DISTRIBUTION OF EPICENTRES IN THE SCOTIA ARC, 1957–62

By R. E. J. Lewis*

Abstract. Seismograms recorded at the Argentine Islands (lat. 65°15′S., long. 64°17′W.) and Stanley (lat. 52°S., long. 58°W.) during the years 1957 to 1962, and at Halley Bay (lat. 75°30′S., long. 26°42′W.) for 1957 to 1959, have been analysed in conjunction with data published by the Bureau Central International de Seismologie (B.C.I.S.). In this period 162 seismic events were located in the region of the Scotia arc (seismic region 10).

Two aspects have then been considered: first, the geographical distribution of epicentres and, secondly, the agreement of observation with the travel-time tables of Jeffreys and Bullen (1948) for *P*-phase arrivals and for some phases reflected at the outer core. Finally, other features of interest on the Argentine Islands and Halley Bay seismograms are discussed.

The present paper has set out to extend our knowledge of the seismicity of seismic region 10, as defined by Gutenberg and Richter (1954) and shown in the accompanying map, by considering the distribution of epicentres and also to see whether the motion of seismic waves in the crust of the region can be used to improve our knowledge of the geological structure.

The situation of the observatories is shown on the map. The one at Stanley, Falkland Islands, was operated by personnel of the D.S.I.R. Radio Research Station. The Halley Bay station was set up by the Royal Society's International Geophysical Year Expedition in 1957 and it was taken over by the Falkland Islands Dependencies Survey in 1959; the one at the Argentine Islands was operated by Falkland Islands Dependencies Survey personnel. All stations were equipped with Willmore 1-sec. seismometers.

These local stations suffer, at times severely, from microseisms of meteorological origin and events have to be of at least magnitude $4\frac{1}{2}$ before they can be identified. At Halley Bay and the Argentine Islands the recordings were much better in the winter when pack and fast ice reduced the sea-seisms.

As can be seen from the table of epicentres (Table I), the increase in the world network of seismological observatories and the use of digital computers to operate on the subsequent data have increased the sensitivity of the international centres to activity in seismic region 10. Hence, most of the 49 newly documented events occurred in the period prior to 1960. Recomputation of the 113 events listed by B.C.I.S. has improved their accuracy in nearly all cases.

Determination of Epicentres

In many cases provisional data from B.C.I.S. were used as an initial estimate of the epicentral position. However, when no estimate was available, data from the local stations were used graphically to produce an approximate starting point for the computer calculation.

The most suitable map available was a Mercator projection of the South Atlantic Ocean (scale 1 : 5,174 000 at lat. 45°) and on this curves equidistant from each station were plotted in the range 16° to 23° at 1° intervals. From the points of intersection of two sets of these curves a further family of curves was drawn, these being equidistant from the two stations. This was repeated for another pair of stations.

The positions thus estimated to $\pm 0\cdot 5°$ in latitude and longitude were used in the final computer determinations of the epicentres.

One of the first papers on epicentral determinations using a high-speed computer was that by Bolt (1960). The method depends on *P* arrival times at many stations and, after working out distances from an estimated epicentre, reiterative least-squares operations reduce the standard error to the smallest possible value. The programme outlined also considers *pP* arrivals for initial depth determination and weighting factors are introduced at various stages. A weighting factor of 0·5 is applied to stations outside the range 30° to 90° distance and, by considering azimuth, quadrant weighting is applied to reduce the effect of a high density of stations in a particular direction. Finally, residual weighting eliminates errors of misinterpretation.

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The programme used in this paper is similar to that outlined above, and it was developed at the International Seismological Centre (I.S.C.) in Edinburgh, but no *pP* times were used as these were rarely documented or recorded in the events being studied.

After preliminary work with this programme, it was found that errors in depth cannot be eliminated (International Seismological Centre, 1965). For *P* waves, $dT/d\Delta$ is more or less the same for all epicentre depths and so there is an infinite set of solutions to any event, origin time and depth varying together to give a fairly constant standard error to the computation. However, this does not affect the hypocentre determination (see below). Consequently, unless there was strong evidence to indicate sub-normal depths, a value of 33 km. has been adopted as likely to cause fewer errors in computation.

Altogether 49 stations were used in the computations, though the maximum number in any one determination was 33 and frequently the number was less than ten. The coordinates of the epicentres are arranged topographically in Table I, in which they are given to 0·01° for ease of reference. However, these may be in error by as much as 0·1° in latitude and 0·2° in longitude. A number marked (?) may be less accurate. As mentioned above, depths have been taken as normal unless there was evidence to the contrary; in these cases the depth is appended in parentheses. Core-phase residuals have been used to confirm depths in a number of cases and these are marked with an asterisk (*) against the depth.

During the period under analysis (May 1957 to February 1962), 180 events were investigated and 162 of these were eventually computed.

It is interesting to note that the difficulty in determining the depth of events does not lead to very serious errors in hypocentre computation. The result of one calculation, given in Table III in connection with core-phase residuals, shows a change in latitude of 0·06° and in longitude of 0·17° for a depth variation of 100 km. With an incorrect depth estimate, it is only the origin time of the event which is affected seriously, though it is a shortcoming of the analysis that all depths have not been computed accurately.

As in all work of this type, it is never possible to be completely convinced that the best use has been made of the available data. It is conceivable that better results could be obtained from a series of re-computations as follows:

Procedure	*Outcome*
1. Run programme for position with stations 30° to 90° only at full weight; depth fixed at 33 km.	Standardized residuals for local stations; preliminary coordinates.
2. Re-run at estimated depth (from core phases, etc.) with depth fixed.	Check that residuals and coordinates are not drastically affected by ignoring depth as in (1).
3. Include PKP and allow depth variation; use range, azimuth and residual weightings.	Final attempt at geographical distribution, including depth.

It might be necessary to vary the scheme of this work as results of each stage became available.

However, this type of approach would only be fruitful for the well-documented events and, although in the future (with the great increase in the number of seismological stations and their improved technology) this analysis might be worthwhile, it was considered unlikely to improve the present survey materially, since the number of epicentres at other than normal depth was relatively small.

Geographical Distribution of Epicentres

"Seismic mapping is difficult in this area which is remote from all stations. Location depends principally on the records at La Paz, with data from La Plata, Cape Town, Tananarive and stations in Australia and New Zealand. Some of the epicentres mapped may be in error by as much as 5°." Such was the view of Gutenberg and Richter (1954).

TABLE I. SEISMIC EVENTS IN REGION 10

(Although given to 0·01°, the coordinates may be in error by 0·1° in latitude and 0·2° in longitude. Times are given primarily for identification purposes and occasionally may be in error by as much as 10 sec. due to uncertainty in depth.)

Event number	*Date* day	mon.	yr.	*Time* (U.T) hr.	min.	sec.	*Coordinates* lat. °S.	long. °W.	*Notes*
1	12	5	57	12	55	03	58·93	22·39	?
2	12	5	57	04	47	45	60·56	24·49	* (0)
3	25	5	57	18	50	58	57·88	24·31	
4	17	7	57	01	13	46	57·29	26·77	+
5	25	7	57	22	43	03	63·20	53·46	? +
6	25	8	57	14	55	47	57·90	25·53	? +
8	12	10	57	16	46	30	59·21	16·38	
9	20	10	57	15	57	12	56·17	27·12	+
10	24	11	57	07	53	08	58·04	25·82	? +
11	6	12	57	09	41	21	56·33	26·83	
12	18	12	57	20	44	52	59·98	28·29	
13	27	12	57	07	16	33	58·13	64·33	+
14	25	2	58	05	27	35	59·69	25·89	
15	7	4	58	03	28	51	55·94	27·11	
16	8	4	58	16	42	04	60·41	30·90	? +
17	20	4	58	21	14	58	59·62	26·17	× (0)
18	21	4	58	10	03	01	56·65	48·11	+
19	3	5	58	15	11	31	56·78	48·58	? +
20	8	5	58	14	36	39	57·54	26·02	
22	15	6	58	11	25	51	56·76	25·50	? +
23	20	6	58	14	02	35	59·47	25·81	? +
87	25	6	58	20	56	45	56·30	26·69	+
25	4	9	58	17	08	01	60·73	20·66	? +
26	6	9	58	00	16	23	58·68	25·74	+
27	18	9	58	03	35	31	56·01	27·05	
28	2	10	58	04	25	25	58·35	10·25	
29	9	10	58	11	20	18	55·59	27·78	(0) ×
30	11	10	58	02	00	24	58·71	26·09	? +
31	18	10	58	17	29	56	57·99	25·42	+
32	19	10	58	21	05	48	56·41	25·62	+
37	18	11	58	23	08	11	55·71	20·17	+
33	20	11	58	22	01	03	59·70	26·34	+
35	21	11	58	09	42	55	58·03	26·07	+
34	24	11	58	06	48	58	57·64	63·35	(0) ×
40	13	12	58	09	07	34	56·63	23·54	(0) ×
41	15	2	59	03	59	24	59·62	25·57	* (0)
42	15	2	59	04	42	34	59·91	25·46	* (0)
43	24	2	59	10	57	46	59·88	25·54	+
44	24	2	59	11	31	08	60·06	25·60	+
45	17	3	59	12	58	54	57·69	25·24	
46	17	3	59	15	04	13	57·02	26·49	
47	17	3	59	23	04	19	57·37	25·33	+
49	30	4	59	13	25	37	55·98	28·07	* (33)
50	4	5	59	10	14	03	56·34	26·76	+
52	23	5	59	21	19	15	58·83	25·40	+
53	8	6	59	22	05	31	57·12	63·15	? +
54	9	6	59	14	21	20	62·23	25·83	+
55	9	6	59	23	10	43	58·25	8·95	
56	10	6	59	02	03	42	62·72	61·45	+
59	11	7	59	18	42	33	59·09	25·24	+

TABLE I—*continued*

Event number	*Date* day	mon.	yr.	*Time* (U.T) hr.	min.	sec.	*Coordinates* lat. °S.	long. °W.	*Notes*
61	24	7	59	23	03	07	56·54	26·81	* (80)
62	28	7	59	10	53	31	63·04	61·18	+
63	15	8	59	03	28	55	59·48	25·88	+
67	8	9	59	20	18	37	58·70	24·95	
68	18	9	59	12	01	11	57·78	25·10	* (0)
69	18	9	59	18	32	52	58·56	25·49	? +
70	18	9	59	20	11	06	59·81	59·70	? +
71	15	10	59	13	54	00	57·77	24·98	
72	19	10	59	15	55	35	54·41	27·78	
73	21	10	59	06	07	15	56·36	26·73	+
74	30	10	59	11	27	37	60·00	26·83	
76	26	11	59	05	59	52	56·17	27·03	
77	3	12	59	01	55	11	57·05	25·38	
78	14	12	59	23	22	02	59·85	26·37	* (33)
79	14	12	59	23	51	21	59·69	25·88	+
82	15	12	59	00	18	22	57·98	21·03	? +
83	15	12	59	05	23	13	60·12	25·91	+
84	15	12	59	12	15	55	59·93	26·15	* (33)
85	22	12	59	11	30	56	56·38	26·78	+
101	2	1	60	08	27	18	57·34	24·74	
102	7	1	60	13	28	18	55·45	27·64	
103	7	1	60	14	36	04	55·92	26·95	
105	8	1	60	02	35	07	58·82	25·30	
106	8	1	60	10	04	34	55·33	26·95	+
107	8	1	60	11	29	22	55·36	27·67	* (33)
109	8	1	60	15	28	39	59·41	24·34	+
108	8	1	60	14	45	58	55·39	27·82	* (33)
110	10	1	60	05	20	30	55·76	25·88	+
111	12	1	60	03	09	14	55·61	27·51	
112	14	1	60	07	31	25	55·30	27·29	+
113	14	1	60	18	57	06	55·94	27·13	+
114	8	2	60	12	45	39	58·30	65·96	
115	26	2	60	05	18	22	55·62	27·04	+
116	16	3	60	00	33	07	60·43	26·55	
117	22	3	60	19	55	43	57·87	25·68	
118	5	4	60	07	17	49	60·86	24·91	
119	5	4	60	12	36	19	60·81	25·14	
120	28	4	60	02	10	18	59·74	26·44	
121	29	4	60	02	15	42	56·80	27·00	
122	29	4	60	03	43	04	55·41	25·90	
123	29	4	60	05	45	18	56·74	26·90	+
124	5	5	60	15	57	24	59·39	25·90	+
125	10	5	60	10	56	08	55·96	27·08	
126	27	5	60	17	19	46	57·47	26·71	
127	7	6	60	10	54	35	56·16	26·94	
128	17	6	60	17	45	47	59·96	26·52	
129	21	6	60	21	33	52	60·77	20·76	
130	28	6	60	15	30	22	60·05	18·27	
131	2	7	60	11	55	45	56·17	27·60	* (100)
132	9	7	60	17	47	36	56·68	26·52	
133	27	7	60	03	57	26	59·77	26·04	
134	31	8	60	05	36	54	58·97	26·50	? +
135	2	10	60	04	37	51	61·05	24·71	(77)
137	9	11	60	03	18	01	60·92	25·48	
138	26	12	60	04	32	32	57·37	26·05	* (80)
139	7	1	61	18	17	02	57·51	25·78	(94)
140	15	1	61	19	53	07	56·07	27·51	+
142	17	3	61	20	35	13	56·10	27·10	
143	7	7	61	15	33	37	60·70	56·26	+
144	19	7	61	03	50	44	58·99	25·53	

TABLE I—*continued*

Event number	*Date* day	mon.	yr.	*Time* (U.T) hr.	min.	sec.	*Coordinates* lat. °S.	long. °W.	*Notes*
148	29	7	61	11	55	34	57·22	24·64	?
149	1	8	61	07	21	14	56·91	24·74	* (44)
150	1	8	61	09	24	26	56·95	24·92	(61)
151	1	8	61	09	34	39	57·06	25·13	* (31)
152	1	8	61	14	42	28	57·06	25·73	
153	2	8	61	02	31	28	56·97	24·94	
156	2	8	61	03	59	17	56·39	22·05	(67)
158	26	8	61	18	42	19	60·51	31·03	?
160	1	9	61	00	09	37	59·28	26·65	* (131)
161	8	9	61	11	26	33	56·35	27·32	* (125)
162	12	9	61	19	29	08	59·87	30·58	
163	19	9	61	21	34	44	60·40	24·40	
164	24	9	61	16	52	44	56·95	26·37	
165	27	9	61	12	07	33	59·43	23·45	* (33)
166	7	10	61	08	15	14	56·17	26·88	
167	7	10	61	19	24	32	56·07	26·49	
168	13	10	61	04	59	02	55·96	27·76	* (100)
169	13	10	61	10	46	46	60·45	33·83	
170	23	10	61	00	08	37	60·38	34·29	
171	24	10	61	18	04	34	58·92	25·01	
172	15	11	61	22	01	43	56·49	25·56	(40)
173	17	11	61	09	16	15	58·80	25·47	
174	18	11	61	07	27	42	56·46	25·33	
175	27	11	61	01	54	18	55·90	27·83	(163)
176	21	12	61	12	07	32	55·33	32·67	?
178	10	2	62	12	58	19	56·61	25·82	
189	5	3	62	06	45	52	55·09	26·69	?
190	5	3	62	08	45	58	55·42	27·27	
179	5	3	62	10	15	23	55·78	27·78	
191	25	3	62	14	17	03	56·34	25·34	
192	31	3	62	12	02	09	57·43	25·47	
201	8	7	62	04	03	56	55·24	29·21	
202	26	7	62	21	32	17	56·13	25·16	
203	3	8	62	12	04	58	55·51	26·54	
204	8	8	62	08	41	18	58·27	25·28	(54)
205	12	8	62	10	38	02	58·23	25·10	
206	23	8	62	20	52	53	56·33	26·57	
207	3	9	62	22	06	08	56·54	27·25	
208	21	9	62	22	38	52	57·85	64·55	(51)
209	3	10	62	18	48	55	57·91	25·33	
210	7	10	62	16	00	20	57·84	25·55	
211	19	10	62	09	39	43	56·46	26·69	(86)
212	21	10	62	23	10	50	55·42	26·01	
213	26	10	62	15	58	35	55·69	26·65	
214	26	10	62	22	09	06	55·92	27·08	
215	13	11	62	21	47	47	56·11	27·47	
216	12	12	62	13	56	33	60·61	26·53	
217	24	12	62	00	23	54	59·33	26·30	
218	21	1	63	07	00	59	62·53	36·09	
219	30	1	63	10	10	03	55·49	28·39	
220	6	2	63	20	46	50	56·65	28·50	
221	19	2	63	16	39	16	55·33	28·57	

Notes:
? Some inaccuracy in coordinates.
* Core phases used for depth estimate.
(*N*) Depth estimated at *N* km.
\+ Events not included in *B.C.I.S. Bulletin.*
× Epicentres computed by I.S.C. and not re-computed.

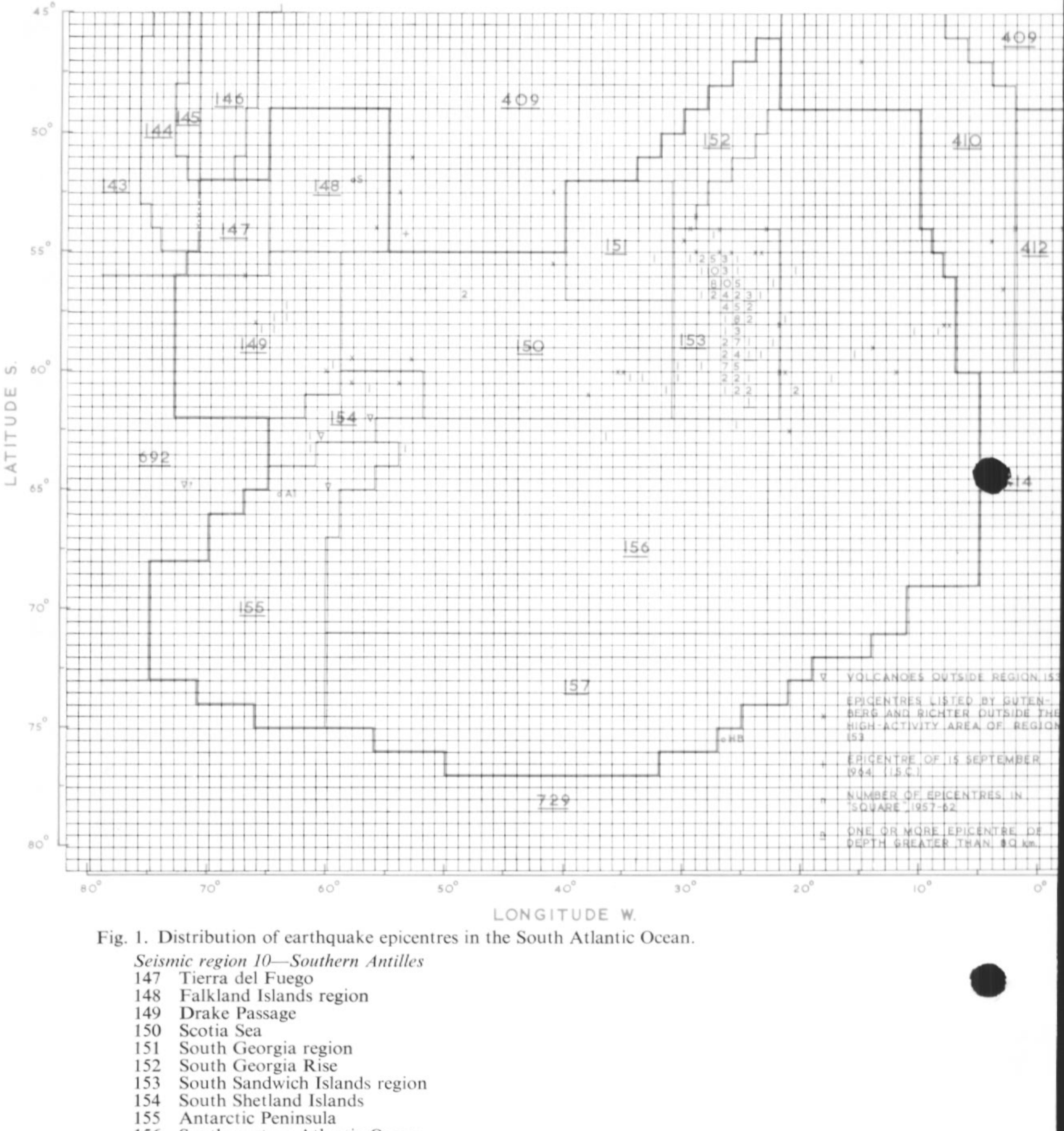

Fig. 1. Distribution of earthquake epicentres in the South Atlantic Ocean.

Seismic region 10—Southern Antilles

147 Tierra del Fuego
148 Falkland Islands region
149 Drake Passage
150 Scotia Sea
151 South Georgia region
152 South Georgia Rise
153 South Sandwich Islands region
154 South Shetland Islands
155 Antarctic Peninsula
156 South-western Atlantic Ocean
157 Weddell Sea

and adjoining geographical regions:

		Seismic region
143	Off coast of southern Chile	9 Extreme South America
144	Near coast of southern Chile	
145	Southern Chile–Argentina border region	
146	Argentina	
409	South Atlantic Ocean	32 Atlantic Ocean
410	South Atlantic Ridge	
412	Bouvetøya region	
414	South-eastern Atlantic Ocean	
729	Antarctica	50 Antarctica
692	Southern Pacific Ocean	43 South-eastern and Antarctic Pacific Ocean

S Stanley, Falkland Islands; AI Argentine Islands; HB Halley Bay.

Fig. 1 (of seismic region 10) shows the distribution of epicentres in the present survey in addition to those listed by Gutenberg and Richter (1954). The sub-boundaries, originating from work by Flinn and Engdahl (1965), are those now used by the I.S.C.

In general, the distribution now examined agrees very well with that of Gutenberg and Richter, who were only able to document the largest events in the period prior to 1953. A number of these epicentres near the Falkland Islands were considered suspect but an event recently reported by I.S.C. in that region supports the view that this area may not be aseismic.

The present study confirms the original seismic picture of the region. In particular, regions 147, 151, 152, 155 and 157 are aseismic, as is region 156 apart from the line of epicentres trending towards Bouvetøya and the Mid-Atlantic Ridge. (A more appropriate sub-division of this area is fairly obvious.)

Regions 148, 149, 150 and 154 include the extensions of the Scotia arc towards the Andes and towards the Antarctic Peninsula, with the expected seismicity.

Region 153 is the most active area, displaying the features of an active island arc:

i. A large number of shallow shocks on the outer side of the arc, lying between the 2,000 and 4,000 m. bathymetric contours.
ii. No activity inside the arc.
iii. The intermediate shocks lie nearer the islands of the arc.
iv. No deep events, which is atypical of Pacific-type arcs but similar to the Lesser Antilles.

The first discussion of the seismicity of the Scotia arc was by Tams (1930), who commented on the similarity with the Lesser Antilles island arc. Earlier, during his *Meteor* Expedition, Suess had discovered the deep trench to the east of the South Sandwich Islands and had applied the name Southern Antilles to the whole system connecting South America with Antarctica.

The similarity between the Scotia arc and the Lesser Antilles arc has also been referred to by Matthews (1959).

Since that time a detailed picture of the geophysical features of this island arc has been assembled. Seismic studies, following observations made during the International Geophysical Year, have revealed some crustal and mantle features beneath the Scotia arc and western Antarctica. The work of Evison and others (1960), using surface-wave dispersion, gave a crustal thickness of not more than 25 km. in western Antarctica, contrasting with 35 km. in the eastern part of the continent. Woollard (1960), following sea-refraction measurements, found a layered crust south of South Georgia with the deepest measured layer having a seismic velocity of 7·6 km. sec.$^{-1}$; this he interpreted as being due to a mantle-crust mix similar in origin to that of the Caribbean (Officer and others, 1957; Cook, 1962). This may have some significance in the interpretation of some of the phases recorded at the Argentine Islands and examined below.

Griffiths and others (1964) have described their recent work in the Scotia arc and this paper also contains full references.

Recent submarine volcanic activity has been reported from the South Sandwich Islands (Gass and others, 1963) but this was not recorded in any of the published data examined.

Phase Travel-times and Depths

A detailed investigation of *P* residuals at the Argentine Islands failed to produce any systematic deviation from Jeffreys and Bullen's (1948) tables. The analysis was carried out taking epicentres in small ranges and calculating the mean residual. Only those determinations using more than ten stations have been included, thus making the epicentre determinations more or less independent of the Argentine Islands travel-times. The results are given in Table II.

The depths to which the waves penetrate (even at these short ranges) is quite large, i.e. 500 km. for $\Delta = 20°$, and so the effect of local crustal variations will not play a significant role in the *P* travel-times. This negative result does not, therefore, exclude the possibility of peculiar crustal features in this region, e.g. the crust-mantle mix referred to earlier.

Core-reflected phases were identified on the Argentine Islands records for 23 shocks and a

TABLE II. *P*-PHASE RESIDUAL ANALYSIS (FROM ARGENTINE ISLANDS RECORDS)

Range (Δ)	17·0 to 17·5	17·5 to 18·0	18·0 to 18·5	18·5 to 19·0	19·0 to 19·5	19·5 to 20·0	20·0 to 20·5	20·5 to 21·0
Number of events	1	3	13	7	12	30	29	12
Σ of residuals	−1	+4	+13	−3	0	+13	+18	+3
Σ/N	−1·0	+1·3	+1·0	−2·3	0	+0·4	+0·6	+0·2

detailed analysis of these was made. Two test events showed quite clearly the power of *ScP* and *ScS* phases in determining depth where *P*-phase analysis gave no clear indication. One of these is examined in Table III.

The core-phase residuals of Table III indicate quite clearly that solution A is the correct one, though the standard errors from the computed results are not very different.

TABLE III. CORE-PHASE RESIDUALS (*u/c* sec.) FOR EVENT NO. 160

Station	*Solution A* Depth 131 km. SE = 1·26 lat. 59·28°S., long. 26·65°W.				*Solution B* Depth 33 km. SE = 1·67 lat. 59·22°S., long. 26·48°W.			
	Range	*PcP*	*ScP*	*ScS*	*Range*	*PcP*	*ScP*	*ScS*
Argentine Islands	18·3	0	+2	0	18·4	+1	+12	+10
Stanley	19·1	—	+3	+3	19·1	—	+13	+14

LOCAL FEATURES OF INTEREST

During the detailed analysis of the Argentine Islands seismograms a number of anomalous features were found. A completely satisfactory explanation of these has not been possible but the following discussion considers several hypotheses.

The features of the seismograms are illustrated in Figs. 2–5. Measurements referred to were taken from the originals.

(a) Events of the type illustrated in Figs. 2 and 3 were quite frequently recorded and, due to lack of correlating evidence from any other stations, they are considered as being of local origin and have been interpreted as *P* and *S* waves as indicated. The time interval *P–S* varied from 10 to 50 sec. It appears that there are two possible causes for these events:

i. Small local earthquakes.

ii. Ice falls or calving from adjacent glaciers.

There are a number of references to seismic activity near the Antarctic Peninsula south of Deception Island (lat. 62°57′S., long. 60°38′W.). Rudolph (1887) gave an account (translated): "On 10 December 1877, in lat. 65°10′S., long. 72°10′W., Capt. Lunginers of the Danish ship *Lutterfeld* found a small island 20 m. high. At daybreak the island was approached in a small boat. It had meantime increased in size. The water in contact with the rock hissed and, although no smoke rose, the island was too hot to land on. Later the island sank quickly and by 8 a.m. was completely covered. An hour later the *Lutterfeld* was able to sail across the site of the island."

Larsen (1894) mentioned activity at Lindenberg Island (lat. 64°55′S., long. 59°42′W.) off the east coast of Graham Land. Thus it is not impossible that small tremors originating in the range 100 to 400 km. from the Argentine Islands are responsible for these records.

Hatherton and Evison (1962) have considered one mechanism for Antarctic earthquakes from the standpoint of energy release in strained ice masses. By making measurements on a typical record, it is possible to calculate the energy required to cause this earth movement.

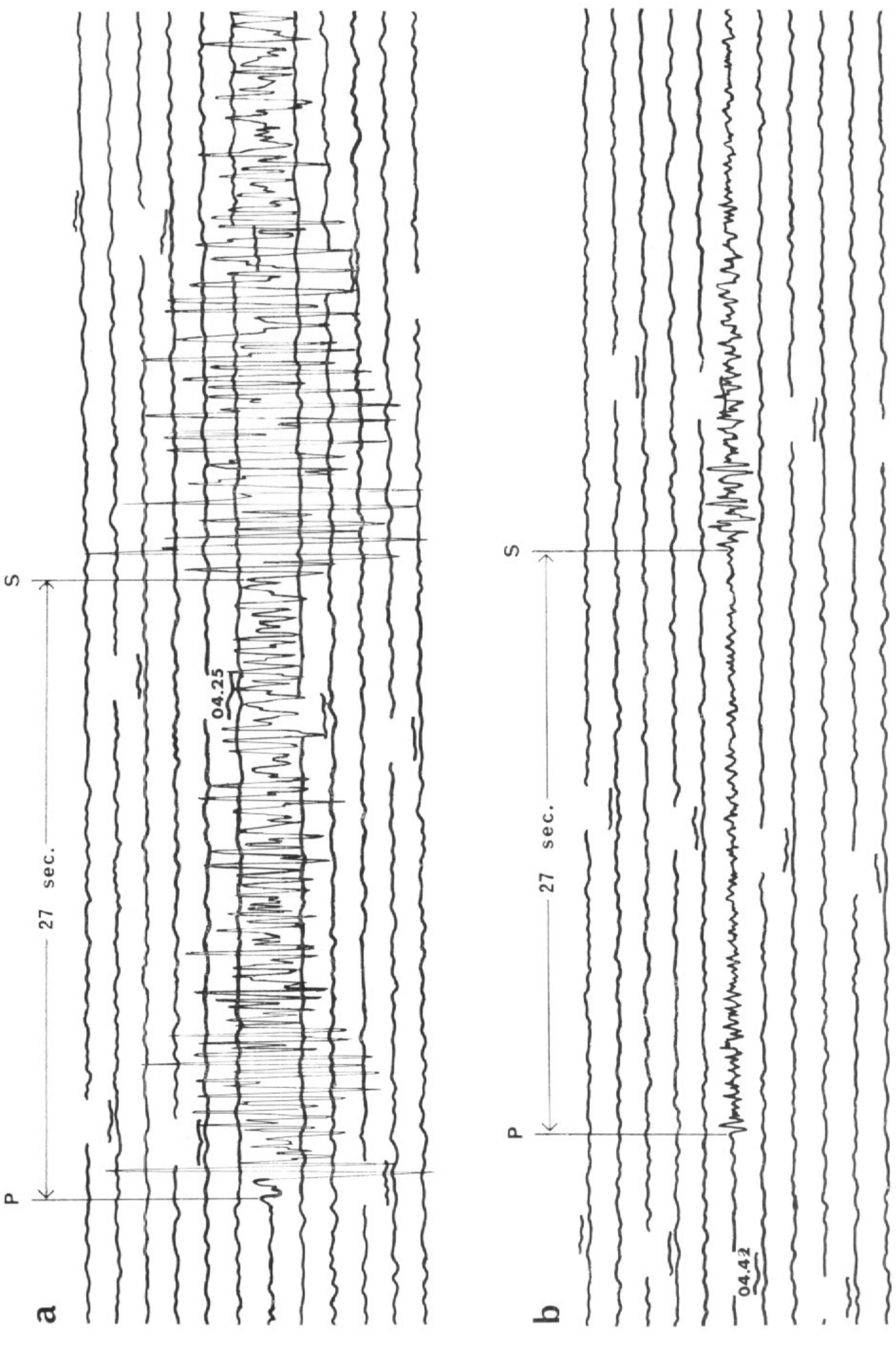

Fig. 2a and b. Seismogram from Argentine Islands; north–south component for 18 November 1962.

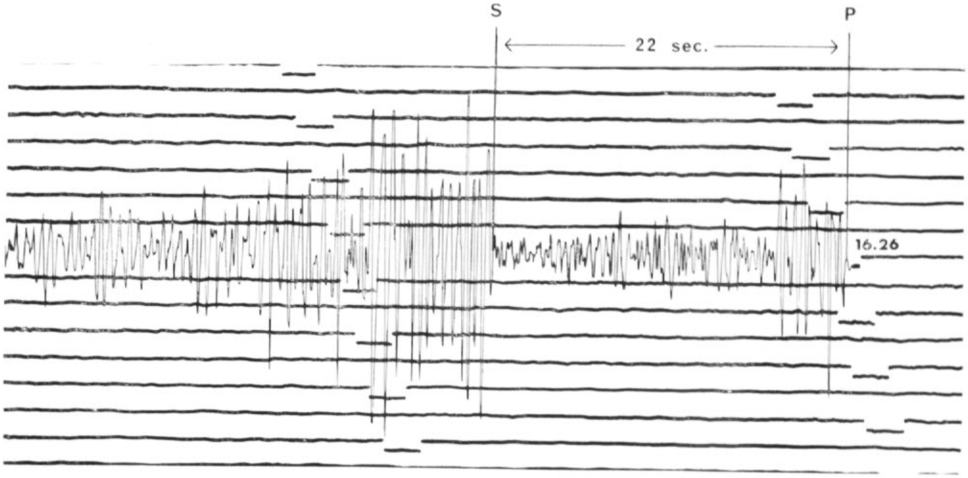

Fig. 3. Seismogram from Argentine Islands; vertical component for 1 July 1960.

Bullen (1953, p. 229) has given the energy of S_g at range Δ resulting in an earth movement c of period τ as

$$E_{S_g} = (2\pi H r_0 \sin \Delta)\,(2\pi^2 \rho\, L c^2 \tau^{-2})$$

$$= \pi \rho\, H L V_m{}^2 r_0 \sin \Delta,$$

where H is the thickness of the granitic layer, ρ is the density, L is the length of the wave train, r_0 is the radius of the Earth, V_m is the maximum velocity of the earth movement. Taking $H = 15$ km., $\rho = 3\cdot3$ g. cm.$^{-3}$ and $r_0 = 6{,}370$ km., measurements from a typical record give $V_m{}^2 = 0\cdot79 \times 10^{-6}$ cm.^{2} sec.$^{-2}$ with $\Delta = 3°$ and $L = 800$ km., i.e.

$$E_{S_g} = 2\cdot5 \times 10^{16} \text{ erg.}$$

This corresponds to a magnitude 3 to 4 earthquake.

To produce this seismic wave energy the mass of ice falling 100 m. would have to be in excess of 10^{10} g., i.e. a volume equivalent to a 100 m. long terrace of houses.

Considering iceberg calving, the strain energy released when a volume V of ice is strained to breaking is given approximately by $V = \frac{4\mu E}{S^2}$ (Bullen, 1953, p. 244), where μ is the rigidity and S is the shear strength having values 10^{10} dyne cm.$^{-2}$ and 10^7 dyne cm.$^{-2}$, respectively for ice. This leads to a value for V of 10^{13} cm.^{3}, which is approximately a 30 m. cliff of area 10 km.^{2} becoming detached. This is only really possible in regions where there are extensive ice shelves.

Thus it seems unlikely that either of these latter solutions explain the recorded phases and so it must be concluded that minor seismic tremors do occur in this area.

(b) The interpretation of Fig. 5 caused some difficulty. The Argentine Islands seismograms rarely detect near reflections, *pP* or *sP*, from any earthquake and so this solution for the Bouvetøya shock of 2 October 1958 was originally overlooked. A similar record was obtained for an event of 9 June 1959. The time intervals between the two phases were 31·6 and 30·4 sec., and it was not impossible that the second waves were channelled waves. The travel-time for the second waves was 364 sec. and the epicentral distance 2,900 km.; this requires a velocity of 7·97 km. sec.$^{-1}$. Recent seismic refraction measurements (Cox, 1964; Griffiths and others, 1964) indicate high-velocity layers up to 7·0 km. sec.$^{-1}$, while Officer and others (1957) have explained a velocity layer of 7·6 km. sec.$^{-1}$.

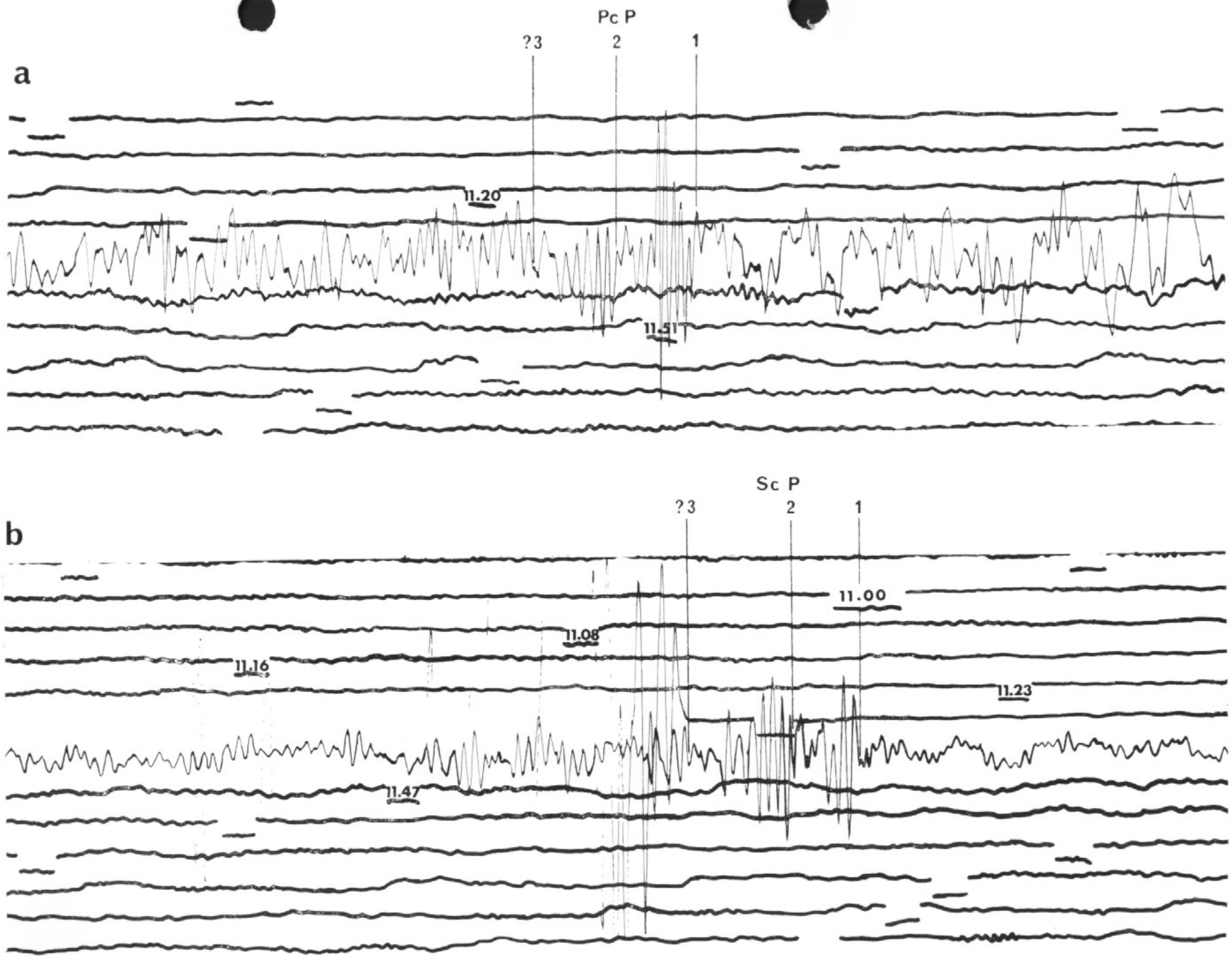

Fig. 4a and b. Seismogram from Argentine Islands; vertical component for 8 September 1961.

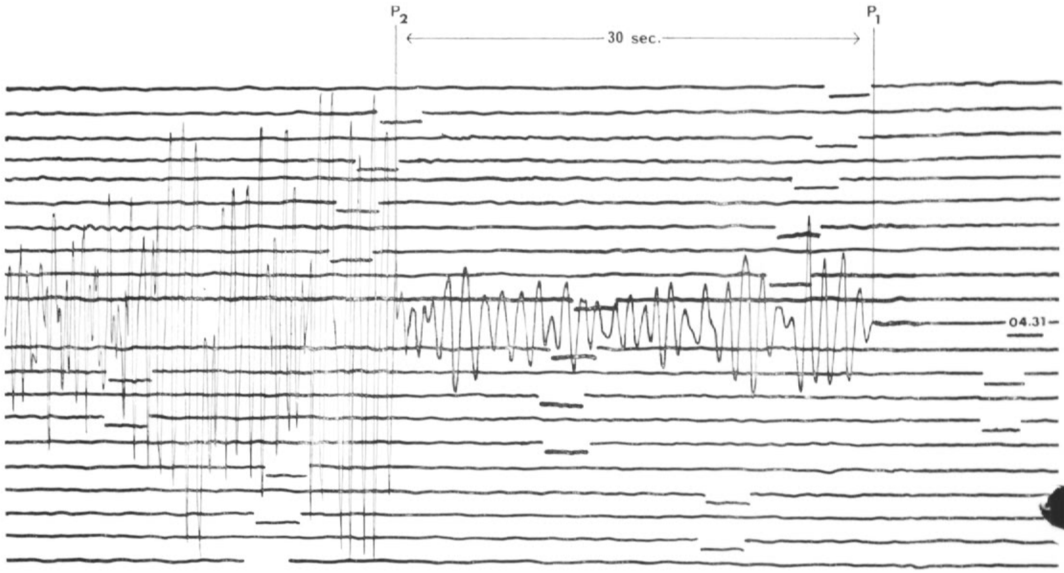

Fig. 5. Seismogram from Argentine Islands; east–west component for 2 October 1958.

However, the interpretation of the phase as *pP* or *sP* would in general be more likely, the former indicating an earthquake depth of 160 km., and the latter one of 80 km. A sub-normal depth has not been attributed to this shock by provisional data from the U.S. Coast and Geodetic Survey or B.C.I.S., while the present computation would not show other than normal depth.

The main difficulty in the interpretation lies in explaining the very much larger movement of the second phase. To support the suggested solution of *sP*, it is known that more than half the energy of the vertically polarized part of *S* can be transferred to *P* on reflection at a free boundary (Jeffreys, 1959, p. 31). In these examples, the angle of emergence of the ray of the point of reflection is about 69° and the reflected *P* energy recorded could well exceed the *P*-wave energy transmitted directly to the observatory.

(c) Four manifest examples of multiple core-reflection phases have been observed; one of these is reproduced in Fig. 4. The phases occurred after single events of intermediate and deep origin. *ScP* was observed to be multiple on all occasions, while *PcP* was multiple from one shock. Details of the analysed records are given in Table IV.

In a recent paper, Caloi (1961) considered, among other things, multiple *ScS* observations and he attributed them to reflections of the emergent ray in the layers below the recording station. The reflections considered are as shown in Fig. 6. These times correlate with refraction measurements giving the velocity in each layer as 3·8, 3·7 and 3·6 km. sec.$^{-1}$, respectively.

TABLE IV. MULTIPLE CORE-REFLECTED PHASES

Date	*Time* (hr. U.T.)	*Epicentre* *Locality*	*lat., long.*	*Depth* (km.)	*Phase arrivals* (sec.) *After PcP*	*After ScP*
1.9.1961	00.09	South Sandwich Islands	59°S., 27°W.	131		4 8
8.9.1961	11.27	South Sandwich Islands	56°S., 27°W.	125	4 9	3½ 9½
19.8.1961	05.10	Brazil	10°S., 71°W.	650		6 12
31.8.1961	01.57	Brazil	11°S., 71°W.	630		6 12

Attempts have been made to obtain some tentative figures for the layer depths and velocities for the region near the Argentine Islands using the observed delay times in Table IV. However, no unique solution was possible even when the different ranges and hence different emergent angles of the rays were taken into account. It may eventually be possible to use these results in a critical analysis of seismic refraction work.

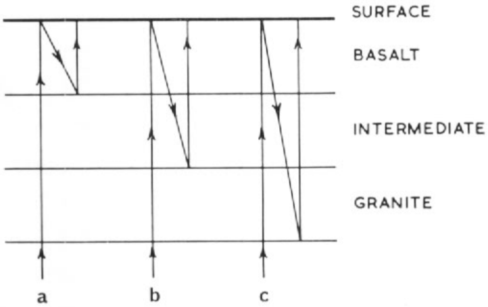

Fig. 6. Reflection of seismic waves in a layered crust.

Path	*Thickness* (km.)	*Time delay* (sec.)
a	8·5	4·5
b	22	12
c	36	20

The Halley Bay records were discontinued in 1960 because of the difficulty in reading true seismic events from a background of local microseisms. Particularly on the horizontal channels, these microseisms took the form of fairly continuous 2-sec. waves. These are possibly similar in source to the air-coupled waves associated with flexural movement reported by Hatherton and Evison (1962) from the Ross Ice Shelf; they do not require strain energy alone for initiation, small tidal movements are sufficient. It is possible that the occasionally observed large amplitude of the *P* movement is caused by an ice-shelf phenomenon similar to the *Untergrundsfaktor* referred to by Gutenberg (1929, p. 193).

Frequent groups of phases not inconsistent with shocks originating at the junction of the ice shelf with the continental mainland were observed.

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