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Beirut Explosion Yield and Mushroom Cloud Height – Effects of the Near Source Environment

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Beirut Explosion Yield and Mushroom Cloud Height – Effects of the Near Source Environment

By Peter Goldstein

Abstract

I use crater dimensions to estimate the yield of the August 4th, 2020 Beirut explosion to be equivalent to approximately 1.4 kilotons of TNT with a lower bound of about 0.7 kilotons. Based on the amount of ammonium nitrate reported to have been stored at the Beirut harbor, I assume an upper bound for the yield of 2.75 kilotons. However, it is highly likely that the yield was less than 2.75 kilotons, since reported values for TNT equivalence of ammonium nitrate are typically much less than one hundred percent. The crater-size based yield estimates are based on crater radius estimates from satellite imagery and empirical curves and data for scaled crater radius from past chemical and nuclear explosions. I present evidence that suggests that the relatively large crater radius is due to a high degree of coupling of shock wave energy to the surrounding medium and a reduction of the effective stress because of a high level of saturation of the geologic media beneath the explosion. I provide yield estimates based on seismic body-wave magnitude and crater depth as corroborating evidence.

I compare preliminary estimates for the maximum debris cloud height, based on cell phone videos/images, with predicted maximum heights for this yield range from empirical formulas and numerical cloud-rise models. Based on a preliminary analysis of cell phone footage, the observed maximum cloud height appears to be approximately 1600 m. This is much lower than that predicted using standard empirical formulas and buoyant cloud rise models.

I present results from a modified buoyant cloud rise model that more accurately predicts the maximum cloud height by allowing for the inclusion of a fixed amount of air and/or water into the fireball at the start of cloud rise. The amount of mass that needs to be added at the start, to reproduce the observed maximum cloud height, is relatively small compared to the total mass entrained during cloud rise. A much greater amount of dry air or debris is required, relative to water, for an equivalent reduction in maximum cloud height. The ammonium nitrate is one possible source for water in the fireball since it was being stored in a very humid environment and ammonium nitrate is known to be hygroscopic. The ground beneath the explosion, especially if it were saturated, and the nearby harbor could also have been sources for water or debris in the fireball.

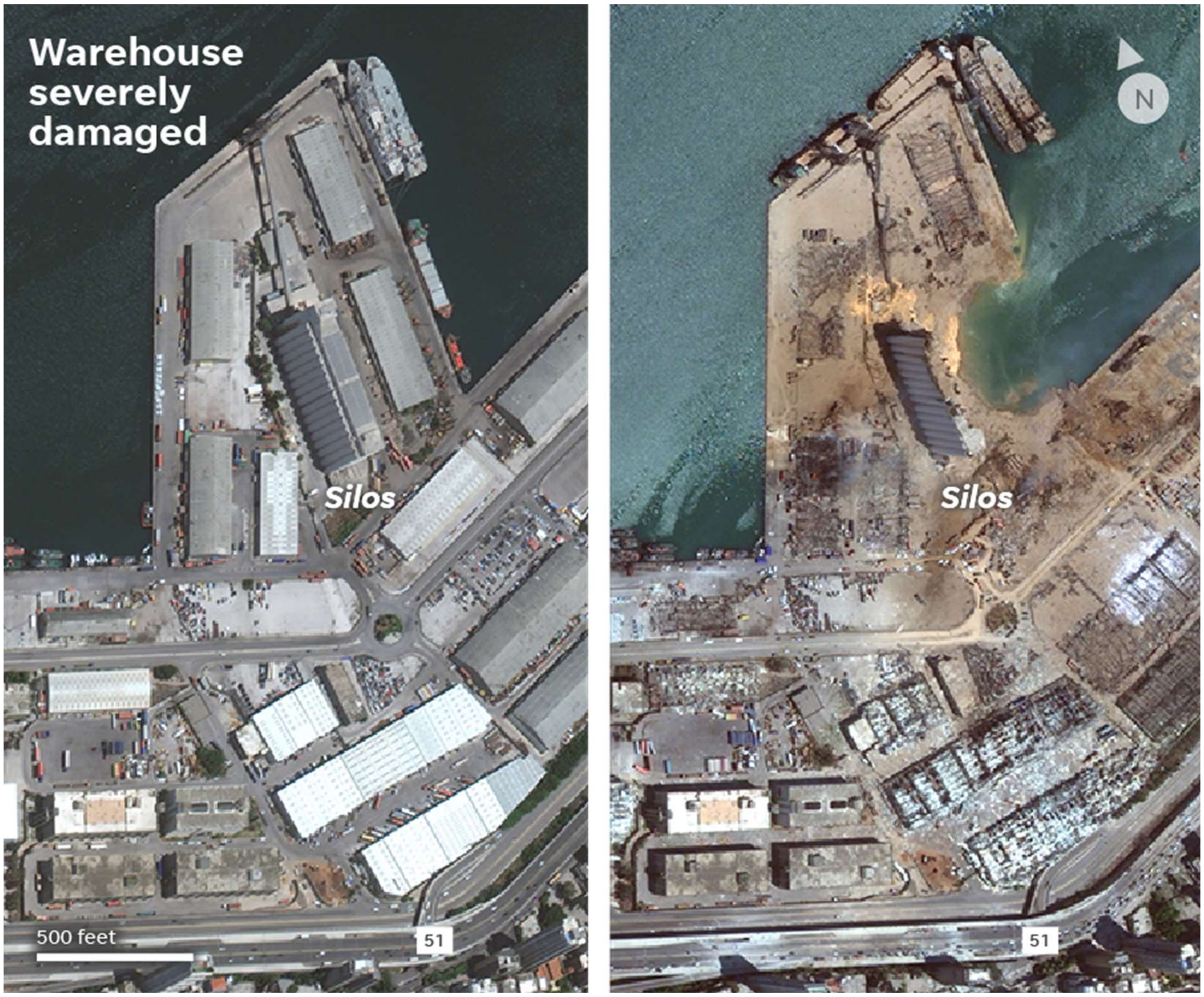

Figure 1. Before (left) and after (right) image of the crater caused by the August 4th, 2020 Beirut explosion (USA Today, August 6th, 2020).

Introduction

An accurate estimate for the yield of the Beirut explosion and its relationship to crater dimensions and cloud rise is important for understanding and mitigating blast damage and other risks from large explosions. Understanding the relationship between yield, crater radius and depth, and debris cloud height of large surface explosions is also important for the development of accurate models of the hazard from the transport of debris to surrounding areas. Confidence in the reliability of such models is critical for emergency response planning to mitigate potential consequences from improvised nuclear devices or radioactive dispersal devices.

Extensive work has been done on the relationship between crater dimensions and explosive yield and much of that work can be found in the impact and explosion cratering literature (e.g., Roddy et al., 1977). Prior work on the relationship of cloud rise to explosive yield is also extensive. Much of the early work related to nuclear explosion crater radii and cloud rise can be found in Glasstone and Dolan (1977). Recent work by Spriggs et al., (2019) is increasing our understanding of these phenomenology substantially.

Yield estimate based on prior scaled crater radius data

Estimates of the crater diameter of the Beirut explosion have been obtained from Satellite imagery and values are provided in multiple news media reports (e.g., Figure 1) with typical values ranging between 120 m and 140 m (radius between 60 and 70 m). Using this crater radius range and prior explosion scaled crater radius measurements as a function of depth in wet and dry media (Figures 2 and 3), I estimate a yield of 1.4 kilotons with a range between 0.7 and 2.75 kilotons of TNT (Table 1).

I use a yield value based on the scaled crater radius in wet media (1.4 kilotons) as my preferred yield because it seems likely that the media below the explosion was highly-saturated due to its proximity to the harbor. Furthermore, the yield range based on previous estimates of chemical explosion scaled crater-radius values in dry media are well above the likely maximum yield of 2.75 kilotons which is based on the reported amount of ammonium nitrate stored at the Beirut harbor, 2750 tons, and a TNT equivalence of 100% (Table 1).

Table 1. Yield estimate based on crater radius in wet and dry media				
	Observed Radius (m)	Chemical Explosion Scaled Radius ($m/kt^{1/3.4}$)	TNT Equivalent Yield(kt)	TNT equivalent Yield/2.75
Preferred yield - Y(kt)	**65**	**59.5**	**1.4**	**0.49**
Wet soil lower bound	60	68	0.7	0.24
Upper bound from amount of ammonium nitrate assuming 100% TNT equivalence			2.75	1.00
Wet soil upper bound	70	42.5	5.5	1.98
Best dry soil value	65	35	8.2	2.98
Dry soil lower bound	60	40	4.0	1.44
Dry soil upper bound	70	25	33.1	12.05
Dry to wet media crater radius scale factor			1.7	

Table 1. Beirut explosion crater-size and yield. The ratio of the yield to 2.75 kilotons of TNT is given in the far-right column.

In the following, I explain how I estimated the scaled crater radius for a large surface chemical explosion over wet soil. Unfortunately, there is limited if any data for such explosions. As an alternative, I used scaled crater-radius data for chemical explosions in dry media (Nordyke and Williamson, 1965, Figure 2), and estimates for the relationships between scaled crater-radii in wet and dry media based on observations of nuclear explosion in wet and dry media in Nordyke (1977) and Patteson (1960), Figure 3.

Figure 2 shows the apparent crater radius from several chemical and nuclear explosions in dry alluvium. These data suggest that a surface chemical explosion in dry alluvium would produce a scaled crater radius of roughly $35 m/kt^{1/3.4}$ and that the range would likely be between about $25\ m/kt^{1/3.4}$ and $40\ m/kt^{1/3.4}$.

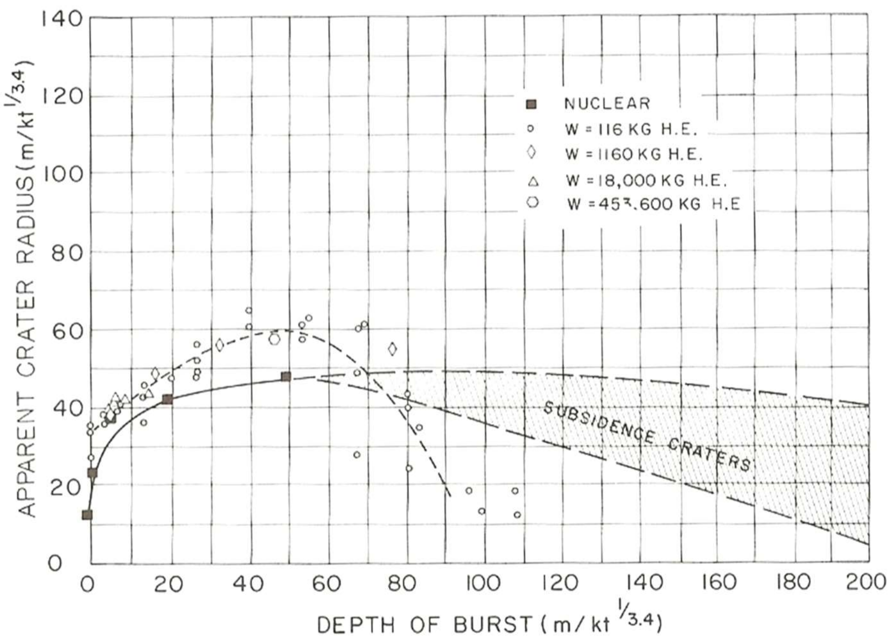

Figure 2. Scaled crater radius vs depth of burst in dry media. The scaled radius for a chemical surface burst (y-axis intercept of dashed curve) is approximately 35 m/kt$^{1/3.4}$ with scatter in the data suggesting an approximate range between 25 and 40 m/kt$^{1/3.4}$ (Nordyke and Williamson, 1965).

Figure 3 (Nordyke, 1977, Patteson, 1960) includes additional data on crater radius vs yield from explosions in or near highly saturated media. This data and many of the observations in Nordyke (1977) and Patteson (1960) suggest that an explosion in saturated media is likely to produce a much larger crater. Based on these data, Patteson suggest that, on average, the scaled crater radius of explosions in wet soil are approximately 1.5 times those in dry soil. The surface explosion scaled crater radius values on the right-hand-side in Figure 3 suggest a wet-to-dry, scaled crater radius ratio of about 1.7 with a lower bound of about 1.5. The data also suggest an upper bound of about 2.0, but that value is based on very large, megaton explosions where the crater boundary was much more difficult to determine and was often affected by phenomena that aren't present at the sub-100 kiloton range that we are interested in. I use a ratio of the surface values from the Patteson's (1960) curves, 1.7, to calculate the preferred yield, 1.4, and lower bound, 0.7, in Table 1. Switching to Patteson's average value of 1.5 would change my preferred yield and lower bound to 2.1 and 1.0 kilotons, respectively. Using an upper bound of 2.0 would change the preferred yield and lower bound to 0.8 and 0.4 kilotons, respectively. However, the larger scaling factor is based on megaton explosions and probably does not apply here.

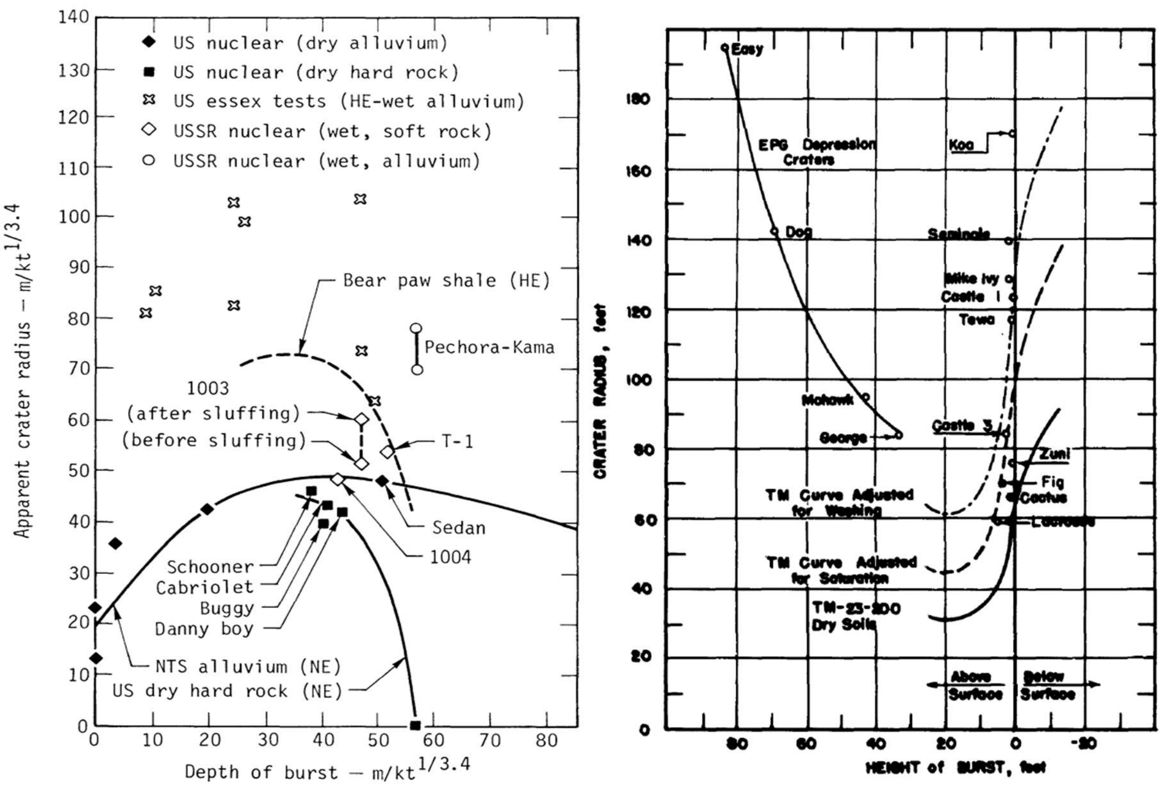

Figure 3. Scaled crater radius vs depth of burst in wet and dry media. At the surface, the wet media crater radii are roughly a factor of 1.7 times those for dry media (Nordyke, 1977, Patteson, 1960).

When estimating the yield, I also account for the uncertainties in the observed crater diameter shown in Figure 1. The primary uncertainty is caused by its elliptical shape. I use typically reported values (120 to 140 m) for the crater diameter range and use the midpoint of these values as the preferred estimate. Estimates for the yield and its range, based on these values and the above values for scaled crater radius, are provided in Table 1.

Yield estimate based on prior scaled crater depth data

There is limited and conflicting information on the depth of the Beirut explosion crater. Dadouch (2020) reports a crater depth of about 15 yds (14 m) and multiple sources report a depth of 43 m (Wikipedia, 2020). Dadouch's (2020) value is probably the more accurate one since the larger depth, 43 m, would imply a very large yield (approximately 47 kilotons) based on the prior crater-depth scaling data. The larger value probably should have been reported as feet rather than meters. If so, both values would be very similar.

Unfortunately, scaled crater-depth data from large chemical explosion is also limited and, as indicated by Nordyke (1977), highly variable. Data from nuclear explosions in Patteson (1960) appear to be more reliable (Figure 4). Excluding the very large nuclear tests, these data suggest scaled crater-depths ranging from 6.4 to 9.4 m/kt $^{1/3}$ with the larger value applying to explosions in wet soils. I use these values to estimate an equivalent nuclear yield and apply a scale factor based on observations by Glenn and Goldstein (1994) and Goldstein and Jarpe (1994) to convert them to equivalent chemical explosion yields (Table 2).

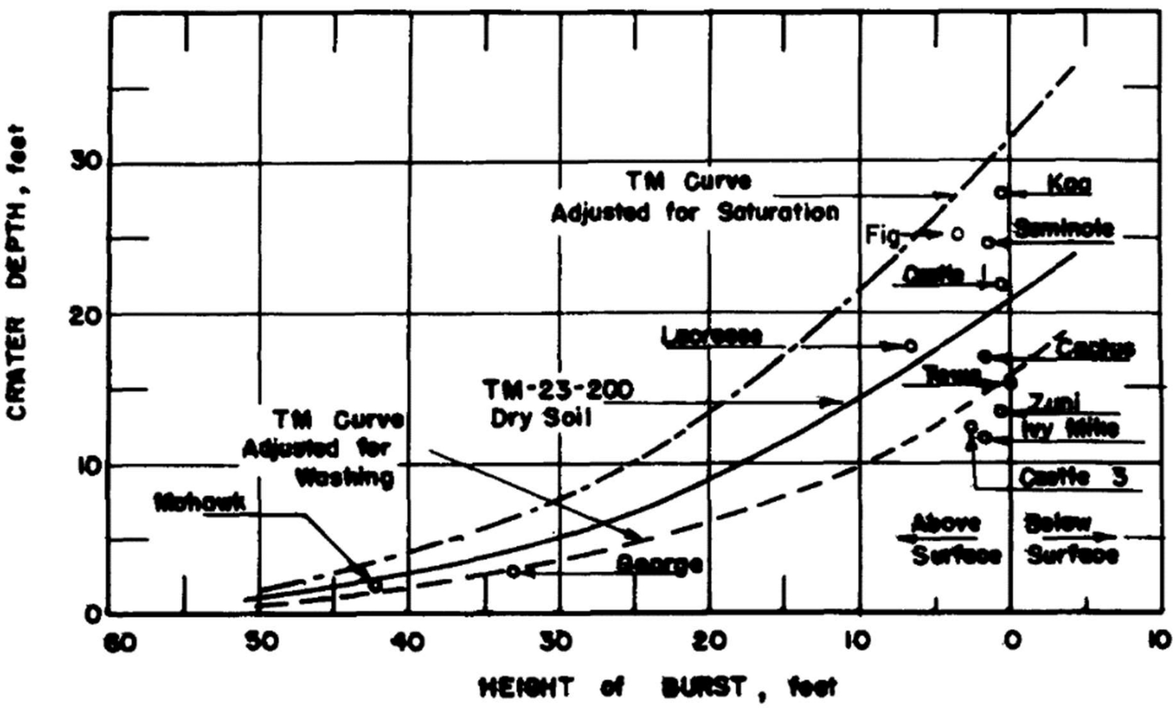

Figure 4. Scaled crater depth vs height of burst in wet and dry media (Patteson, 1960). The intercept of the dry and saturated media curves with the vertical axis at a height of burst of zero (surface burst) are given in meters in Table 2.

Table 2. Yield estimates based on crater depth.					
	Observed depth (m)	Nuclear Explosion Scaled Depth (m/kt$^{1/3.4}$)	Equivalent Nuclear Yield (kt)	TNT Equivalent Yield (kt)	TNT Equivalent Yield/2.75 kt
Wet soil	14.0	9.4	3.3	1.6	0.6
Dry Soil	14.0	6.4	10.5	5.2	1.9
Chemical/nuclear explosion yield scale factor (Glenn and Goldstein, 1994; Goldstein and Jarpe, 1994)			2.0		

Table 2. Beirut explosion crater-depth and yield. The adjustment to correct for differences in chemical and nuclear explosion scaled crater depths is explained in the text. The ratio of the chemical explosion yield to 2.75 kilotons of TNT is given in the far-right column.

Crater-size yield estimate summary

In the remainder of this paper I use the yield based on the crater radius as my preferred yield. I provide additional estimates of yield from crater depth measurements and seismic magnitude estimates for comparison but prefer the crater radius based estimate because I believe the Beirut explosions crater diameter measurements and scaled radius estimates are reliable and lead to yield estimates with less uncertainty than the other methods. My preferred estimate for the yield, 1.4 kiloton, is about 49% of what would be expected from 2.75 kilotons of TNT (Table 1). This value for TNT equivalence is consistent with the range of typical values cited for ammonium nitrate (e.g., Torok and Ozunu 2015).

There are many other factors that could have affected the yield estimate. For example, it is likely that the ammonium nitrate absorbed a significant amount of water while it was stored for seven years in the high humidity environment of Beirut harbor (66% - https://weather-and-climate.com/average-monthly-Humidity-perc,Beirut,Lebanon). It also seems likely that there were other energetic materials in the vicinity of the ammonium nitrate. In fact, many small fireworks-like explosions were seen in videos of the event (Gambrell and Federman, AP news, August 5, 2020, https://apnews.com/article/israel-ap-top-news-international-news-middle-east-lebanon-cbeb3263d6fc30a63a0300f588e7207b) prior to the main blast. In addition to saturation of the medium beneath the explosion, many other structural and geologic features could have affected the explosion. Nordyke (1977) describes examples where sharp transition from soft alluvial layers to a hard rock layers can have significant effects on crater dimensions. Such transitions can trap energy in the surface layers and direct it laterally enhancing crater formation. Additional information on the underlying geology and more sophisticated modeling is needed to evaluate this possibility.

The configuration of the explosives and the confinement of the explosion by its surroundings may have also played a role in crater formation. The consistency between the shape and orientation of the visible crater rim and the warehouse the explosive was stored in prior to detonation provides some evidence that the explosion configuration and surrounding man-made or geologic structures may have played some role. The lack of crater boundary on the harbor side of the crater is evidence of this. However, the lack of significant asymmetry in the harbor direction suggest its influence was probably small.

Constraints on the yield from seismic body wave magnitudes

Seismic magnitudes are another measure that is frequently used to estimate explosion yields and significant work has been done to develop magnitude-yield relationships for explosions (e.g., Mueller and Murphy, 1971). However, there is a high degree of uncertainty associated with chemical explosion magnitude-yield relationships due to a variety of factors including variations in near-source and near-receiver geologies, and the explosion emplacement conditions including the depth of the explosive, its spatial distribution, its firing sequence, and the level of media saturation (e.g., Khalturin et al., 1996).

Estimating yield for large chemical explosions is particularly challenging because they occur relatively infrequently and, as in the case of the Beirut explosion, their yields can be affected by a variety of factors including emplacement conditions and firing sequence. However, the method and its limitations are well documented and understood. Furthermore, there are readily available estimates for the magnitude of the Beirut explosion from reliable sources (e.g., the U.S. Geological Survey, USGS, mb=3.3, the German Research Centre for Geosciences, GFZ, mb=3.5, and the UC Berkeley Seismology Laboratory, mb=3.4). These magnitudes provide an additional observation to compare with my crater-size based estimates.

My seismic yield estimate is based on prior observations from nuclear explosions that caused cratering. I account for the well documented systematic difference in the magnitudes expected from chemical and nuclear explosions (e.g., Glenn and Goldstein, 1994 and Goldstein and Jarpe, 1994). Chemical explosions have been shown to generate seismic signals that are roughly a factor of two greater than those from a similar yield nuclear explosion. These differences are largely due to the significant amount of nuclear explosion energy that goes into radiation.

I use the median of three estimates from the USGS (mb=3.3), Germany's GFZ (mb=3.5), and the Berkeley seismological laboratory (mb=3.4) because these organizations routinely estimate magnitudes from a large number of events and their estimates are considered to be reliable by the seismic community.

In the following, I compare the median seismic body-wave magnitude estimate with values found for prior nuclear explosions that caused cratering (Rodean, 1970). My analysis of these measurements and their relationship to the yield is not intended to be precise since there are many factors that introduce significant uncertainties. My primary interest is to see if a seismic magnitude-based estimate is consistent with the crater-size based yield estimates.

A modified version of Rodean's data are shown in Figure 5. I focus my attention on the data for explosions in alluvium and have drawn a line through the data to approximate the overall trend. I have ignored the data points for Sedan, Fisher and Haymaker because these explosions were buried at significant depths compared to near surface detonations. I have placed a red circle at the estimated magnitude, 3.4, on the trend line and added a horizontal line corresponding to a magnitude of 3.4 and a vertical line through the Beirut explosion to facilitate reading the corresponding equivalent nuclear yield.

The equivalent nuclear yield is a little less than 4 kilotons. After correcting for the difference between chemical and nuclear explosions (Glenn and Goldstein, 1993, Goldstein and Jarpe, 1994) the body-wave magnitude suggests a chemical explosion yield of roughly 2 kilotons. Given that uncertainties in Seismic yield estimates are likely to be at least a factor of two (Khalturin et al., 1996), this result is consistent with those obtained using the crater-size measurements.

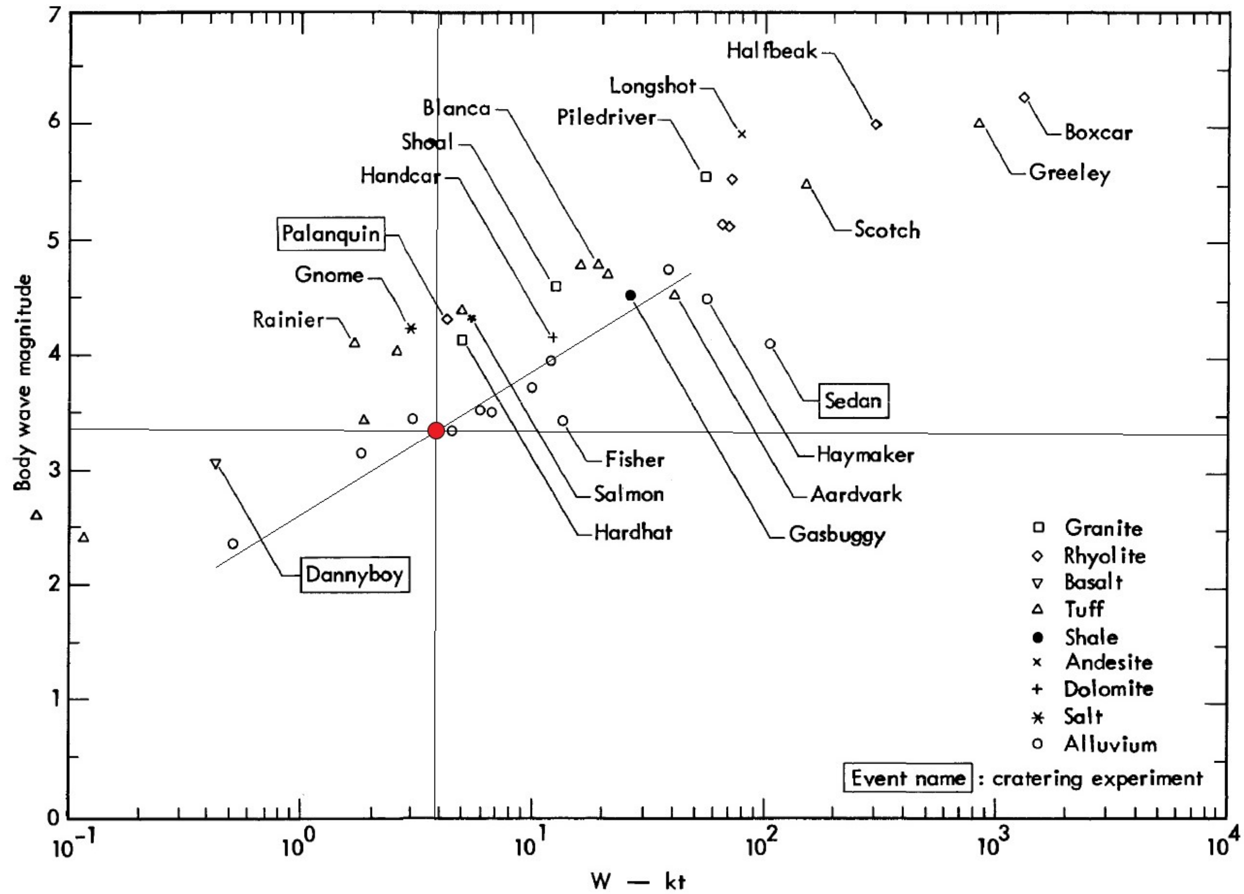

Figure 5. Seismic magnitude vs yield for nuclear explosions that caused cratering and the Beirut explosion. The Beirut explosion is shown as a red circle. The inferred nuclear yield would be approximately 4 kt. The equivalent chemical yield is about 2 kt.

Constraints on the potential amount of debris entrainment using crater size

This section uses crater size to provide a rough estimate of the upper bound for crater mass that could be entrained by the Beirut explosion debris cloud. In subsequent sections I focus on the effect that this entrainment could have on the debris cloud height.

I treat the crater as the lower half of an ellipsoid with a volume:

$$V = 4\pi * R_a * R_b * R_c / 6$$

Where R_a, R_b, and R_c are the radii of the ellipsoid along its three axes. Using the previously stated bounds on the crater radius (120 and 140 m) and a depth of 14 m (Dadouch, Washington Post, August 11th, 2020) the crater volume is roughly 5×10^5 m^3. If we assume an average density of 2500 kg/m^3, (Manger, 1963) the total crater mass is about 1.25×10^9 kg. This suggests that crater debris could account for a significant amount of any entrained mass.

In highly saturated media roughly half the volume of the medium can be water (water availability fact sheet, http://www.soilquality.org.au/factsheets/water-availability). Even if the porosity of the crater region is relatively low, say 10%, that would still correspond to roughly 5×10^4 m^3 or 5×10^7 kg, respectively. I will return to this point later when discussing the debris cloud height.

Comparison of empirical and numerical predictions with the observed debris cloud height

In this and the following sections I focus on empirical and numerical estimates of maximum debris cloud height and show that the entrainment of a fixed amount of mass at the beginning of the explosion can explain the relatively low maximum cloud height, approximately 1600 m, that was observed. I find that entrainment of a relatively modest amount of water, possibly from the ammonium nitrate, can explain the lower than expected cloud height. Alternatively, a larger amount of dry air/debris or a combination of wet and dry debris, possibly from the crater, can also explain the observed cloud height.

My estimate for the observed cloud height is based on images of the late-time debris cloud in post explosion video footage (e.g., Figure 6). The height of the cloud relative to the buildings, in the image on the left, suggest a cloud height that is only seven or eight times the height of the tallest building on the Beirut skyline (the tallest building is approximately 195 m according to Wikipedia, https://en.wikipedia.org/wiki/List_of_tallest_buildings_in_Lebanon), or less than about 1600 m. The image on the right is part of a longer lasting video where the height of the debris cloud has reached its maximum. The similarity of clouds in these images suggests the image on the left also corresponds to a time where the cloud is close to or at its maximum. Even if I increase this cloud height by 25% to account for uncertainties in my estimate, the maximum cloud height would be no more than 2000 m.

Figure 6. Late-time cell phone images of August 4th, 2020 Beirut explosion debris cloud. Note the maximum cloud height is about 7 or 8 times the maximum height of the buildings on the skyline in the images on the left. (Video News Today, August 4th, 2020, YouTube, August 11th, 2020).

Table 3 compares cloud rise predictions from three models. Church's (1969) empirical relationship between the maximum cloud height and yield of a chemical explosion (H=76W**0.25, W in pounds and H in m) suggest we should have seen a maximum cloud height of approximately 3184 m for our preferred yield of 1.4 kilotons; roughly twice the observed cloud height. Similarly, large values are found using a nuclear explosion based empirical model (Harvey et al., 2006) that predicts a maximum height of approximately 3801 m (Table 3). Even the lower bound yield leads to cloud heights well above what was observed. However, most of the data used to calibrate these models were from explosions in dry media and in arid conditions. Furthermore, the comparison with the nuclear explosion based empirical model may not be justified.

Simulations with integral cloud rise models such as DELFIC (Norment, 1977), PUFF (Boughton and DeLaurentis, 1987), and Bubble (Spriggs, 2019) also produced maximum cloud heights that were much greater than those observed. A potential advantage of the integral cloud rise models over the empirical models is that they can account for atmospheric conditions such as relative humidity. However, the high relatively humidity in Beirut exacerbates the difference between the observed and predicted maximum cloud height because the water vapor in the cloud condenses as it rises releasing latent heat which warms the cloud and causes it to rise higher.

Buoyant cloud rise models can also account for effects of the amount and energy released by the explosive mass and entrainment of ambient air during cloud rise. I hypothesize that the Beirut explosion fireball entrained water, air, and debris from the source and/or near source environment shortly after it detonated and that the water or debris cooled the fireball significantly causing the lower than expected maximum cloud height. I tested this hypothesis by modifying Boughton and DeLaurentis's (1987) buoyant cloud rise model (PUFF) for chemical explosions. I modified their algorithm to allow for the initial entrainment of a fixed amount of mass (dry air or water) and implemented the ability to specify the proportion of that mass that was water.

I use this capability to consider two cases, one where the initial injected mass is all dry air and the other where it is all water. For dry air I find that I needed to inject approximately 3.8×10^5 kg of mass to produce a cloud height of approximately 2000 m. I find that more than an order of magnitude less mass is required if I inject water into the fireball instead of dry air or debris (Table 3).

Table 3. Empirical and bouyant cloudrise model predictions of maximum debris cloud height.

Yield	Conditions	Church (1969) - max cloud height	Harvey et al (2006)	Modified Boughton and DeLaurentis (1987, this paper)
1.4	Preferred Yield	3184	3801	4960
1.4	Preferred Yield with 3.8×10^5 kg of near-source dry debris			2000
1.4	Preferred Yield with 8.4×10^3 kg of near-source wet debris			2000
0.7	Lower bound yield	2677	2894	3390
2.7	Upper bound Yield	3752	4920	5600

The ability to significantly reduce the maximum cloud height, to a level that is consistent with the observations, by entraining a relatively small amount of water is supportive of the hypothesis that the early entrainment of water caused the relatively low maximum cloud height. The ammonium nitrate explosive may provide the simplest explanation for entrained water since it is known to be hygroscopic and it sat in the high humidity environment of Beirut harbor for about seven years. Other factors that are consistent with this hypothesis include the explosions proximity to the harbor, a potential source for the water. Similarly, the ground beneath the explosion may have been a source of water if it had become saturated because of its proximity to the harbor.

Additional visual evidence that may be helpful in constraining the Beirut source

A unique aspect of the Beirut explosion was the rapid availability of satellite data and the large amount of cell phone videos and images. These data may provide useful constraints on the source and the near source environment. In prior sections, satellite and cell phone images have been used to constrain post-detonation crater size and maximum debris cloud height. They can also provide information about the source and near source environment prior to and during the early part of the explosion.

For example, there appears to be a well-defined debris cloud from ground shock (a base surge cloud) running ahead of the fireball in early images of the larger explosion (Figure 7). Directly above and behind this cloud appears to be the start of a condensation cloud and possibly some aerosolized debris. It seems plausible that some of this dust and debris might eventually be entrained by the debris cloud. If so, this could also be a source of material that could be entrained by the fireball.

Figure 7. Early-time image of the large part of the Beirut explosion. Note what appears to be a visible cloud of debris along the ground, some of which might eventually be entrained, that is presumably generated by the advancing shock front.

Future analysis of early images of the fireball (Figure 8) may provide additional constraints on the explosive source, such as, any effects of nearby structures such as the grain silos at the lower left in the figure or the harbor (not visible in these photos) or the effects of the asymmetric distribution of the explosive in the elongated rectangular warehouse it was stored in. The image on the left in Figure 8 suggests that the grain silos may have blocked some of the very early time effects from the explosion. Perhaps protecting some residents of Beirut. Some asymmetries in the explosion are discernible in the image on the right.

Figure 8. Early images of the Beirut explosion fireball. The very early time image on the left seems to suggest that the large grain silos may have blocked some of the effects from the explosion.

Figure 9 is from a cell phone video that shows what appears to be a large condensation cloud, also known as a Wilson cloud (Waltz, 1975), that formed shortly after the detonation of the larger explosion. Theoretical arguments by Waltz indicate a minimum relative humidity of approximately 70% is needed to form the Wilson cloud, corroborating the estimated near surface relative humidity used to model cloud rise.

Figure 9. A large condensation cloud forms shortly after the main blast in the Beirut explosion. (Video News Today, August 4th, 2020).

Conclusions

I have used estimates of crater radius from satellite imagery to estimate the yield of the August 4th, 2020 Beirut explosion to be approximately 1.4 kilotons with a lower bound of 0.7 kilotons. Estimates from measurements of crater depth and seismic magnitude are consistent with these estimates.

I have explained how the crater radius and debris cloud height of this explosion may have been affected by the environment at the source and/or in its vicinity. I presented visual evidence of a maximum cloud height (1600 m) that is much less than predicted by standard cloud rise models. I modified a buoyant cloud rise model to allow for the entrainment of water or dry air at the start of cloud rise and used this modified cloud rise model to show that the entrainment of a relatively modest amount of water at the start of the explosion can explain the observed difference in maximum cloud height. I suggest that entrained water could have come from the ammonium nitrate explosive, the soil beneath the explosion, or the nearby harbor. The hygroscopic nature of ammonium nitrate and the high humidity environment in Beirut harbor suggest that it is a likely source for water entrainment in the fireball. The early-time entrainment of a much larger amount of dry air or debris could also explain the difference between the predicted and observed cloud height.

An improved understanding of the Beirut explosion can help improve our understanding of the relationship between explosion yield, crater formation, entrainment, and cloud rise and should help us develop better models for the transport, deposition, and mitigation of debris from explosions.

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