Table A1**. The updated relationship confirms the near cube-root law between energy and crater diameter. The regression line of the scaling relationship (**Fig. 1**) is expressed as follows:

$$\log D = 0.29 \log E - 1.79, \tag{1}$$

where E and D are explosion energy and crater diameter, respectively. The relationship gives a standard error for crater diameter on a logarithmic scale of 0.25, which is estimated by standard error = $\{\Sigma(\log D\text{-}\log D')^2/(n\text{-}2)\}^{0.5}$, where D' and n are the crater diameter calculated from the regression line and the number of data points, respectively. The slope of the scaling relationship obtained in this study, 0.29, is smaller than a cube-root law [3),4)], and consistent with a 1/3.4 law [2)]. The fact would suggest that experimental data used in previous studies were not enough to represent the relationship. The result of Bjelovuk *et al.* (2015) [18)] gives a smaller crater diameter relative to the scaling, possibly because the asphalt surface used in their study is stronger than soil.

The scaled diameter has a maximum value around the scaled depth of 0.004 m $J^{-1/3}$, except for the results of Pacheco-Vazquez *et al.* (2017) [15)] (**Fig. 2**). The optimal scaled depth for excavating the crater is similar with the result of previous studies [4),9)]. In contrast, the results of Pacheco-Vazquez *et al.* (2017) [15)] show a larger scaled diameter. Their experiment employed downward explosions, which might explain the greater excavation depth and larger craters in their results. This indicates that the optimal scaled depth depends on the explosion mechanism.

3. Energy of two explosion incidents

We apply our updated scaling relationship to two recent explosion incidents, in Tianjin and Beirut, to evaluate the explosion energy. Our updated scaling relationship can be rewritten as follows:

$$\log E = 3.45 \log D + 6.17, \tag{2}$$

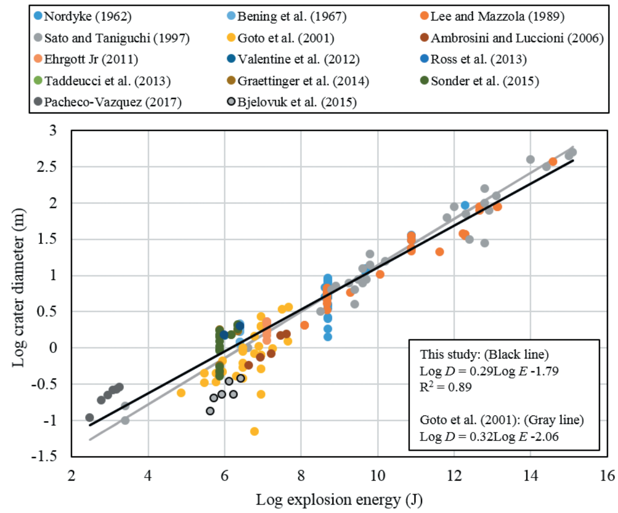

Fig. 1 Updated scaling relationship between explosion energy and crater diameter in single-burst explosion experiments. The data plotted are provided in **Table A1**.

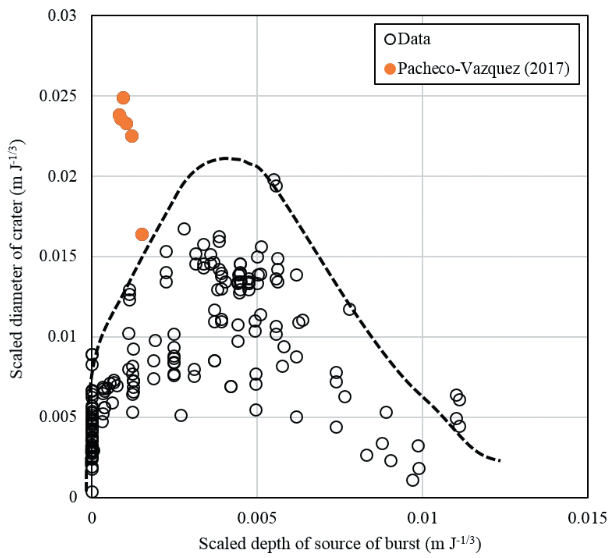

Fig. 2 Scaled depth as a function of scaled diameter in single-burst explosion experiments. The data of Sato and Taniguchi (1997) are not included in this figure because the burst depth was not specified. Dashed line indicates the possible upper limit.

In the following sections, we use this relationship to estimate the explosion energy.

A powerful explosion occurred in Tianjin port, China, on 12 August 2015, producing a mushroom cloud consisting of the dissipated wetting agents of nitrocellulose that was housed in containers [20)]. Two explosions were observed, at 23:34:06 (Tianjin-01) and 23:34:36 (Tianjin-02) local time [20)], producing craters with diameters of 15 m and 97 m, respectively [20)]. The larger crater is located ~70 m north of the smaller crater [21)]. Seismic analysis revealed the source of

Tianjin-02 was located 64 ± 10 m northwest of the source of Tianjin-01 [22], indicating that Tianjin-01 and -02 produced the smaller and larger craters, respectively. Seismic analysis quantified the explosive yields of the two explosions to be 15–49 tons of TNT equivalent for Tianjin-01 and 128–430 tons for Tianjin-02 [20),22], giving explosion energy of 6.3×10^{10} to 2.1×10^{11} J for Tianjin-01 and 5.4×10^{11} to 1.8×10^{12} J for Tianjin-02.

A massive explosion occurred in Beirut, Lebanon, at 18:08 local time on 4 August 2020. The explosion was caused by the combustion of ammonium nitrate stored in a harbor warehouse. The explosion created a crater with diameter of 124 m and depth of 43 m. Combined analysis by seismological, hydroacoustic, infrasonic, and radar remote sensing approaches yielded an estimated explosive yield of 130 to 2000 tons of TNT equivalent [23], indicating an explosion energy of 5.4×10^{11} to 8.4×10^{12} J.

Using the observed crater diameters for these three explosions, our updated scaling relationship gives explosion energy of 9.6×10^{9}, 2.9×10^{12}, and 6.3×10^{12} J for Tianjin-01, Tianjin-02, and Beirut, respectively (**Table 1**). **Fig. 3** compares the energy of these three explosions as estimated from the scaling relationship (2) and from geophysical methods, including seismic, infrasonic and remote sensing analyses. The consistent results show that our scaling relationship yields reliable estimates of explosion energy, although the source conditions of the explosions (e.g., the mechanism of explosion and the properties of the ground materials at the explosion site) must also affect the scaling [15),18]. Our updated scaling relationship can therefore be used to estimate the energy of past explosions, including both man-made explosions and those of volcanic origin, from the diameter of the resultant crater. We note that such evaluations should be limited to discrete volcanic explosions with a short duration of energy release, as the scaling relationship is determined using data from single-burst experiments.

Table 1 Energy of two explosion incidents, as derived from our updated scaling relationship (2).

Event	Diameter of crater (m)	Log E from the scaling (J)
Tianjin-01	15	10.2
Tianjin-02	97	13.0
Beirut	124	13.4

4. Conclusion

We have summarized the results of single-burst explosion experiments in terms of explosion energy, diameter of resultant crater, and source depth. The data were used to update the scaling relationship between explosion energy and the diameter of the resultant crater. Explosion energy of two incidents (Tianjin and Beirut) estimated by our updated relationship is consistent with that determined using geophysical methods. We conclude that our updated scaling relationship can be used to evaluate the energy of single-burst explosion phenomena that occurred in the past, including discrete volcanic explosions, if the diameter of the resultant crater is known.

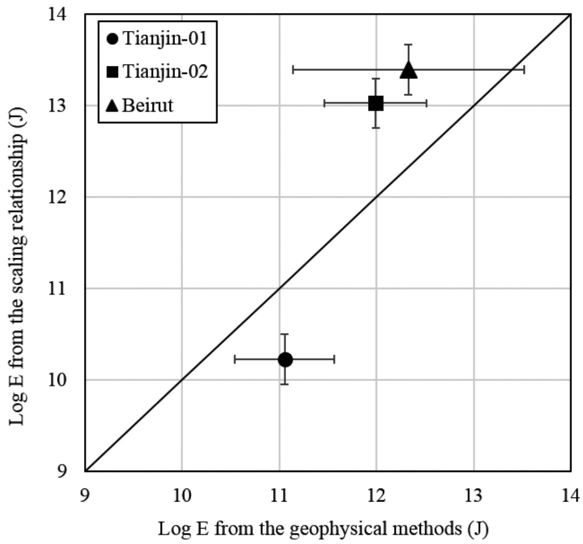

Fig. 3 Comparison between explosion energy derived from our scaling relationship and that from seismic, infrasonic, and remote sensing data. Vertical error bars are originated from the 20% of relative uncertainty of crater diameter, and horizontal error bars indicate the range of plausible explosion energies obtained from the geophysical methods. Thick black line is the 1:1 line (identity line).

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Table A1.1 Summary of explosion experiments.

Literature	Explosion name	Log explosion energy (J)	Log diameter (m)	Depth of burst (m)	Scaled diameter (m $J^{-1/3}$)	Scaled depth (m $J^{-1/3}$)	Charge*
Nordyke (1962)	Jungle high explosive HE-1	9.69	1.05	0.62	0.0067	0.0004	TNT
Nordyke (1962)	Jungle high explosive HE-7	9.69	1.06	0.79	0.0068	0.0005	TNT
Nordyke (1962)	Jungle high explosive HE-6	9.69	1.08	0.92	0.0071	0.0005	TNT
Nordyke (1962)	Jungle high explosive HE-5	9.69	1.07	1.25	0.0070	0.0007	TNT
Nordyke (1962)	Jungle high explosive HE-3	9.69	1.09	2.08	0.0073	0.0012	TNT
Nordyke (1962)	Jungle high explosive HE-2	10.88	1.38	1.56	0.0056	0.0004	TNT
Nordyke (1962)	Jungle high explosive HE-9	8.61	0.70	0.26	0.0068	0.0003	TNT
Nordyke (1962)	Jungle high explosive HE-10	8.61	0.84	0.91	0.0093	0.0012	TNT
Nordyke (1962)	Mole 206	8.69	0.59	0.00	0.0049	0.0000	TNT
Nordyke (1962)	Mole 205	8.69	0.73	0.25	0.0069	0.0003	TNT
Nordyke (1962)	Mole 204	8.69	0.76	0.50	0.0073	0.0006	TNT
Nordyke (1962)	Mole 203	8.69	0.71	0.97	0.0065	0.0012	TNT
Nordyke (1962)	Mole 202	8.69	0.84	1.94	0.0088	0.0025	TNT
Nordyke (1962)	Mole 212	8.69	0.83	1.94	0.0087	0.0025	TNT
Nordyke (1962)	ERDL 403	8.69	0.71	0.25	0.0065	0.0003	TNT
Nordyke (1962)	ERDL 405	8.69	0.75	0.50	0.0072	0.0006	TNT
Nordyke (1962)	ERDL 401	8.69	0.81	0.97	0.0082	0.0012	TNT
Nordyke (1962)	ERDL 406	8.69	0.78	0.97	0.0077	0.0012	TNT
Nordyke (1962)	ERDL 402	8.69	0.83	1.45	0.0086	0.0018	TNT
Nordyke (1962)	ERDL 404	8.69	0.87	1.94	0.0094	0.0025	TNT
Nordyke (1962)	Sandia, series Ⅰ 8	8.69	0.90	1.94	0.0102	0.0025	TNT
Nordyke (1962)	Sandia, series Ⅰ 2	8.69	0.96	2.90	0.0117	0.0037	TNT
Nordyke (1962)	Sandia, series Ⅰ 9	8.69	0.94	2.90	0.0110	0.0037	TNT
Nordyke (1962)	Sandia, series Ⅰ 10	8.69	0.91	3.87	0.0104	0.0049	TNT
Nordyke (1962)	Sandia, series Ⅰ 16	8.69	0.94	3.87	0.0110	0.0049	TNT
Nordyke (1962)	Sandia, series Ⅰ 4	8.69	0.84	4.85	0.0088	0.0062	TNT
Nordyke (1962)	Sandia, series Ⅰ 11	8.69	0.60	4.85	0.0051	0.0062	TNT
Nordyke (1962)	Sandia, series Ⅰ 12	8.69	0.76	5.81	0.0073	0.0074	TNT
Nordyke (1962)	Sandia, series Ⅰ 17	8.69	0.54	5.81	0.0044	0.0074	TNT
Nordyke (1962)	Sandia, series Ⅰ 15	8.69	0.41	7.74	0.0032	0.0098	TNT
Nordyke (1962)	Sandia, series Ⅱ S-12	8.69	0.72	0.00	0.0066	0.0000	TNT
Nordyke (1962)	Sandia, series Ⅱ S-13	8.69	0.71	0.00	0.0065	0.0000	TNT
Nordyke (1962)	Sandia, series Ⅱ 11	8.69	0.95	3.99	0.0114	0.0051	TNT
Nordyke (1962)	Sandia, series Ⅱ 10	8.69	0.93	4.91	0.0109	0.0062	TNT
Nordyke (1962)	Sandia, series Ⅱ 9	8.69	0.94	5.00	0.0111	0.0064	TNT
Nordyke (1962)	Sandia, series Ⅱ 8	8.69	0.79	5.79	0.0078	0.0074	TNT
Nordyke (1962)	Sandia, series Ⅱ 7	8.69	0.70	6.00	0.0063	0.0076	TNT
Nordyke (1962)	Sandia, series Ⅱ 6	8.69	0.43	6.89	0.0034	0.0088	TNT
Nordyke (1962)	Sandia, series Ⅱ 5	8.69	0.27	7.10	0.0023	0.0090	TNT
Nordyke (1962)	Sandia, series Ⅱ 4	8.69	0.16	7.77	0.0018	0.0099	TNT
Nordyke (1962)	Stage coach 2	10.88	1.49	5.21	0.0073	0.0012	TNT
Nordyke (1962)	Stage coach 3	10.88	1.55	10.42	0.0084	0.0025	TNT
Nordyke (1962)	Stage coach 1	10.88	1.54	24.38	0.0082	0.0058	TNT
Nordyke (1962)	Scooter	12.28	1.97	38.10	0.0076	0.0031	TNT
Bening et al. (1967)	b1	6.40	0.09	0.00	0.0090	0.0000	TNT
Bening et al. (1967)	b2	6.40	0.05	0.00	0.0083	0.0000	TNT
Bening et al. (1967)	b3	6.40	0.09	0.00	0.0090	0.0000	TNT
Bening et al. (1967)	b4	6.40	0.25	0.15	0.0130	0.0011	TNT
Bening et al. (1967)	b5	6.40	0.24	0.15	0.0127	0.0011	TNT
Bening et al. (1967)	b6	6.40	0.22	0.15	0.0123	0.0011	TNT
Bening et al. (1967)	b7	6.40	0.26	0.30	0.0134	0.0022	TNT
Bening et al. (1967)	b8	6.40	0.32	0.30	0.0154	0.0022	TNT
Bening et al. (1967)	b9	6.40	0.28	0.30	0.0140	0.0022	TNT
Bening et al. (1967)	b10	6.40	0.30	0.43	0.0146	0.0031	TNT
Bening et al. (1967)	b11	6.40	0.32	0.43	0.0152	0.0031	TNT
Bening et al. (1967)	b12	6.40	0.30	0.46	0.0146	0.0034	TNT
Bening et al. (1967)	b13	6.40	0.33	0.46	0.0158	0.0034	TNT
Bening et al. (1967)	b14	6.40	0.29	0.46	0.0143	0.0034	TNT
Bening et al. (1967)	b15	6.40	0.31	0.49	0.0151	0.0036	TNT
Bening et al. (1967)	b16	6.40	0.30	0.49	0.0146	0.0036	TNT
Bening et al. (1967)	b17	6.40	0.27	0.53	0.0138	0.0039	TNT
Bening et al. (1967)	b18	6.40	0.28	0.53	0.0140	0.0039	TNT
Bening et al. (1967)	b19	6.40	0.26	0.55	0.0134	0.0040	TNT
Bening et al. (1967)	b20	6.40	0.28	0.60	0.0139	0.0044	TNT
Bening et al. (1967)	b21	6.40	0.24	0.61	0.0128	0.0045	TNT

*TNT (trinitrotoluene); ANFO (94% ammonium Nitrate + 6% fuel oil); PETN (pentaerythritol tetranitrate)

Table A1.2 Summary of explosion experiments.

Literature	Explosion name	Log explosion energy (J)	Log diameter (m)	Depth of burst (m)	Scaled diameter (m $J^{-1/3}$)	Scaled depth (m $J^{-1/3}$)	Charge*
Bening et al. (1967)	b22	6.40	0.28	0.61	0.0139	0.0045	TNT
Bening et al. (1967)	b23	6.40	0.26	0.61	0.0134	0.0045	TNT
Bening et al. (1967)	b24	6.40	0.26	0.61	0.0134	0.0045	TNT
Bening et al. (1967)	b25	6.40	0.25	0.61	0.0130	0.0045	TNT
Bening et al. (1967)	b26	6.40	0.28	0.61	0.0140	0.0045	TNT
Bening et al. (1967)	b27	6.40	0.30	0.61	0.0146	0.0045	TNT
Bening et al. (1967)	b28	6.40	0.30	0.61	0.0146	0.0045	TNT
Bening et al. (1967)	b29	6.40	0.26	0.61	0.0134	0.0045	TNT
Bening et al. (1967)	b30	6.40	0.27	0.64	0.0137	0.0047	TNT
Bening et al. (1967)	b31	6.40	0.25	0.64	0.0130	0.0047	TNT
Bening et al. (1967)	b32	6.40	0.26	0.64	0.0134	0.0047	TNT
Bening et al. (1967)	b33	6.40	0.26	0.64	0.0133	0.0047	TNT
Bening et al. (1967)	b34	6.40	0.26	0.64	0.0133	0.0047	TNT
Bening et al. (1967)	b35	6.40	0.26	0.68	0.0133	0.0050	TNT
Bening et al. (1967)	b36	6.40	0.28	0.68	0.0139	0.0050	TNT
Bening et al. (1967)	b37	6.40	0.28	0.69	0.0139	0.0051	TNT
Bening et al. (1967)	b38	6.40	0.31	0.76	0.0149	0.0056	TNT
Bening et al. (1967)	b39	6.40	0.29	0.76	0.0142	0.0056	TNT
Bening et al. (1967)	b40	6.40	0.26	0.76	0.0134	0.0056	TNT
Bening et al. (1967)	b41	6.40	0.28	0.84	0.0139	0.0062	TNT
Lee and Mazzola (1989)	Air Vent II 3	8.69	0.61	0.26	0.0052	0.0003	TNT
Lee and Mazzola (1989)	Air Vent II 4	8.69	0.67	0.48	0.0059	0.0006	TNT
Lee and Mazzola (1989)	Air Vent II 5A	8.69	0.73	0.97	0.0069	0.0012	TNT
Lee and Mazzola (1989)	Air Vent II 5B	8.69	0.71	0.97	0.0066	0.0012	TNT
Lee and Mazzola (1989)	Air Vent II 6	8.69	0.77	1.45	0.0074	0.0018	TNT
Lee and Mazzola (1989)	Air Vent II 7A	8.69	0.78	1.94	0.0076	0.0025	TNT
Lee and Mazzola (1989)	Air Vent II 7B	8.69	0.78	1.94	0.0077	0.0025	TNT
Lee and Mazzola (1989)	Air Vent II 8	8.69	0.80	2.42	0.0080	0.0031	TNT
Lee and Mazzola (1989)	Air Vent II 9A	8.69	0.83	2.91	0.0085	0.0037	TNT
Lee and Mazzola (1989)	Air Vent II 9B	8.69	0.83	2.91	0.0085	0.0037	TNT
Lee and Mazzola (1989)	Jangle He 2	10.88	1.38	1.56	0.0056	0.0004	TNT
Lee and Mazzola (1989)	Stage Coach 2	10.88	1.49	5.21	0.0073	0.0012	TNT
Lee and Mazzola (1989)	Stage Coach 3	10.88	1.55	10.43	0.0084	0.0025	TNT
Lee and Mazzola (1989)	Jangle U	12.66	1.90	5.10	0.0048	0.0003	Nuclear
Lee and Mazzola (1989)	Johnie Boy	12.27	1.56	0.58	0.0030	0.0000	Nuclear
Lee and Mazzola (1989)	Sedan	14.58	2.57	193.60	0.0051	0.0027	Nuclear
Lee and Mazzola (1989)	Teapot S	12.66	1.95	20.40	0.0054	0.0012	Nuclear
Lee and Mazzola (1989)	Mill Race	12.23	1.58	0.00	0.0032	0.0000	ANFO
Lee and Mazzola (1989)	Minor Scale	13.13	1.95	0.00	0.0037	0.0000	ANFO
Lee and Mazzola (1989)	Misty Picture	13.12	1.95	0.00	0.0037	0.0000	ANFO
Lee and Mazzola (1989)	Mixed Company 3	12.28	1.55	0.00	0.0028	0.0000	TNT
Lee and Mazzola (1989)	Flat Top II	10.88	1.34	0.00	0.0051	0.0000	TNT
Lee and Mazzola (1989)	Flat Top III	10.88	1.37	0.00	0.0056	0.0000	TNT
Lee and Mazzola (1989)	Air Vent II 2A,B	8.69	0.52	0.00	0.0043	0.0000	TNT
Lee and Mazzola (1989)	Air Vent III 1A,B	8.08	0.32	0.00	0.0042	0.0000	TNT
Lee and Mazzola (1989)	Air Vent III 1C,D	8.08	0.31	0.00	0.0042	0.0000	TNT
Lee and Mazzola (1989)	Air Vent III 2A,B,C	9.28	0.76	0.00	0.0046	0.0000	TNT
Lee and Mazzola (1989)	Air Vent III 3A,B	10.06	1.02	0.00	0.0046	0.0000	TNT
Lee and Mazzola (1989)	Pre-mine Throw IV-6	11.58	1.33	0.00	0.0028	0.0000	Nitrometane
Sato and Taniguchi (1997)	Chemical 1	3.40	-1.00	Unknown	0.0074	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 2	3.40	-0.80	Unknown	0.0117	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 3	6.60	0.00	Unknown	0.0063	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 4	8.50	0.50	Unknown	0.0046	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 5	9.40	0.60	Unknown	0.0029	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 6	8.80	0.80	Unknown	0.0074	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 7	8.90	0.85	Unknown	0.0076	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 8	9.25	0.90	Unknown	0.0066	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 9	9.40	0.80	Unknown	0.0046	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 10	9.60	0.90	Unknown	0.0050	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 11	9.70	0.95	Unknown	0.0052	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 12	9.50	0.95	Unknown	0.0061	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 13	9.60	1.10	Unknown	0.0079	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 14	9.80	1.15	Unknown	0.0076	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 15	10.20	1.20	Unknown	0.0063	Unknown	Unknown
Sato and Taniguchi (1997)	Chemical 16	9.80	1.30	Unknown	0.0108	Unknown	Unknown

*TNT (trinitrotoluene); ANFO (94% ammonium Nitrate + 6% fuel oil); PETN (pentaerythritol tetranitrate)

Table A1.3 Summary of explosion experiments.

Literature	Explosion name	Log explosion energy (J)	Log diameter (m)	Depth of burst (m)	Scaled diameter (m $J^{-1/3}$)	Scaled depth (m $J^{-1/3}$)	Charge*
Sato and Taniguchi (1997)	Nuclear 1	12.80	1.45	Unknown	0.0015	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 2	12.40	1.50	Unknown	0.0023	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 3	12.30	1.85	Unknown	0.0056	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 4	11.80	1.80	Unknown	0.0074	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 5	12.00	1.95	Unknown	0.0089	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 6	12.90	1.90	Unknown	0.0040	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 7	12.80	2.00	Unknown	0.0054	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 8	12.80	2.20	Unknown	0.0086	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 9	13.10	2.10	Unknown	0.0054	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 10	14.40	2.50	Unknown	0.0050	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 11	14.00	2.60	Unknown	0.0086	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 12	15.00	2.65	Unknown	0.0045	Unknown	Nuclear
Sato and Taniguchi (1997)	Nuclear 13	15.10	2.70	Unknown	0.0046	Unknown	Nuclear
Goto et al. (2001)	1996-E1	4.87	-0.62	0.00	0.0057	0.0000	TNT
Goto et al. (2001)	1996-E2	5.48	-0.48	0.00	0.0049	0.0000	TNT
Goto et al. (2001)	1996-E3	5.77	-0.47	0.00	0.0041	0.0000	TNT
Goto et al. (2001)	1996-E4	6.47	-0.21	0.00	0.0043	0.0000	TNT
Goto et al. (2001)	1996-E5	6.77	-0.08	0.00	0.0046	0.0000	TNT
Goto et al. (2001)	1996-E6	6.47	-0.05	0.00	0.0063	0.0000	TNT
Goto et al. (2001)	1996-E7	5.48	-0.35	0.00	0.0067	0.0000	TNT
Goto et al. (2001)	1996-E8	5.77	-0.35	0.00	0.0054	0.0000	TNT
Goto et al. (2001)	1996-E9	6.47	-0.27	0.00	0.0038	0.0000	TNT
Goto et al. (2001)	1996-E10	6.90	0.03	0.00	0.0053	0.0000	TNT
Goto et al. (2001)	1998-E4	6.31	-0.39	0.00	0.0032	0.0000	TNT
Goto et al. (2001)	1998-E5	6.77	-1.15	0.00	0.0004	0.0000	TNT
Goto et al. (2001)	1998-E6	7.25	-0.01	0.00	0.0038	0.0000	TNT
Goto et al. (2001)	1998-E7	7.08	0.35	1.01	0.0097	0.0044	TNT
Goto et al. (2001)	1998-E8	6.77	0.16	0.20	0.0080	0.0011	TNT
Goto et al. (2001)	1998-E9	6.48	0.00	0.61	0.0069	0.0042	TNT
Goto et al. (2001)	1998-E10	7.65	0.10	0.00	0.0035	0.0000	TNT
Goto et al. (2001)	1998-E11	6.47	-0.42	1.19	0.0027	0.0083	TNT
Goto et al. (2001)	1999-E1	6.95	-0.64	2.01	0.0011	0.0097	TNT
Goto et al. (2001)	1999-E2	6.95	0.29	1.20	0.0094	0.0058	TNT
Goto et al. (2001)	1999-E3	6.95	0.43	0.81	0.0130	0.0039	TNT
Goto et al. (2001)	1999-E4	5.95	-0.33	0.00	0.0049	0.0000	TNT
Goto et al. (2001)	1999-E5	6.95	-0.10	0.81	0.0110	0.0039	TNT
Goto et al. (2001)	1999-E6	6.95	-0.28	0.00	0.0025	0.0000	TNT
Goto et al. (2001)	1999-E7	7.51	0.54	1.40	0.0108	0.0044	TNT
Goto et al. (2001)	1999-E8	5.95	-0.17	0.40	0.0070	0.0042	TNT
Goto et al. (2001)	1999-E9	6.95	-0.10	0.81	0.0111	0.0039	TNT
Goto et al. (2001)	1999-E11	7.67	0.57	0.40	0.0103	0.0011	TNT
Goto et al. (2001)	1999-E12	6.95	0.31	0.39	0.0098	0.0019	TNT
Ambrosini and Luccioni (2006)	No name	6.62	-0.24	0.00	0.0036	0.0000	TNT
Ambrosini and Luccioni (2006)	No name	6.92	-0.13	0.00	0.0036	0.0000	TNT
Ambrosini and Luccioni (2006)	No name	7.22	-0.08	0.00	0.0033	0.0000	TNT
Ambrosini and Luccioni (2006)	No name	7.47	0.17	0.00	0.0048	0.0000	TNT
Ambrosini and Luccioni (2006)	No name	7.62	0.19	0.00	0.0045	0.0000	TNT
Ehrgott Jr (2011)	BM-1-02	7.10	0.11	1.15	0.0055	0.0049	TNT
Ehrgott Jr (2011)	BM-1-03	7.10	0.18	4.00	0.0064	0.0172	TNT
Ehrgott Jr (2011)	BM-1-05	7.10	0.23	4.00	0.0073	0.0172	TNT
Ehrgott Jr (2011)	BM-C-02	7.10	0.25	1.15	0.0077	0.0049	TNT
Ehrgott Jr (2011)	BM-C-03	7.10	0.34	4.00	0.0093	0.0172	TNT
Ehrgott Jr (2011)	BM-C-05	7.10	0.36	4.00	0.0099	0.0172	TNT
Ehrgott Jr (2011)	BM-S-02	7.10	0.22	1.15	0.0071	0.0049	TNT
Ehrgott Jr (2011)	BM-S-03	7.10	0.33	4.00	0.0091	0.0172	TNT
Ehrgott Jr (2011)	BM-S-05	7.10	0.36	4.00	0.0099	0.0172	TNT
Valentine et al. (2012)	Pad2-1	6.00	0.18	0.50	0.0150	0.0050	TNT
Ross et al. (2013)	Pad1	6.40	0.30	0.50	0.0147	0.0037	TNT
Graettinger et al. (2014)	Pad1-1	6.35	0.23	0.50	0.0130	0.0038	TNT
Graettinger et al. (2014)	Pad2-1	6.18	0.18	0.50	0.0134	0.0044	TNT
Graettinger et al. (2014)	Pad3-1	5.88	0.26	0.50	0.0198	0.0055	TNT
Graettinger et al. (2014)	Pad4-1	5.88	-0.35	1.00	0.0050	0.0110	TNT
Graettinger et al. (2014)	Pad5-1	5.88	-0.24	1.00	0.0064	0.0110	TNT

*TNT (trinitrotoluene); ANFO (94% ammonium Nitrate + 6% fuel oil); PETN (pentaerythritol tetranitrate)

Table A1.4 Summary of explosion experiments.

Literature	Explosion name	Log explosion energy (J)	Log diameter (m)	Depth of burst (m)	Scaled diameter (m $J^{-1/3}$)	Scaled depth (m $J^{-1/3}$)	Charge*
Bjelovuk et al. (2015)	No name	5.62	-0.87	0.00	0.0018	0.0000	TNT
Bjelovuk et al. (2015)	No name	5.92	-0.64	0.00	0.0024	0.0000	TNT
Bjelovuk et al. (2015)	No name	6.22	-0.64	0.00	0.0019	0.0000	TNT
Bjelovuk et al. (2015)	No name	5.72	-0.69	0.00	0.0026	0.0000	PETN
Bjelovuk et al. (2015)	No name	6.11	-0.46	0.00	0.0032	0.0000	PETN
Bjelovuk et al. (2015)	No name	6.41	-0.42	0.00	0.0028	0.0000	PETN
Sonder et al. (2015)	1305-p1b1	6.34	0.27	0.50	0.0142	0.0038	TNT
Sonder et al. (2015)	1305-p2b1	6.17	0.18	0.50	0.0135	0.0044	TNT
Sonder et al. (2015)	1305-p3b1	5.86	0.09	0.50	0.0137	0.0056	TNT
Sonder et al. (2015)	1305-p4b1	5.86	-0.26	1.00	0.0061	0.0111	TNT
Sonder et al. (2015)	1305-p5b1	5.86	-0.39	1.00	0.0045	0.0111	TNT
Sonder et al. (2015)	1310-p1b1	6.34	0.32	0.50	0.0160	0.0038	TNT
Sonder et al. (2015)	1310-p2b1	5.86	-0.04	0.50	0.0102	0.0056	TNT
Sonder et al. (2015)	1311-p3b1	6.34	0.33	0.50	0.0163	0.0038	TNT
Sonder et al. (2015)	1311-p4b1	5.86	0.18	0.25	0.0168	0.0028	TNT
Sonder et al. (2015)	1406-p1	5.86	0.03	0.70	0.0118	0.0078	TNT
Sonder et al. (2015)	1406-p2	5.86	-0.02	0.50	0.0107	0.0056	TNT
Sonder et al. (2015)	1406-p3	5.86	-0.32	0.80	0.0053	0.0089	TNT
Sonder et al. (2015)	1406-p4b1	5.86	0.15	0.46	0.0156	0.0051	TNT
Sonder et al. (2015)	1406-p5b1	5.86	0.24	0.50	0.0194	0.0056	TNT
Pacheco-Vazquez et al. (2017)	E1	2.48	-0.96	0.01	0.0164	0.0015	Potassium nitrate
Pacheco-Vazquez et al. (2017)	E2	2.78	-0.72	0.01	0.0225	0.0012	Potassium nitrate
Pacheco-Vazquez et al. (2017)	E3	2.95	-0.65	0.01	0.0233	0.0010	Potassium nitrate
Pacheco-Vazquez et al. (2017)	E4	3.08	-0.58	0.01	0.0249	0.0009	Potassium nitrate
Pacheco-Vazquez et al. (2017)	E5	3.18	-0.57	0.01	0.0236	0.0009	Potassium nitrate
Pacheco-Vazquez et al. (2017)	E6	3.26	-0.54	0.01	0.0238	0.0008	Potassium nitrate

*TNT (trinitrotoluene); ANFO (94% ammonium Nitrate + 6% fuel oil); PETN (pentaerythritol tetranitrate)

表面・地下爆発におけるエネルギーとクレーター径のスケーリング関係の更新

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要　旨

本報告は単発的な表面・地下爆発実験における爆発エネルギーとクレーター直径のスケーリング関係を以下のように更新する．

$$\log D = 0.29 \log E - 1.79$$

ここで，E と D はそれぞれ爆発エネルギーとクレーターの直径である．このスケーリング関係を 2 例の爆発事故に適用し，その爆発エネルギーを推定した．得られた爆発エネルギーは，地球物理観測から推定されたエネルギーと調和的であった．このことは，本報告で更新したスケーリング関係が，人工爆発や火山爆発を含む爆発現象のエネルギー評価に適用できることを示唆している．

キーワード：爆発実験，爆発エネルギー，クレーター直径，スケーリング