SEISMOLOGICAL SERIES

of the

DOMINION OBSERVATORY

#58

1969-4

Canadian Seismic Data for Project Rulison

P.W. Basham and R.J. Halliday

Seismological Service of Canada

OTTAWA, CANADA

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INTRODUCTION

The primary purpose of the United States' Project Rulison is to investigate the feasibility of recovering natural gas by fracturing the reservoir medium with a nuclear detonation. The shot data for the explosion were as follows:

Date:	10 September, 1969
Time:	21:00:00.1 GMT
Yield:	40 KT
Location:	39.4058° N, 107.9481° W
Depth:	8443 feet
Medium:	sandstone and shale

A secondary purpose was to promote international seismic data exchange on underground nuclear explosions. The project was well advertized in advance so that national agencies could do independent studies on detection and identification of the explosion, contribute data to a world-wide data pool, and have access to all data for comprehensive studies.

This report is intended as a preliminary data file for Canadian Seismograph Network observations of the Rulison explosion. The principle data included are P and Rayleigh wave travel times, and period and A/T measurements for use in magnitude computations. Short discussions of some aspects of the Rulison data are included to relate them to past experience with Nevada Test Site (NTS) explosions. In particular, the magnitude data are grouped and adjusted to provide best estimates of Canadian body-wave and surface-wave magnitudes of the event.

The data have been collected at short notice and may be subject to errors. Their collection here is in no way intended to preclude perusal of original records by anyone interested.

CANADIAN STATIONS

Table I lists Canadian seismograph stations that were operational at the time Rulison was detonated. Included in the table are the international station code (to be used in subsequent tables), the coordinates and the station altitude (where known). Second-order stations operate only short-period vertical seismographs.

Calibration curves for the Canadian stations are available on request from Dominion Observatory, or can be found in any recent Canadian Seismological Bulletin.

MAGNITUDES

Table II gives epicentral distances to Rulison, and short-period vertical P wave and long-period vertical Rayleigh wave T and A/T data. Twenty-eight stations had short-period records available; Rulison P waves were observed on 22. Twenty-

Table I

CANADIAN SEISMOGRAPH STATIONS OPERATIONAL DURING PROJECT RULISON

International Code	Station Name	Coordinates (N)	Coordinates (W)	Altitude in Metres
*ALB	Alberni, B.C.	49°16'	124°49'	25
ALE	Alert, N.W.T.	82°29'	62°24'	65
BLC	Baker Lake, N.W.T.	64°19'	96°01'	16
CMC	Coppermine, N.W.T.	67°50'	115°05'	30
EDM	Edmonton, Alta.	53°13.3'	113°21'	730
FFC	Flin Flon, Man.	54°43.5'	101°58.7'	338
FCC	Fort Churchill, Man.	58°45.7'	94°05'	39
FSJ	Fort St. James, B.C.	54°26'	124°15'	772
FBC	Frobisher Bay, N.W.T.	63°44'	68°28'	45
GWC	Great Whale River, Que.	55°17.5'	77°45.2'	8
HAL	Halifax, N.S.	44°38'	63°36'	56
*HMQ‡	Holland Mills, Que.	45°45.5'	75°38.9'	175
INK	Inuvik, N.W.T.	68°17.5'	133°30'	(40)
LHC	Lakehead, Ont.	48°25'	89°16'	196
*MCC	Mica Creek, B.C.	52°03'06"	118°35'07"	
MNT	Montreal, Que.	45°30'09"	75°37'23"	112
MBC	Mould Bay, N.W.T.	76°14.5'	119°21.6'	(15)
OTT	Ottawa, Ont.	45°23'38"	75°42'57"	83
PNT	Penticton, B.C.	49°19'	119°37'	550
PHC	Port Hardy, B.C.	50°42'	127°26'	33
STJ	St. John's, Nfld.	47°34.3'	52°44.0'	62
SCH	Schefferville, Que.	54°49'	66°47'	540
*SIC	Sept-Iles, Que.	50°10'30"	66°44'30"	283
SFA	Seven Falls, Que.	47°07.4'	70°49.6'	232
*SUD	Sudbury, Ont.	46°28'	80°58'	267
SES	Suffield, Alta.	50°23'45"	111°02'30"	770
VIC	Victoria, B.C.	48°31'10"	123°24'55"	197
YKC	Yellowknife, N.W.T.	62°28.7'	114°28.7'	198

*2nd order stations. ‡Temporary station.

Note: The standard station RES (Resolute, N.W.T.) was closed for maintenance at the time of Rulison.

Table II

VERTICAL P AND RAYLEIGH WAVE DATA FOR PROJECT RULISON

Station		P Wave			Rayleigh Wave		
		T	$\frac{A}{T}$	m‡	T	$\frac{A}{T}$	M
		(sec)	$(\frac{m\mu}{sec})$		(sec)	$(\frac{m\mu}{sec})$	
SES	11.2	0.5	44	5.04	10	132	4.16
PNT	12.9	0.6	44	5.04	10	80	4.04
VIC	14.4	0.8	45	5.06	13	57	3.97
EDM	14.5	0.7	27	4.83	11	83	(4.15)*
MCC	14.6	0.8	19	4.67**			
ALB	15.6	0.8	45	5.05			
FFC	15.9	0.5	25	4.79	14	46	3.96
LHC	16.2	0.6	31	4.90	11	142	4.46
PHC	17.8	1.0	25	4.80			
FSJ	18.6	0.8	55	5.04	14	17	(3.64)
SUD	20.9	1.0	96	5.08			
FCC	21.1	0.8	46	4.76	11	104	4.52
YKC	23.5	0.8	53	5.02	13	75	4.46
OTT	24.4	0.8	58	5.16	12	39	4.20
HMQ	24.5	0.9	21	4.72			
GWC	25.6	--	--	---	18	16	(3.83)
MNT	25.9	0.7	12	(4.58)	12	42	4.27
BLC	25.9	0.7	45	5.15	11	72	4.50
SFA	27.9	--	--	---	14	54	4.43
CMC	28.8	--	--	---	14	22	4.06
SIC	31.0	--	--	---			
SCH	31.4	0.8	21	5.03	12	66	4.60
INK	32.1	1.0	13	4.80	12	47	4.47
HAL	33.0	--	--	---	--	---	---
FBC	33.7	0.7	20	(5.01)	9	50	4.54
MBC	37.3	0.5	10	4.48	13	39	4.50
STJ	40.1	--	--	---	16	40	4.56
ALE	45.7	0.6	26	5.22	12	21	4.38

‡m computed using Q for $\Delta > 20°$; Q* for $\Delta < 20°$. *Bracketed values are inaccurate because of low SNR. **Recording sensitivity is in doubt.

Note: Blanks indicate no record available; dashes indicate record available but no phase observed.

two stations had long-period records available; Rulison Rayleigh waves were observed on 21. The raw magnitudes given in Table II are computed according to the following formulae:

$$m = \log A/T - 3 + \begin{matrix} Q \; ; \; \Delta > 20° \\ Q^* \; ; \; \Delta < 20° \end{matrix}$$

where Q is the zero-depth distance calibrating function from Gutenberg and Richter (1956), and Q* is a modified calibrating function determined by Basham (1969a); and

$$M = \log A/T + 1.66 \log \Delta + 0.3$$

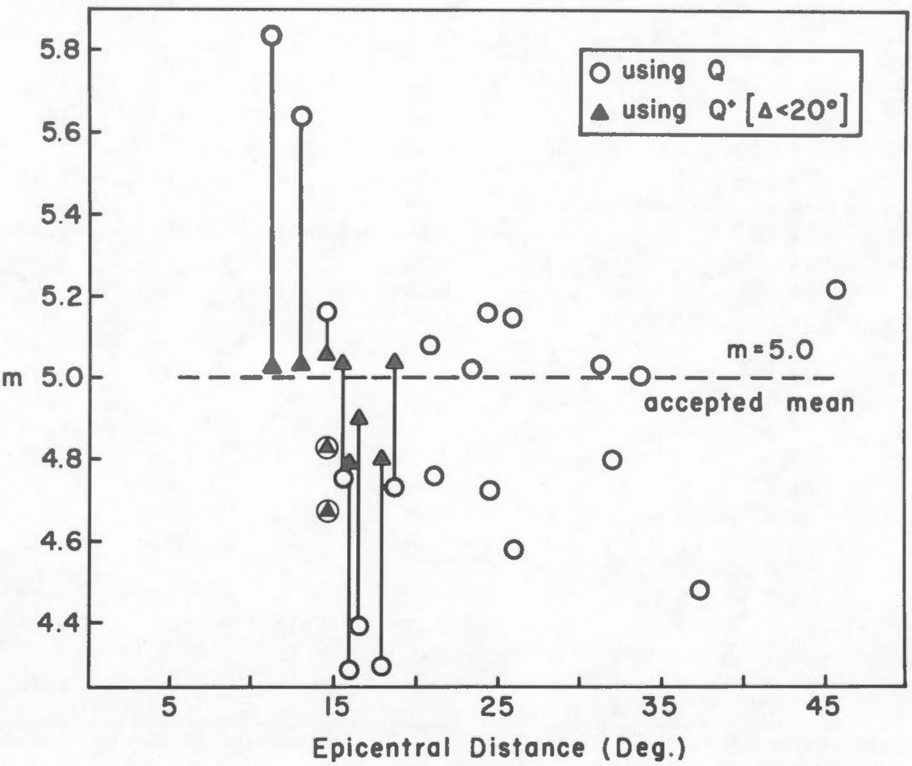


Figure 1. Rulison P wave magnitude (m) versus epicentral distance using Q at all distances and Q* for $\Delta < 20°$.

The effect of the Q* function on equalizing body-wave magnitudes is shown in Figure 1, which is a plot of all m values versus distance using the original Q at all distances and the modified Q* for distances less than 20°. Entries (a) and (b) in Table III show that Q* yields a mean m equal to the teleseismic mean m and which, perhaps fortuitously, has a smaller scatter.

P wave and Rayleigh wave magnitude station corrections for NTS explosions are available for 19 Canadian stations (Basham, 1969a). It is of interest to test their effectiveness in reducing magnitude scatter when applied to the Rulison data. Table III shows mean m and rms scatter values for those of the 19 stations at distances greater than 20° that recorded Rulison: entry (c) with the NTS corrections applied, and entry (d) without corrections. In either case, the mean P wave magnitude is greater for this calculation; the rms scatter is, however, greatest with the corrections applied, suggesting that the NTS corrections are not generally applicable to Rulison. Entry (e) in Table III gives mean m and rms scatter using all raw m values from Table II.

From the results shown in Table III the choice for Rulison m, to the nearest tenth of a unit, is 4.9 or 5.0. We prefer to accept m5.0 to remain compatible with those stations previously used for NTS events.

Table III

MEAN MAGNITUDES

	No. Stations	Mean	Rms Scatter
m			
(a) Δ < 20° (from Table II; using Q*)	10	4.92	.13
(b) Δ > 20° (from Table II; using Q)	12	4.92	.23
(c) Δ > 20° (stations with NTS corrections applied)	7	5.07	.27
(d) Δ > 20° (same stations; no corrections applied)	7	5.01	.23
(e) All stations (uncorrected)	22	4.92	.19
M			
(f) Δ < 20° (from Table II; uncorrected)	7	4.05	.23
(g) Δ > 20° (from Table II; uncorrected)	14	4.38	.21
(h) Δ < 20° (stations with NTS corrections applied)	5	4.18	.29
(i) Δ > 20° (stations with NTS corrections applied)	11	4.29	.26
(j) All stations with NTS corrections	16	4.25	.28
(k) All stations (uncorrected)	21	4.27	.27

Accepted Canadian values: m 5.0
M 4.3

Canadian Rayleigh wave magnitudes of western United States events have in the past been based on measurement of Rayleigh waves with periods much smaller than 20 seconds. This is also the case for Rulison; see the measured Rayleigh wave periods in Table II. There is no possibility of measuring 20-second trace motion from the photographic records of Rulison Rayleigh waves; some seismogram copies are appended to this report. The consequences of computing magnitudes from these shorter-period surface waves have been discussed by Basham (1969b); the general effect is to produce M values for explosions which are about 1.0 units larger than those based on 20-second waves.

As with m, the M data can be tested for consistency over the epicentral distance range covered by Canadian stations and for reduction in scatter when NTS Rayleigh wave station corrections are applied. The results are summarized in the second section of Table III. Entries (f) and (g) show that mean M is about 0.3 smaller for $\Delta < 20°$ than for $\Delta > 20°$; entries (h) and (i) show that this difference is reduced if NTS station corrections are applied. This reflects the fact that the distance decrement inherent in the M computation formula is not strictly appropriate over all distances for a purely continental propagation path. Each of the entries (i), (j) and (k) are equally acceptable means; we accept a value M4.3 for Rulison which will be compatible with previous Canadian data for NTS.

ARRIVAL TIMES

Table IV gives the times at Canadian stations of the first-arriving P wave and the maximum-amplitude Rayleigh wave. The accuracies attributed to the P wave readings are given as a footnote in Table IV; the Rayleigh wave times are accurate to within about one period of measured motion.

The P wave first arrivals and a number of clear secondary arrivals (for $\Delta < 25°$) are plotted in Figure 2 on a western United States regional travel time chart from Evernden (1967). Evernden has emphasized the great regional variability in first-arrival P phase identification. The multiplicity of paths from Rulison to Canadian stations at $\Delta < 20°$ makes it impossible to identify all Canadian first arrivals from one group of regional travel times. It is this difficulty in identifying the first-arriving phase which prohibits routine calculations of regional P wave magnitudes from formulae of the type derived by Evernden. The use of an average Q* is shown in the previous section to be an adequate alternative.

The travel times of the maximum amplitude in the Rayleigh wave train are plotted versus distance in Figure 3. The approximate straight-line fit to these Rayleigh travel times yields an average group velocity of 3.05 km/sec. No measured maximum amplitude Rayleigh travel time differs by more than 1 minute from the value predicted using this velocity.

RULISON EPICENTRE LOCATION

An operational computer program for determining epicentres from P arrival times at Canadian stations is available at Dominion Observatory (Newton and Weichert,

Table IV

FIRST P AND MAXIMUM RAYLEIGH ARRIVAL TIMES FOR PROJECT RULISON
(minutes and seconds after 21 hours, 10 September 1969)

Station	Δ	P	Rayleigh
SES	11.2	02:40.5	07:30
PNT	12.9	03:06.2	08:15
VIC	14.4	03:21	09:00
EDM	14.5	03:22.5	09:20
MCC	14.6	03:(32)	
ALB	15.6	03:47	
FCC	15.9	03:42	09:50
LHC	16.2	03:(47)	09:40
PHC	17.8	04:09	
FSJ	18.6	04:21.0	11:30
SUD	20.9	04:44.8	
FCC	21.1	04:49	13:00
YKC	23.5	05:10.5	14:30
OTT	24.4	05:21	14:40
HMQ	24.5	05:21.3	
GWC	25.6	-----	15:10
MNT	25.9	05:(38)	15:30
BLC	25.9	05:33.1	16:15
SFA	27.9	-----	16:40
CMC	28.8	-----	17:30
SIC	31.0	-----	
SCH	31.4	06:24	18:40
INK	32.1	06:29.2	20:30
HAL	33.0	-----	----
FBC	33.7	06:42	20:00
MBC	37.3	07:12	23:10
STJ	40.1	-----	24:00
ALE	45.7	08:21.9	28:45

Note: P times given to tenth of second are accurate to about ±0.2 seconds; times without tenths are accurate to about ±0.5 seconds; bracketed seconds may be in error by 2 or 3 seconds.

Blanks indicate no record available; dashes indicate no phase observed.

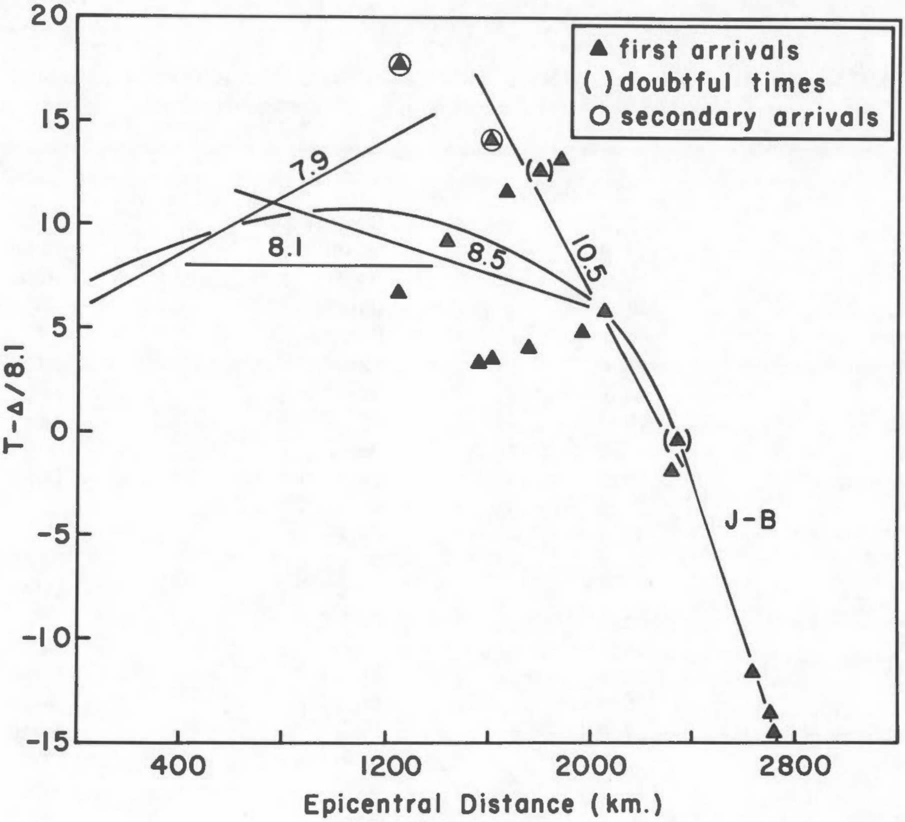


Figure 2. Rulison P wave first arrivals and clear secondary arrivals plotted on a U.S. regional travel-time chart from Evernden (1967). Numbers on straight-line segments are equivalent head-wave compressional velocities.

1969). Although this program is used only for quick epicentre determinations of limited accuracy, it is of interest to test it in the location of Rulison. Using 10 Canadian P wave first arrivals at $\Delta > 20°$ and Herrin (1968) P travel-time tables, the computed location of Rulison is 39.45°N, 108.06°W with an origin time of 21:00:01.2. Compared with the true location and origin time (see page 1) this is a mislocation of about 10 km to the north-northwest with an origin-time error of +1.1 seconds. Application of station corrections determined by Newton and Weichert for NTS events does not improve the epicentre or origin-time accuracy.

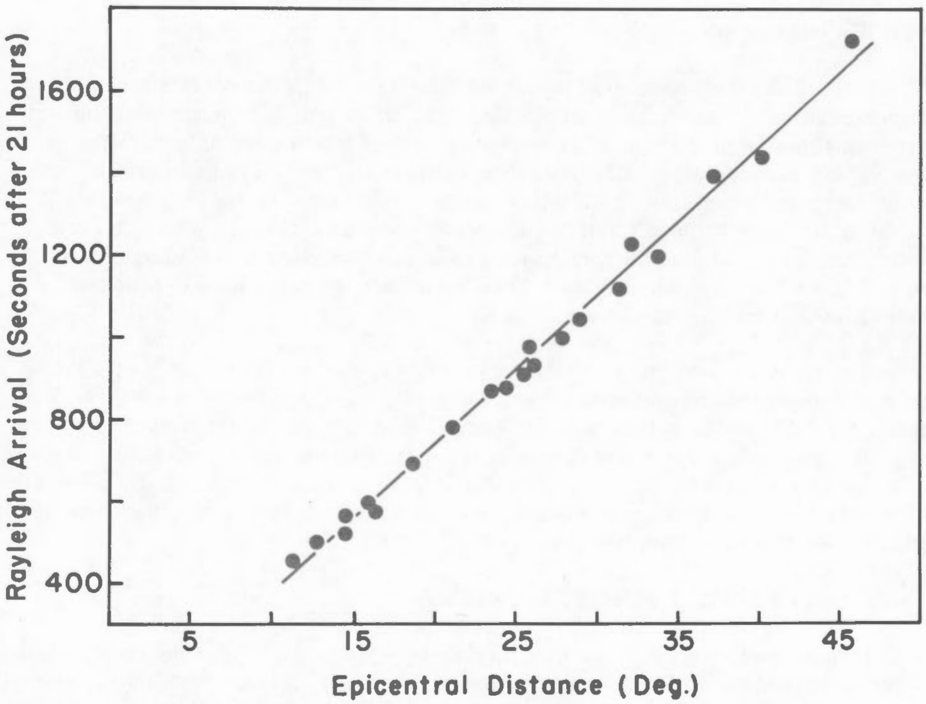


Figure 3. Rulison Rayleigh wave arrival times versus epicentral distance. Approximate straight-line fit represents a velocity of 3.05 km/sec.

Epicentres of third zone ($30^\circ \leq \Delta \leq 90^\circ$) seismic events are computed routinely using the data from the Yellowknife medium aperture short-period seismic array. The Rulison azimuth determined from the array processing is 166.9°, which is within 0.1 degrees of the great circle azimuth. Conversion of computed $dt/d\Delta$ into epicentral distance using Herrin (1968) tables yields 22.8°, which is 0.7° smaller than the true distance. Thus, the Yellowknife array process mislocates Rulison about 80 km too near to Yellowknife; this is due mainly to poorly known $dt/d\Delta$ versus distance relationships for this distance range.

IDENTIFICATION OF RULISON

Most of the data presented here have been related to the detection of and magnitude computation for the Rulison explosion. The other point of fundamental importance is identification of Rulison as an explosion rather than an earthquake. The numerous earthquake-explosion discrimination criteria will not be tested here; however, using the computed magnitudes, Rulison can be quickly tested using the Canadian M versus m criterion developed for NTS explosions (Basham, 1969a). Using m5.0 and M4.3 for Rulison would place the event very near the explosion least-squares line shown in Figure 2 of Basham (1969a). This is virtually positive identification of Rulison as an underground explosion.

The relative completeness of data in Table II shows that a continental United States explosion of this magnitude has well observed P and Rayleigh waves throughout the entire Canadian seismograph network under relatively quiet background noise conditions. However, as magnitudes decrease from the Rulison values of m5.0 and M4.3, detection of events, and particularly their Rayleigh waves, becomes rapidly more difficult, in which case only the more sensitive Canadian stations are of value in detection and identification studies (see Basham, 1969a).

ADDITIONAL CANADIAN RULISON RECORDINGS

In addition to the Canadian standard network stations, whose records will be deposited as microfilm with the Seismological Data Center, Federal Building, Asheville, North Carolina 28801, U.S.A., the Dominion Observatory had in operation during the Rulison explosion three specialized seismograph systems. These three systems, with comments on the form of available data, are:

1. The Yellowknife 19-element vertical short-period array, the data from which are most easily made available in the form of digital magnetic tape. (No analog reproducing facility for the Yellowknife array tapes is available in Ottawa.)

2. The experimental Yellowknife two-element long-period vertical system (separation of 16 km between elements). This system records on half-inch IRIG compatible FM magnetic tape; data can be made available either as an IRIG compatible half-inch tape or as hard copy playouts.

3. Three network stations, SES, OTT and ALE, operate, in addition to the standard set of instruments, a vertical double-band high-sensitivity (at 0.7 and 18.2 seconds) seismograph recording on a single helicorder hot-pen recorder. Calibration curves and record copies can be made available on request. The ALE record for Rulison was spoiled by local interference.

Except for the Yellowknife short-period array data, with which standard array processing can be accomplished, these specialized systems did not add significantly to Canada's detection of the Rulison event; the explosion was well enough recorded on the standard network.

REFERENCES

Basham, P.W., 1969a. Canadian magnitudes of earthquakes and nuclear explosions in southwestern North America. Geophys. J.R. Astr. Soc., 17:1-13.

Basham, P.W., 1969b. Canadian detection and discrimination thresholds for earthquakes and underground explosions in Asia. Can. J. Earth. Sci., 6(6).

Evernden, J.F., 1967. Magnitude determinations at regional and near-regional distances in the United States. Bull. Seism. Soc. Am., 57:591-639.

Gutenberg, B., and C.F. Richter, 1956. Magnitude and energy of earthquakes. Ann. Geofis., 9:1-15.

Herrin, E., 1968. 1968 seismological tables for P phases. Bull. Seism. Soc. Am., 58:1193-1241.

Newton, J.C., and D.H. Weichert, 1969. Epicentre determination from first arrival times at Canadian stations. Seism. Ser. Dom. Obs. In preparation.

APPENDIX

Copies of Selected Seismograms

Copies of six seismograms of Rulison are shown on the following pages. All records have the same time scale with minute breaks shown and 1-minute break identified. The pertinent information is as follows:

A. SES long-period vertical Rayleigh wave, Δ 11.2°; the Canadian station nearest to Rulison.

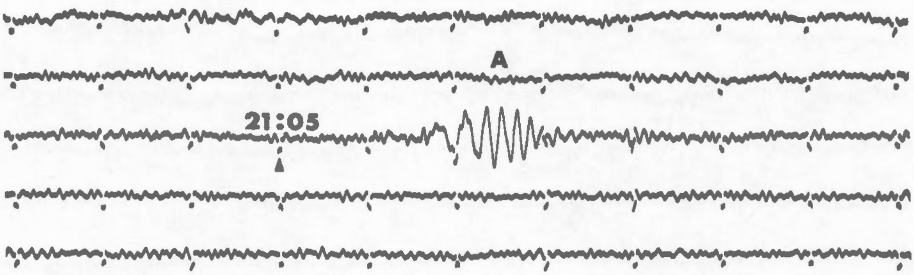
B. SES vertical double-band high-sensitivity record showing P waves (high frequency) followed by Rayleigh waves (low frequency).

C. LHC long-period vertical Rayleigh wave, Δ 16.2°; note that dominant energy appears as a single cycle.

D. FCC long-period vertical Rayleigh wave, Δ 21.1°; note that Rayleigh wave is more dispersed; background noise is relatively high.

E. YKC long-period vertical Rayleigh wave, Δ 23.5°.

F. Strip-chart playout of Yellowknife two-element long-period vertical (separation 16 km) Rayleigh wave through a 10-40 second analog bandpass filter.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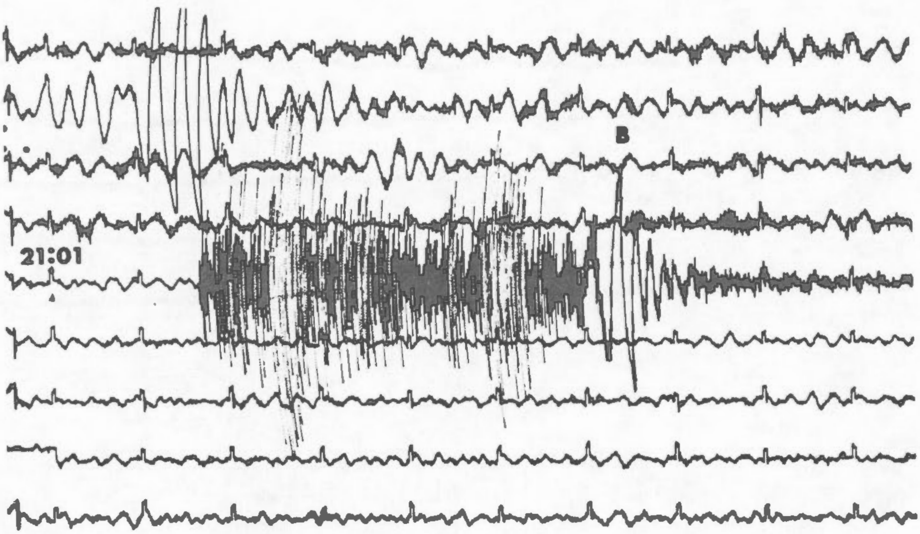
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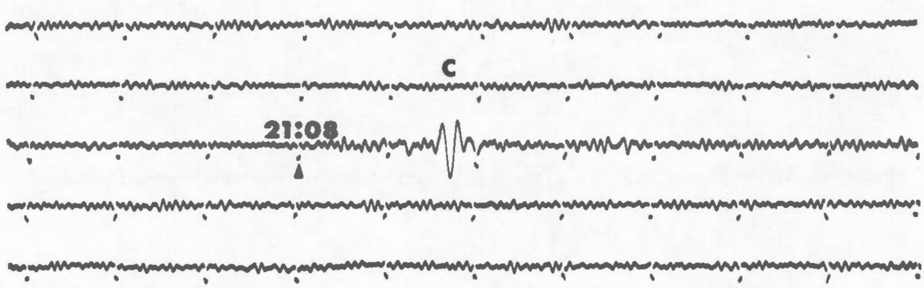
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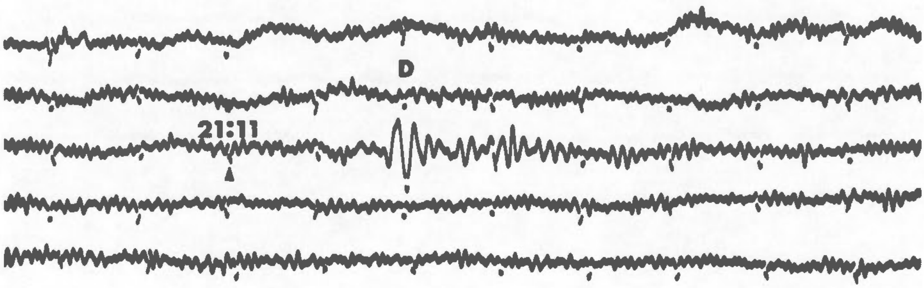
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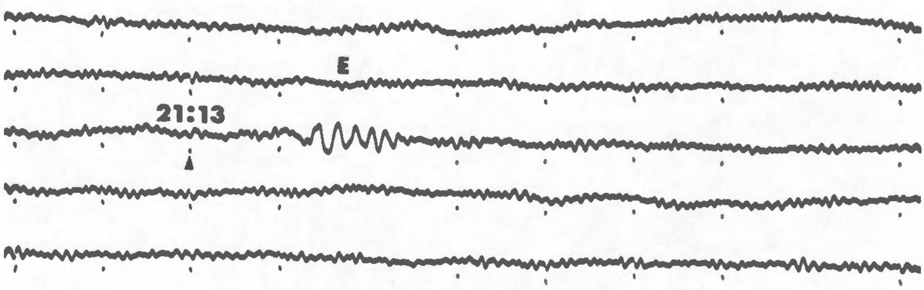
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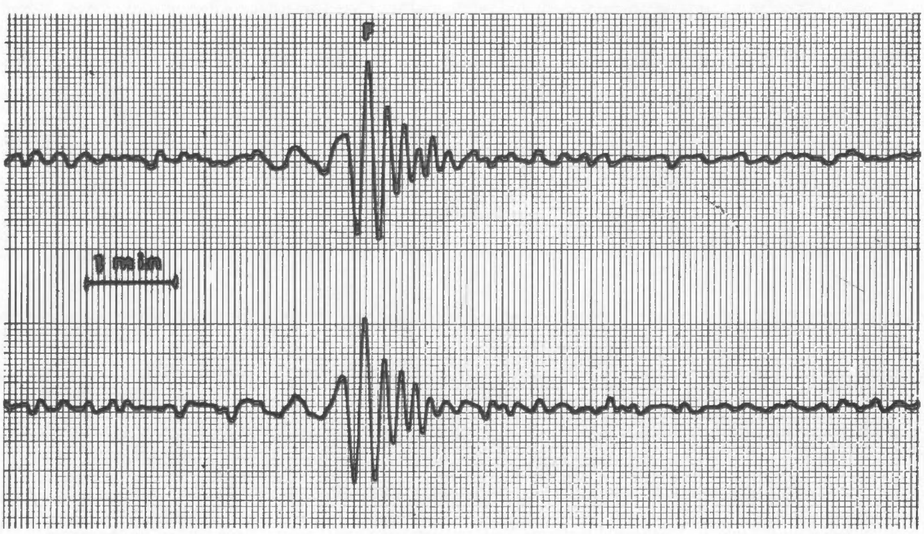
F
1 min