3. N. M. Short, *J. Geol. Educ.* **14**, 149 (1966).
4. M. R. Dence, *Meteoritics* **2**, 249 (1964); *Ann. N.Y. Acad. Sci.* **123**, 941 (1965).
5. W. von Engelhardt and D. Stöffler, *Naturwissenschaften* **17**, 489 (1965).
6. N. L. Carter, *Amer. J. Sci.* **263**, 786 (1965).
7. D. Stöffler, *Contrib. Mineral. Petrol.* **12**, 15 (1966).
8. E. M. Shoemaker and E. C. T. Chao, *J. Geophys. Res.* **66**, 3371 (1961); F. Hörz, *Beitr. Mineral. Petrog.* **11**, 621 (1965).
9. Because of controversy about the origin, method of emplacement, and subsurface shape of the igneous body, the nongenetic term "irruptive" has come into general use.
10. G. Faure, H. W. Fairbairn, P. M. Hurley, W. H. Pinson, *J. Geol.* **72**, 848 (1964); H. W. Fairbairn, P. M. Hurley, W. H. Pinson, *Proc. Geol. Ass. Can.* **16**, 95 (1965).
11. H. W. Fairbairn and G. M. Robson, *Rep. Ontario Dep. Mines* **50**, pt. 6, 18 (1941).
12. E. C. Speers, *J. Geol.* **65**, 497 (1957).
13. A complete Sudbury bibliography cannot be cited here. Early detailed geological studies include: A. P. Coleman, *Rep. Ontario Bur. Mines* **12**, 235 (1903); *ibid.* **13**, pt. 1, 192 (1904); *ibid.* **14**, pt. 3, 1 (1905); and A. E. Barlow, *Annu. Rep. Geol. Surv. Can.* **14**, pt. H, 1 (1904). Recent bibliographies include J. E. Hawley, *The Sudbury Ores: Their Mineralogy and Origin* (Univ. of Toronto Press, Toronto, 1962); K. D. Card *et al.*, *Guidebook, 12th Annu. Inst. on Lake Superior Geol. Meeting*, Sault Sainte Marie, Michigan, May 1966.
14. R. S. Deitz, *J. Geol.* **72**, 412 (1964).
15. ——— and L. W. Butler, *Nature* **204**, 280 (1964); J. G. Bray and staff, *J. Geol.* **74**, 243 (1966).
16. H. Williams, *Rep. Ontario Dep. Mines* **65**, pt. 3, 57 (1956).
17. J. E. Thomson, *ibid.*, p. 1.
18. T. G. Bonney, *Quart. J. Geol. Soc. London* **44**, 32 (1888); G. H. Williams, *Bull. Geol. Soc. Amer.* **2**, 138 (1891); A. G. Burrows and H. C. Rickaby, *Rep. Ontario Dep. Mines* **38**, pt 3, 1 (1929).
19. J. S. Stevenson, in *Int. Geol. Congr., 21st, Copenhagen, 1960*, pt. 26, suppl. vol., sects. 1–21, p. 32; *Trans. Roy. Soc. Can.* **55**, 57 (1961).
20. ———, *Can. Mineralogist* **7**, 413 (1963).
21. In this basal unit, Stevenson observed quartzite blocks as much as 75 m long. Recently, a block of quartzite at least 27 by 15 m has been discovered in the upper part of the Onaping formation, approximately 1040 m stratigraphically above the lower contact (J. G. Bray, personal communication).
22. A series of road and railroad cuts in Dowling township, in the northwestern part of the Sudbury basin, expose unmetamorphosed Onaping formation generally regarded as typical. The specimens studied were collected from roadcuts on the Copper Cliff–Levack highway (Hwy. 144), about 9.2 km south of the town of Levack, immediately west of High Falls on the Onaping River.
23. N. L. Carter and M. Friedman, *Amer. J. Sci.* **263**, 747 (1965).
24. R. B. Baldwin, *The Face of the Moon* (Univ. of Chicago Press, Chicago, 1949); R. S. Dietz, *Trans. Amer. Geophys. Union* **43**, 455 (1962); P. D. Lowman, *Icarus* **2**, 35 (1963); L. B. Ronca, *ibid.* **5**, 515 (1966).

25. The assistance given me by many individuals does not necessarily reflect agreement with the conclusions reached in this report. The data, interpretations, and conclusions are my own, as are any errors contained in them. I am particularly grateful to J. G. Bray and to other individuals of The International Nickel Co. of Canada, Ltd., for providing geological information and for supplying many of the specimens. I also acknowledge helpful comments, suggestions, and criticisms from many individuals with a great diversity of views about Sudbury, including J. S. Stevenson, R. L. Smith, N. M. Short, M. R. Dence, E. C. T. Chao, W. von Engelhardt, P. R. Brett, and A. J. Naldrett.

26. A longer version of this report, including additional petrographic data and photomicrographs, is being prepared as NASA document X-641-67-67.

4 April 1967 ■

Excitation of Surface Waves by Events in Southern Algeria

Abstract. *Surface-wave magnitudes* (M_s) *of 4.1 and 3.2 are determined for two events in southern Algeria. The corresponding body-wave magnitudes* (m_b) *are 5.8 and 4.9, respectively. The surface waves from these events are much smaller than would be expected from most earthquakes of comparable body-wave magnitudes, which fact suggests that these waves were generated by underground explosions.*

This paper reports study of the excitation of body and surface waves by two events in southern Algeria. The epicentral data and magnitude determinations for these two events are given in Table 1. These events appear to be underground explosions, a conclusion based on newspaper reports and on the geographical coordinates, which place the events in an aseismic area. The same data are also given for Long Shot, a nuclear explosion detonated beneath Amchitka Island in the Aleutian Island chain on 29 October 1965 (*1, 2*).

The body-wave magnitude (m_b), which is based on the amplitude of short-period *P* waves recorded at teleseismic distances (*3*), is used as a measure of the short-period excitation. The surface-wave magnitude (M_s), which is based on the vertical amplitude of Rayleigh waves with periods of about 20 seconds (*4, 5*), is used as a measure of the excitation of the long-period waves. Båth (*5*) has emphasized the importance of measuring the amplitude of waves with periods within 2 to 3 seconds of 20 seconds even if this does not represent the maximum amplitude on the record; Richter (*6*) has found that determinations of M_s based on other periods tend to diverge from the standard scale. M_s and m_b measurements were obtained for these two events from the records of the World-Wide Standardized Seismograph Network (WWSSN) established by the United States Coast and Geodetic Survey (USCGS). No M_s values were obtained at stations where surface waves could not be seen above the noise levels. Thus, our M_s values represent an upper limit.

For the event of 27 February 1965, we have determined the body-wave magnitude to be $m_b = 5.8$ from the average of measurements at 50 individual stations, and the surface-wave magnitude to be $M_s = 4.1$ from measurements at 34 stations. From previous work on the relationship of M_s to m_b for earthquakes (*3, 7*), we would have expected $M_s \geqq 5.3$ from an earthquake of $m_b = 5.8$. The stations which recorded this event were distributed in all four quadrants of azimuth from epicenter to station and range in distance (Δ) from 15° to 101° from the epicenter.

For the event of 1 December 1965, we determined m_b to be 4.9 from the average of measurements at eight stations, and M_s to be 3.2 from measurements at seven stations. We would have expected $M_s \geqq 3.8$ from an earthquake of $m_b = 4.9$. The stations which recorded this event covered about 180° of azimuth and 17° to 77° in epicentral distance. As can be seen from the individual station magnitudes listed in Table 2, the m_b's for both of these events are not changed if the magnitudes for stations at $\Delta \leqq 20°$ are excluded.

The data from the two events in Algeria are represented by the large solid circles in Fig. 1, which is a plot of surface-wave (M_s) versus body-wave (m_b) magnitude. The smaller circle represents the same determination for Long Shot (*2*), the underground nu-

Table 1. Epicentral and magnitude data for events in Algeria and an underground nuclear explosion in the Aleutian Islands. Data for origin time, latitude, longitude, and m_b (USCGS) for events in Algeria reported by the United States Coast and Geodetic Survey. Data for origin time, latitude, longitude for Long Shot (29 October) are taken from the shot report (*1*). M_s and m_b were computed by the authors from copies of the original seismograms. Number of stations used in the determination of magnitudes is given in parentheses.

Date of event (1965)	Origin time	Latitude	Longitude	m_b (USCGS)	m_b	M_s
27 February	11:29:59.0	24.2 N	5.1 E	5.8	5.8 (50)	4.1 (34)
1 December	10:29:58.0	24.0 N	5.1 E	5.0 (8)	4.9 (8)	3.2 (7)
29 October	21:00:00.1	51.4 N	179.2 E	6.1 (32)	6.1 (56)	3.9 (56)

clear explosion in the Aleutians, and is presented here to provide a comparison between the Algerian events and a large underground nuclear explosion in a different geographic and tectonic environment.

For reference, we have plotted several empirical curves (Fig. 1, *A, B, C, D*) showing the relationship of M_s to m_b.

Table 2. Individual station determinations of body wave (m_b) and surface wave (M_s) magnitudes. Station code is that of USCGS. Distance ($\Delta°$) and azimuth from 27 February 1965 epicenter; values for 1 December 1965 epicenter are only slightly different.

Station	$\Delta°$	Azimuth	27 Feb.		1 Dec.	
			m_b	M_s	m_b	M_s
AAE	35.5	109.4		4.0	4.8	3.2
AKU	44.1	346.4	6.2	4.3		
ALQ	92.5	310.1	5.7			
ANT	87.3	242.7	6.8			
AQU	19.4	18.8	5.5	3.4		
ARE	84.9	249.6	5.9			
ATL	76.6	300.7	6.6			
ATU	21.0	44.8	5.7	3.7	5.2	3.1
BHP	81.6	276.0	6.2			
BLA	72.4	303.4	6.0			
BOZ	89.5	321.0	5.9			
BUL	49.7	150.5	5.5			
CAR	69.5	272.5	5.8			
CHG	85.9	71.4	5.1	4.0		
COL	88.7	348.8	5.1			
COP	31.9	7.9		3.9		
DUG	93.8	317.3	5.5			
ESK	31.7	351.0	6.1	4.0		
FLO	79.3	307.7	6.1	4.7		
GDA	56.6	338.6	6.3			
GEO	69.4	304.3	6.0	4.3		
GOL	89.3	313.7	5.3	4.2		
IST	26.1	44.1		3.9	5.2	3.3
JER	27.6	67.4	5.9	3.9		
KEV	47.4	10.2		4.0		
KOD	69.9	87.6	5.6			
KON	35.6	4.0	5.8			
LAH	60.7	66.2		4.4		
LPA	83.8	227.5		4.1		
LPB	82.1	248.0	5.6			
SDB	39.6	167.2	5.3	4.2		
MAL	14.9	329.0	6.1		4.6	
MDS	77.1	311.8	5.7	4.5		
MNN	78.9	314.2	6.0			
NAI	39.8	124.9		4.3	4.5	3.3
NDI	63.8	68.7	5.8	4.6		
NOR	58.1	356.3	5.3			
NUR	38.7	15.3	5.4			
OGD	67.0	306.1	5.7	4.0		
PDA	29.5	304.5	6.1			
GSC	99.2	315.3	5.4			
POO	63.7	80.5	5.7	3.9		
PRE	54.4	154.2	5.6			
PTO	20.4	329.1	5.3	4.1		
QUE	54.8	69.2	4.8	4.6		
QUI	84.2	267.2		4.4		
RCD	85.6	316.7	6.4	4.2		
KTG	48.9	348.2	5.5	3.8		
SCP	69.5	306.4	6.1			
SHA	80.6	299.3	6.4	3.7		
SHI	42.4	71.9		4.6		
SHL	77.2	67.6	5.5	4.6	4.6	3.2
SIG	101.1	56.4	6.2	4.3		
STU	24.7	6.5	6.0	3.7	5.1	3.3
TOL	17.4	335.9	5.5	3.6	4.8	3.0
TRI	22.5	16.0	5.6			
TRN	64.4	270.5	5.9			
VAL	30.1	340.9	5.6	3.9		
WIN	47.9	165.0	5.2	4.3		

Curve *C* ($M_s = 1.59\ m_b - 3.97$) was determined by Gutenberg and Richter (*3*) using a large body of data from earthquakes with body-wave magnitudes greater than 6; the applicability of this curve in the magnitude range $5 \leq m_b \leq 6$ has been verified (*2*) with body-wave magnitudes (m_b) determined by the USCGS. Curves *A* ($M_s = m_b + 0.44$) and *B* ($M_s = 1.79\ m_b - 4.50$) were formulated by Romney (*7*) with data from earthquakes having magnitudes between 4.5 and 7.0 as recorded on networks of seismographs with uniform instrumental constants (*A*, long-range seismic measurements network; *B*, WWSSN). Curve *D* ($M_s = m_b - 1.8$) is a composite of the magnitude-yield relationships established by Thirlaway and Carpenter (*8*) for underground explosions in granite ($M_s = 2.2 + \log Y$, $m_b = 4.0 + \log Y$, where Y = yield of the explosion in kilotons).

The data for the Algerian events and Long Shot agree well with the predicted curve (*D*) in Fig. 1. All three of these data points fall below the empirical curves for earthquakes, implying that for the magnitude range $5 \leq m_b \leq 6$ these events generate much smaller surface waves than earthquakes of comparable body-wave magnitudes. Even at magnitude $m_b = 4.9$, the discrimination between the surface-wave magnitude of the 1 December 1965 event and the corresponding M_s point on the Gutenberg-Richter curve is 0.6 M_s units. Similar results have been found by Marshall *et al.* (*9*) using data from earthquakes and underground explosions. These results substantiate the assumption that the recorded surface waves were generated by underground explosions.

The method suggested by Brune *et al.* (*10*) would provide sharper discrimination at $m_b = 5$, but for these events the discrimination was sufficiently distinct without use of their method.

The excitation of surface waves by these events may be partially explained by the spatial and temporal dimensions of the source region. Theoretical calculations by Keylis-Borok (*11*) show that the most efficient excitation of surface waves occurs at wavelengths approximately four times the dimension of the source, that is, the source region acts as a quarter-wavelength antenna. In general, the source dimensions for an underground explosion are much smaller than those of an earthquake of comparable energy. Therefore, we would expect explosions to excite the shorter periods of surface waves more efficiently. In addition, his treatment assumes that the source spectrum (that is, the Fourier transform of the time function of the source) is the same for earthquakes and explosions. However, for many earthquakes the time function may be approximated by a step in displacement, while for explosions the time function is a step with an impulse superimposed (*12*). This difference in the source time functions should cause the surface waves from explosions to be richer in short-period energy than those from earthquakes, thus enhancing the distinction between surface waves from the two types of sources. As an example of this difference in spectral

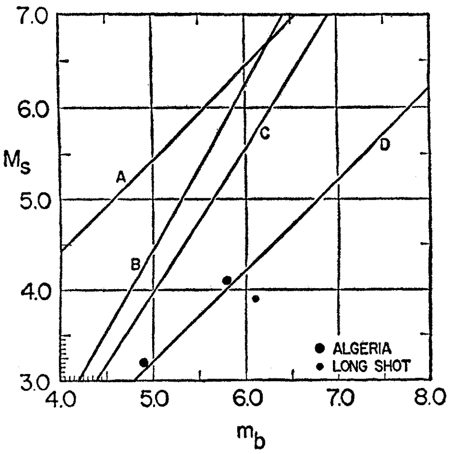

Fig. 1. The surface-wave magnitude (M_s) versus the body-wave magnitude (m_b) for events in Algeria and in the Aleutian Islands. Curves *A*, *B*, and *C* are empirical formulas relating M_s to m_b for earthquakes. Curve *D* is a predicted curve for underground explosions.

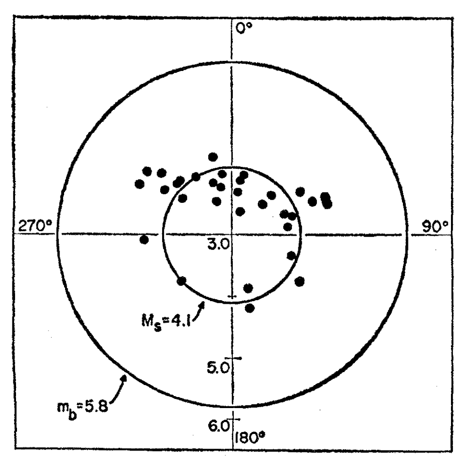

Fig. 2. Surface-wave magnitudes (M_s) for the event of 27 February 1965 measured at different seismograph stations (solid circles) plotted as a function of azimuth from the epicenter to the station. The heavy circles at 4.1 and 5.8 represent the average surface-wave and body-wave magnitudes, respectively, for this event.

content of the surface waves, distinct, inversely dispersed Rayleigh waves with periods of about 8 to 15 seconds were recorded at Addis Ababa, Ethiopia ($\Delta = 35.5°$), from both events in Algeria. In contrast, Gumper at Lamont has found that earthquakes in Algeria recorded at Addis Ababa generate Rayleigh waves belonging to the normally dispersed portion of the continental group-velocity curve in the period range 15 to 36 seconds.

In Fig. 2, we have plotted the individual station determinations of M_s for the 27 February 1965 event in Algeria as a function of azimuth. The M_s values are relatively high in the east-northeast and northwest directions. This effect is evident in the seismograms from Shiraz (Iran), Quetta (Pakistan), New Delhi (India), and Shillong (India) where Rayleigh waves of relatively larger amplitudes were recorded. All of the variations in M_s values may be an effect of the propagation path or of structural asymmetry in the geologic setting of the source region.

Well-developed Love waves from the event of 27 February 1965 were recorded at seven of the 34 stations which recorded distinguishable Rayleigh waves. These seven stations cover the range of 16° to 125° in azimuth. The presence of these Love waves is a further indication that some asymmetrical forces were acting at the origin (*13*).

The events in southern Algeria generated much smaller surface waves than would be expected from earthquakes of comparable body-wave magnitudes. The results illustrate a significant difference in the M_s versus m_b relationships between earthquakes and large underground explosions. Although this difference has been investigated previously (*14*), it assumes a new importance as the result of the study of these three recent explosive events.

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References and Notes

1. D. M. Clark, *Seismic Data Lab. Rept. 133* (United Electrodynamics Earth Sciences Division, 1966).
2. R. C. Liebermann, C. Y. King, J. N. Brune, P. W. Pomeroy, *J. Geophys. Res.* **71**, 4333 (1966).
3. B. Gutenberg and C. F. Richter, *Ann. Geofis. Rome* **9**, 1 (1956).
4. B. Gutenberg, *Seis. Soc. Amer. Bull.* **35**, 3 (1945).
5. M. Båth, *Amer. Geophys. Union Trans.* **33**, 81 (1952).
6. C. F. Richter, in *Rept. 4410-71-X* (VELA Seismic Information Center, 1964), p. 1.
7. C. Romney, *ibid.*, p. 83.
8. H. I. S. Thirlaway and E. W. Carpenter, *Rept. 4410-99-X* (VELA Seismic Information Center, 1966), p. 119.
9. P. D. Marshall, E. W. Carpenter, A. Douglas, J. B. Young, *Rept. 0-67/66* (Atomic Weapons Res. Estab., U.K. Atomic Energy Authority, 1966).
10. J. N. Brune, A. Espinosa, J. Oliver, *J. Geophys. Res.* **68**, 3501 (1963).
11. V. I. Keylis-Borok, *Tr. Inst. Fiz. Zemli Akad. Nauk SSSR* **15**(182), 71 (1961).
12. G. C. Werth and R. F. Herbst, *J. Geophys. Res.* **68**, 1463 (1963).
13. J. N. Brune and P. W. Pomeroy, *ibid.*, p. 5005.
14. F. Press, G. Dewart, R. Gilman, *ibid.*, p. 2909.
15. Supported by the Advanced Research Projects Agency and monitored by the Air Force Office of Scientific Research under Contract AF49-(638)-1723. R.C.L. was partially supported by a grant from the American Chemical Society (PRF 756-A2). Lamont Geological Observatory contribution 1051.

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Isotropy of Cosmic Background Radiation at 4080 Megahertz

Abstract. *We have examined an 18-hour-long record made as part of our program of measurements of the fluxes of a number of discrete radio sources. Since our radiometer employed an absolute reference, it was possible to obtain absolute background data from the reference region observed around each of the 29 sources investigated that day. From the study of a plot mode from this data, we conclude that there is no large-scale deviation from isotropy of more than 0.1°K at 4080 megahertz.*

In the original report of our measurement of the background temperature at 4080 Mhz (*1*) we stated that it was "within the limits of our observations, isotropic, unpolarized, and free of seasonal variation." While the total limit of error in our absolute value was 1.0°K, only the incremental calibration of the reference termination and, to a lesser extent, our determination of atmospheric absorption contributed to the error in our isotropy measurement. The estimated error in our isotropy measurement was therefore approximately 10 percent. Our coverage at that time included points on the zenith where the background temperature was measured and the paths of decreasing elevation (generally to the south) along which we measured the atmospheric radiation. In addition, some data along lines of constant declination, never more than a few hours in length, were taken (i) with the antenna pointed at our zenith (declination $\approx$ 40°), (ii) in the region near Cas A, and (iii) across the galactic plane at five declinations (*2*). The latter two were largely base lines for drift-curve observations. In all these cases, our clear-weather observations were consistent with the conclusion that any variations observed were caused by radiometer noise fluctuations and the warming of the reference termination.

We have received a communication from D. W. Sciama which suggests (*3*) that the universe may be anisotropic on a scale of $Z \approx 1$, with associated anisotropy in the microwave background. We have therefore reexamined our 4080 Mcs records in order to place, if possible, a limit on the anisotropy of the background radiation lower than the one described above, and with more systematic sky coverage. We are reporting here the results of the analysis of a record that provides a sensitive test for anisotropy and yet covers a large portion of the available sky. In particular, it covers the region near the north galactic pole, which has been reported by Strittmatter *et al.* (*4*) to contain a large number of highly redshifted quasars.

The observations were made, during an 18-hour period on 4 and 5 March 1965, as part of a program of measurements of the fluxes of a number of discrete radio sources. Since the radiometer employed an absolute reference, it was possible to obtain absolute

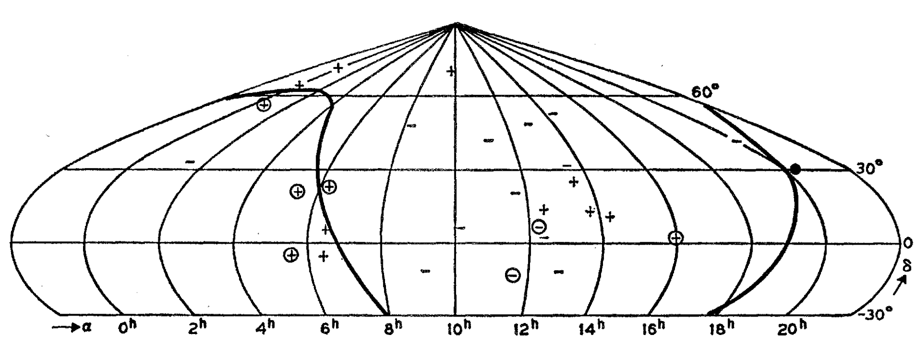

Fig. 1. Relative background temperature at various points in the sky. Plus signs indicate higher than average temperatures and minus signs lower. Points with deviations greater than 0.1°K have been circled.