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Reprinted from the Review
GEOFISICA PURA E APPLICATA - MILANO
Vol. XII (1948), Fasc. 3-4

ON TWO EXPLOSIONS IN DANISH WATERS IN THE AUTUMN OF 1946

by I. LEHMANN (*)

Summary — In ammunition sunk into the sea off the Danish coasts two large explosions occurred. Records of the resulting shocks were obtained at København, Lund and Göttingen. These are discussed and compared with those of some mine-explosions and of the earthquake of Oct. 31. 1930, 2 h. Some macroseismic evidence is given and the methods available for the evaluation of the energy of the shocks are discussed.

When the German Occupation Forces left Denmark in May 1945 they left behind a considerable amount of ammunition. The Allied Forces caused a large part of this to be sunk into the sea. About 15000 tons were sunk North of Sjælland, off Raageleje. It was divided into 15 heaps, each of which was marked by a buoy. The distances between them were a few hundred meter. The smallest distance from the coast was about 7 km. Another 20000 tons were sunk in a bay, Kalövig, on the so-called Koraldyb. The heaps were laid out on two lines. The distances from the coasts on either side were here much shorter, in one place only about 1 km. The town of Aarhus was less than 10 km away.

On Sept. 20. 1946 an explosion occurred in the ammunition field North of Sjælland (⁸) and on Oct. 22. 1946 one occurred in Kalövig. Smaller explosions occurred in the latter field on July 15. 1947 and Febr. 6. 1948. It is the first two explosions that are the main object of the present investigation. They both caused « earthquakes » that were felt up to considerable distances and that were also recorded by seismographs.

On both occasions enormous water-columns arose above the places where the explosions occurred. These were observed, and some of the sight-lines indicated by the observers were so well determined that the explosion centres could be determined with an accuracy that is probably not much less than 1 km. The first centre was at 56° 9′ ½ N, 12° 6 E, the second at 56° 13′N, 10° 20′E. The depth of the sea is at both places 15-20 m.

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Both explosions were recorded at the seismological stations of København and of Lund and also, but quite faintly, by the 17000 kg seismograph at Göttingen.

The short-period Benioff Z seismograph at København reacted so strongly to the first shock that the greater part of the record was unreadable. The second shock was also too strong to give a clear Benioff Z record, but in both records the first onset was very clear. The København Wiechert records are reproduced in Figs. 1 and 2 (See pp. 147 and 149), the first in their original size, the others enlarged 5 : 1. The Lund records have not been reproduced since they were not very clear.

1946 Sept. 20. $3^h24^m14^s$ ($14^s.4$) 56° 9′ ½N, 12° 6′E

Station	Δ km	Component	Arr. time m s	Transm. time s	Phase	O—C s	Period s	Velocity km/sec.
København	57	BZ	24 26.6	12.0	*Pg*			
		N,E,Z	32	18	*Sg(P*)*			
		N,E,Z	40	35	*Ls,1*		1	1.6
		N,E,Z	53	39	*Ls,2*		1	1.5
Lund	86	NE,NW	24 33	18	*Pg*	1		
		NE	40	25				
		NW	45	30	*Sg*			
		NE	46	31				
		NE	52	38	*Lg*		1²/₃	2.3
		NE,NW	54	40				
		NE	69	55	*Ls*		1¹/₃	1.6
Göttingen	531	N	25 27.8	73.4	*Pn*	0.9		
		E	30.1	76				
		N	37.0	83	*(P*)*			
		E	46.1	92				
		E	26 21.6	127	*Sn*			
		N	22.1	128				
		N	28.1	134				
		E	34.6	140	*(S*)*			

1946 Oct. 22. $15^h9^m15^s$ ($15^s.0$) 56° 13′N, 10° 20′E

Station	Δ km	Component	Arr. time m s	Transm. time s	Phase	O—C s	Period s	Velocity km/sec.
København	145	BZ	9 40.4	25.2	*P*			
		N,E	53	38	*P**			3.8
		N,E	59	44	*S*			
		N,Z	10 42	87	*Ls,1*			1.7
		N,Z	47	92	*Ls,2*			1.6
Lund	186	NE,NW	10 11	56	*S*			
Göttingen	520		10 20	65	*Pn*			
			33	78	*(P*)*			

The readings are given in the table. Professor Bartels kindly sent me the readings of the Göttingen records. A copy of those of Sept. 20. was received here, but they were difficult to read. The original records had been blurred somewhat because skellak was not available.

Originally the records were interpreted by means of H. Jeffreys' tables for near earthquakes [1]. Since then the Heligoland explosion has taken place and times for first onsets have been obtained that differ markedly from those of H. Jeffreys. Mr. P. L. Willmore has kindly placed them at my disposal and they have been used here. For later phases, including *S* phases, time-curves could not be very well determined from

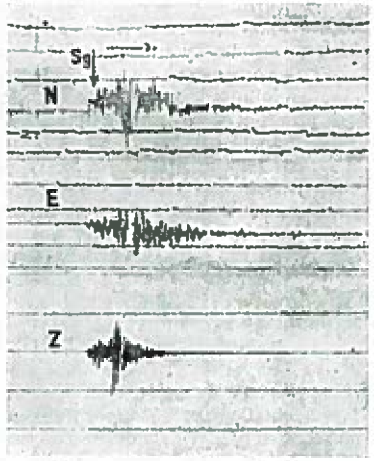

Fig. 1

the Heligoland records. They have been interpreted partly by reference to the Jeffreys tables, partly by appearance.

The Benioff Z recording speed is 60 mm/min, and its onsets were read to 1/10 sec. The accur cy may be slightly smaller, but this is of no consequence, since in the readings of later phases and in those of Lund an accuracy of 1 sec. can hardly be claimed.

Before the Heligoland transmission times were combined, a small reduction was applied to each station according to its subsoil. For København this reduction was $0^s.2$. It should probably be about $0^s.5$ for Lund which rests on moraine deposits. The explosion on Sept. 20. was 57 km from København and the reduced transmission time to be expected by comparison with the Heligoland times is $12^s.0$. The instant of detonation is therefore taken to be $24^m14^s.4$ and the reduced transmission time to Lund 18^s. This is 1^s longer than was expected from the Heligoland results, but

P at Lund is quite small and the record is not clear enough to allow much significance to be attached to the residual. At Göttingen no reduction was applied. The first onset, Pn, was 1ˢ after the time prescribed by the Heligoland results and 4ˢ before the time deduced from JEFFREYS' tables. The agreement with the Heligoland times is as good as can be expected from the quality of the records.

At first sight it does not seem very obvious where Sg should be read at København, but closer inspection of the N record shows that it sets in where it is marked. There is a corresponding increase of movement in the other records, but no clear onsets. It appears that the N component did not function well. It was found afterwards that a tiny spider had spun a hardly visible web across some of the moving parts. This probably prevented the pen from returning to zero position after the first swing. Had it done so, Sg would undoubtedly have been more conspicuous. The phase stands out much more clearly in the Lund records, especially in the NW component, but the onsets are not quite distinct.

At København, Sg is followed by waves that appear to be surface waves. On the E record a period of 5 sec. prevails, but it seems to underlie the short-period movement from the very beginning of the record. On N and Z the movement is less regular and is probably partly due to body waves in the sediments. Onsets can be read in this part of the records, but it does not seem reasonable to put any interpretation on them. Later increases in the movement are due to surface waves of velocities 1.6 km/sec. and 1.5 km/sec. The period of the largest waves is about 1 sec.

At Lund L is, on the whole, larger than at København in spite of the epicentral distance being greater; it also shows greater regularity. On the NE record there is an onset at 24ᵐ52ˢ. At 24ᵐ54ˢ large movement sets in on NW and it continues for about a minute. On the NE record the movement increases 24ᵐ54ˢ, but remains smaller than on the other record until a large increase takes place at 25ᵐ9ˢ. A period of 1 ²/₃ sec. prevails throughout, but it has a smaller period superposed on it. The azimuth of the epicentre is approximately NW; therefore the earliest surface waves on the NE record are probably LOVE waves reaching down into the granitic layer and those immediately following them corresponding RAYLEIGH waves. The later increase of movement seems to be due to surface waves confined to the sedimentary layers since the corresponding velocity is only 1.6 km/sec., but no conspicuous change in the character of the movement takes place.

On Oct. 22. the onset read on the København Benioff Z record is 9ᵐ40ˢ.4. It is abrupt and very large as it is also on the Wiechert Z record of Fig. 2 b. It was originally interpreted as Pg since Pn at that distance, 145 km, was expected to be quite small and apt to get lost and followed by a large Pg. It was seen, however, in the Heligoland records that this is not necessarily so and that Pn may well be the largest phase in the records. The Heligoland time for Pn at a distance of 145 km was 25.ˢ2 and this was used when the explosion time was determined, but it is open to doubt whether the phase is actually Pn. There is no proper check on it since P is missing at Lund and is extremely weak at Göttingen. The velocities calculated for later waves are not altered appreciably if the phase is taken to be Pg.

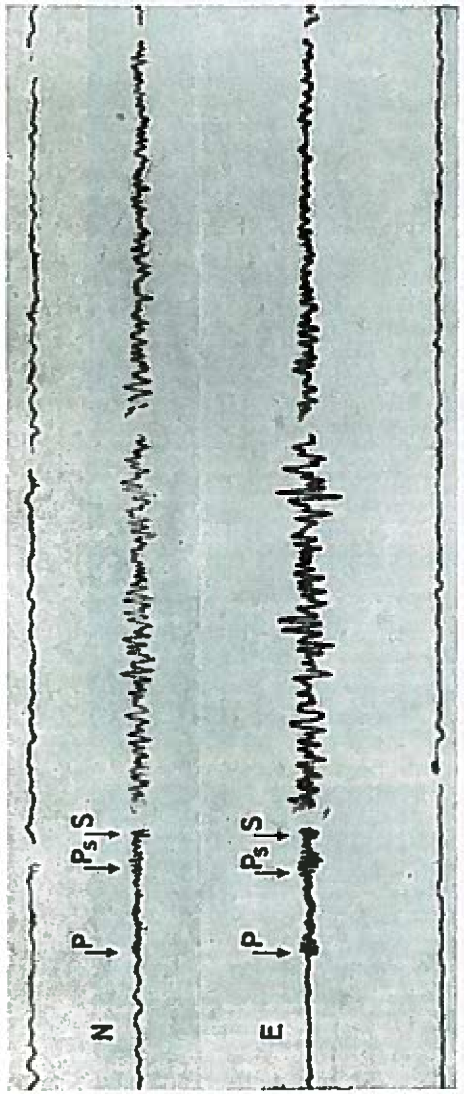

Fig. 2a

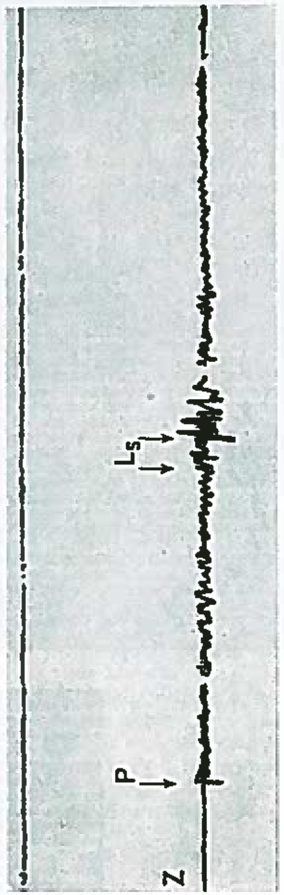

Fig. 2b

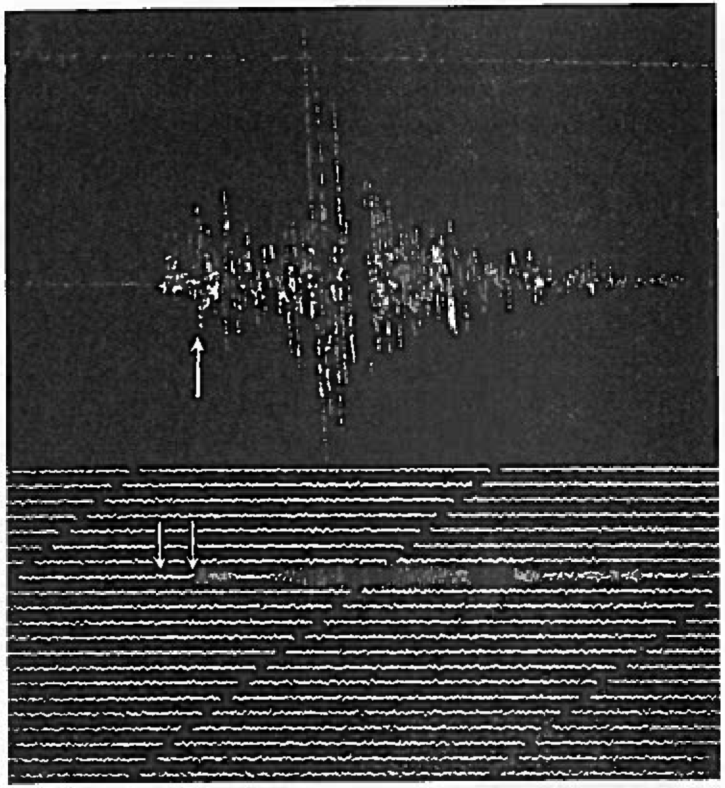

Fig. 3

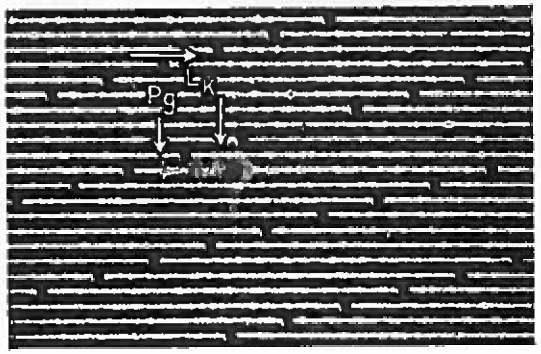

Fig. 4

There is a distinct phase in the København Wiechert E record at 53ˢ and it is traceable also on N. It is very similar in appearance to the *P* phase and has been interpreted as *Pg*. Its mean surface velocity is 3.8 km/sec., which is quite an acceptable value in view of the fact that the velocity in the chalk is about 2.4 km/sec. and that velocities of about 4 km/sec. have been found below.

The phase read on the N and E records at 59ˢ is quite conspicuous on both, but unfortunately the minute gaps that occur 1ˢ later conceal the character of the movement. After the minute gaps the periods are longer than in the first part of the records, and the phase has been interpreted as an *S* phase, *Sn* or *Sg*. The times of these phases have not been very definitely established from the Heligoland explosion records. The successive movement seems to be due to surface waves. The period is about 2 ½ sec., but there are shorter periods superposed. The Z component is at first negligible, but then increases. The waves, therefore, are probably LOVE waves reaching down into the granitic layer followed by RAYLEIGH waves. The vertical movement subsides while rather large movement appears on the horizontal component records. It is irregular, but a period of about 1 ½ sec. seems to be present. The movement may be due to LOVE waves confined to the sedimentary layers. It is succeeded by movement having a large vertical component; there are onsets at 10ᵐ42ˢ and 47ˢ corresponding to velocities of 1.7 km/sec. and 1.6 km/sec. This movement may be interpreted as RAYLEIGH waves confined to the sedimentary layers in accordance with what was done for Sept. 20. The vertical component is rapid, but quite irregular. On the horizontal component records there seem to be periods of about 5 sec. underlying smaller periods.

The explosions here spoken of were very large ones. About 2000 tons of ammunition seems to have exploded on the first occasion and about 1000 tons on the second. But a great many other, small explosions have been recorded by the Benioff seismograph. During and after the War numerous mines exploded in Danish waters near enough to be well recorded. On very few occasions, however, was it known where the explosions occurred, and the exact time was never observed. Many of the records showed great similarity, but it did not seem possible to attempt any interpretation before the location of some of the explosions were known.

An opportunity arose when an unusually large and well recorded explosion occurred on Dec. 18. 1946. It became known that a ship had been wrecked by it and the Company kindly informed us that its position was 55°16'.6 N, 12° 53'.4 E. The distance to København is 52.2 km and as this is only 5 km shorter than the distance on Sept. 20., an attempt could be made to interpret the record of Dec. 18. by comparison with that of Sept. 20. There is however the difficulty that the Benioff Z record of the latter date must be compared with the Wiechert Z of the former, for the Wiechert record of Dec. 18. was so small as to be almost unreadable and the Benioff Z record of Sept. 20. was too strong to be of any use. The magnification of Wiechert Z does not vary greatly for waves of such period as those here concerned whereas the Benioff Z magnification does. It has a maximum for a period of about ½ sec. and it falls off rather steeply on either side. It is undoubtedly partly due to this fact that the two diagrams of Fig. 3 bear little resemblance to each other. The Wiechert record has been so enlarged as to obtain approximately the same time-scale as the Benioff record.

1946 Dec. 18. $2^h53^m47^s$. 55° 16'.6 N, 12° 53'.4 E

Station	Δ km.	Component	Arr. time m s	Transm. time s	Phase	Period s	Velocity km/sec.
København	52.2	BZ	53 58	11	*Pg*		
		»	64	17	*Ps*		3.1
		»	75	28	*Ls*		1.9
		WN	78	31			1.7
		BZ, WZ	82	35			1.5
		» »	88	41			1.3
		BZ, WZ, WN	109	62	*Lk*	½	0.85

The table contains the readings, the interpretations put upon them and the velocities derived.

The first phase read on the BZ record is very small, but on the original record it is quite clear. It has been taken to be *Pg*. The Heligoland time for *Pg* at this distance is 11 sec. and the time of the explosion is therefore taken to be $2^h53^m47^s$. *Pg* is followed 6 sec. later by a group of larger oscillations of very short period. The onset is quite clear. The mean surface velocity is 3.1 km/sec. and the phase is probably *Ps*. In view of the smaller distance, the waves would not have penetrated so deeply as those recorded on Oct. 22., which explains that the mean velocity is smaller. The oscillations following the *Pg* onset have a duration of about 8 sec. and are possibly due to waves passing through different layers or partly to refracted waves. When the record is compared with the WZ record of Sept. 20. it is found that the onset marked by the arrow in the latter record in Fig. 3 is likely to be *Ps*. It occurs at the same time as the phase on N that was interpreted as *Sg*, but the two waves are due to arrive at approximately the same time.

Small waves, to all appearance surface waves, arrive at 75^s on Dec. 18. Their velocity is only 1.9 km/sec. The explosion therefore does not seem to have been strong enough to set up surface waves that reach down into the granitic layer. Larger waves set in at 82^s and again at 88^s. These are discernible also on the Wiechert records; they make their appearance some seconds earlier on the N record, about 78^s. They are irregular, but seem to contain oscillations of a period of about 1 sec. The onset at 82^s evidently corresponds to the onset of the largest waves in the WZ record of Sept. 20. There is no second group on this occasion, but large oscillations may have been lost in the minute gap. The appearance of two wave-groups in the record of Dec. 18. is not «accidental». In a great many mine-explosion records two wave-groups follow closely upon each other as in the record here considered. They are more or less pronounced, sometimes much larger as compared with the other wave-groups of the record.

They are about to die down when a group of much larger surface

waves sets in abruptly. The period is about ½ sec. The Benioff seismograph has maximum magnification for this period wherefore the predominance of the wave-group may be somewhat exaggerated. But there obviously is present a well-defined group of shortperiod and quite regular waves. The onset is at 109^s, the corresponding velocity being 0.85 km/sec. B. BROCKAMP ([17]) found surface waves with approximately this velocity in the chalk that probably extends as a deep and unbroken layer over the region here considered. It may, nevertheless, be difficult to explain how surface waves characteristic of that layer could travel as a distinct group. It is a phenomenon that has been repeated in numerous mine-explosion records obtained at København, and it seems to be characteristic of the region. The explosion of Sept. 20. which occurred in a different region did not give rise to it. The Wiechert vertical seismograph did not record it as is seen in Fig. 3. On the Benioff Z record the movement is still very strong where it could be expected, but smaller than in the preceding part of the record.

Fig. 4 shows a record of a mine-explosion that obviously occurred at a much smaller distance from København than the one of Dec. 18. Except for *Pg* it has the same characteristic wave-groups. If they are interpreted correspondingly the distance is found to be about 12 km.

Records of a different pattern, evidently due to explosions that occurred at much greater distances, have also been obtained and interpretation has been attempted. One of them is shown in Fig. 5. There are several exactly like it wherefore it is evidently due to a single explosion and not to a series of them as might be supposed. The phases marked in the record are interpreted as *P* (*Pn* or *Pg*), *Ps*, *Ls* and *Lk*, and if this interpretation is correct the distance may be taken to be slightly greater than 100 km. The distance cannot be determined accurately since the transmission times of the later phases in the record are not accurately known.

It is not known where these distant explosions occurred, so it could hardly have been on Danish soil or in Danish waters. The fact that they were recorded shows that there is a possibility of investigating travel times up to distances of about 100 km experimentally, by means of explosions in the sea. This is important since earthquake results do not have the desired accuracy.

It is interesting to compare the records of the explosion on Sept. 20. 1946 with those of a small earthquake that occurred on Oct. 31. 1930. 23^h (Nov. 1.

Fig. 5

M.E.M.T.). The Wiechert records are shown in Fig. 6. The surface waves that form the main part of the explosion records are in this case small or almost absent whereas the *P* and *S* waves are large. This indicates focal depth and the macroseismic observations confirm it, for the earthquake was felt out to a distance of about 200 km in spite of the fact that the intensity hardly anywhere exceeded 5 on the international scale. If the results obtained by B. GUTENBERG and C. F. RICHTER ([1]) for California apply here, the depth should be 60-70 km.

The earthquake was felt in København and had an intensity of 4-5 there. The explosion shock was not felt, and yet the records of the latter

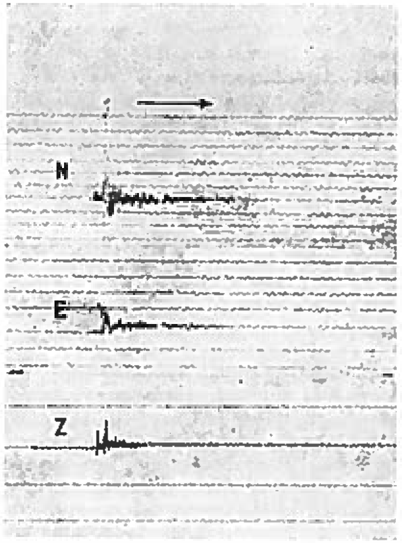

Fig. 6

are on the whole the stronger. The *S* amplitude of the earthquake is considerably larger than any movement caused by the explosion, but it is probably chiefly owing to the high velocity of both *P* and *S* waves that the movement was felt so strongly.

The time-curves of Fig. 7 for the *P* and *S* waves were constructed on the assumption of a focal depth of 60 km and the existence of two crustal layers as determined by H. JEFFREYS [([5]), p. 571.], covered by a sedimentary layer, i. e.

sediments of thickness	2 km	P velocity	3.7 km/sec.
granite — —	15 km	— —	5.6 —
interm. layer —	18 km	— —	6.5 —
lower layer —		— —	7.8 —

The *S* velocities were obtained by division of the *P* velocities by 1.7. The fact that these assumptions may be considerably in error is, as will appear, of little consequence to the deductions that follow.

Soon after the occurrence of the earthquake an attempt was made to determine its epicentre ([7]). At København *S-P* is 7 sec. or slightly less, but hardly readable with greater accuracy than 1 sec. Taking the time-curve to be correct, the epicentral distance may be anything from 10 km to 25 km. If the depth is smaller than assumed the distance may be greater. Originally the epicentral distance was taken to be 50 km. The notion of deep earthquakes was new at the time and although it was obvious that

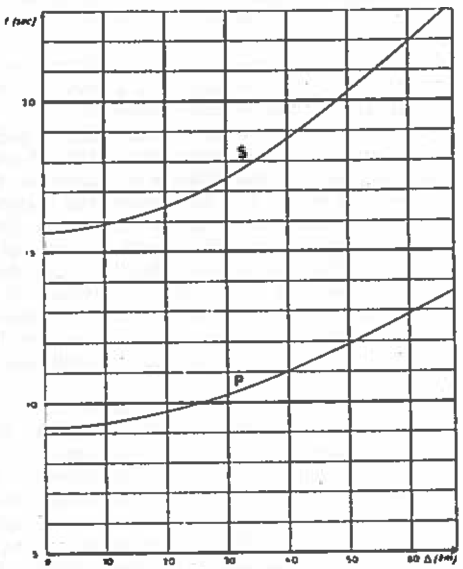

Fig. 7

the shock was not a surface shock, it was not considered to be so deep. Lund recorded *P* 1 sec. later than did København and its epicentral distance was taken to be 6 km greater. It is now seen that the difference in the epicentral distances is far greater. If that of København is 25 km, say, that of Lund must be about 40 km. The horizontal components of the first *P* movement are small at both stations wherefore it is not possible to determine the azimuth of the epicentre with much accuracy. It is approximately SSE at København. It follows from these considerations that an accurate determination cannot be obtained and that the uncertainty can hardly be evaluated. 55°.5N 12°.7 E is likely to be a better approximation than the originally determined point 55° 17′ N 12° 46′ E.

The earthquake was recorded at Hamburg, Göttingen and Jena (see I.S.S.), but the records evidently are weak and the P observations are not consistent enough to be of any use for the determination of the epicentre.

The point 55°.5 N 12°.7 E lies on the extension of a fault line passing through København ([13]), but in consideration of the depth of focus it does not seem plausible that it is associated with this fault. It may have some relation to the Fenno-Scandian zone of disturbance that dips down along a line passing through Skaane in a northwest-southeasterly direction [see e. g. ([8]), p. 104] and that undoubtedly extends to some distance underneath the chalk.

It was not found possible to make detailed macroseismic observations of the areas shaken by the two explosions. For that of Sept. 20. newspapers were the chief source of information; a few inquiries were made on the North coast of Sjælland and some informative letters were received [see ([6])]. Inquiries were made by K. Olesen with a view to determine the boundary of the area shaken by the second explosion.

The conditions for macroseismic observations differed widely on the two occasions. The first explosion occurred about 7 km off a coast that, being a sea-side place, has but few inhabitants at that time of the year, whereas the second one took place in a bay where the distances to the coast on either side were much smaller and the distance to the centre of the big town Aarhus was about 11 km. As a result the second shock was felt more strongly and attracted far greater attention than the first. But it was probably less well observed at the distances where it was weak, for it occurred at 4 p. m. when few people are completely at rest and undisturbed, whereas the first explosion occurred at half past five in the morning. Those who lay awake in bed or slept lightly would feel the shock also where it was quite weak.

Some minor damage was caused by the shock of Oct. 22., primarily in the near surroundings of the explosion point, but also in the town of Aarhus. One or two old chimneys fell, some tiles were thrown off the roofs, plaster cracked and fell, some clocks stopped and pictures fell down from the walls. The maximum intensity on the international scale was about 6.

Most of the newspaper reports came from Aarhus and naturally the impression was gained of its having been comparatively strong where it was felt by so many. The alarm it caused was perhaps greater than would have been the case had not Aarhus on several occasions been afflicted by disastrous events during the time of the German Occupation as, e. g., when a ship carrying ammunition exploded in its harbour on July 4. 1944. A number of explosions succeeded each other with terrific noise and produced a blast strong enough to burst all window panes within a vast area; at great distances it still threw people off their feet. A shower of granates, fortunately unloaded, fell upon the town. There were a great many victims. Therefore, when the shock of Oct. 22. 1946 was first felt, it caused alarm in expectation of what might follow. At a concert the audience arose and began to leave the theatre. There were many other instances of people fleeing into the open. But nothing followed. The blast which caused so much damage in 1944 and which in most explosions is the chief cause of damage, was in this case absent or very slight. This is due to the fact

that the explosion took place on the bottom of the sea. The energy then partly goes into the ground where elastic waves are generated and partly is used up in raising a column of water to great height. An explosion taking place on the surface displaces the air instead and causes a sweeping blast.

The explosion of 1946 was hardly heard in Aarhus. In the nearer surroundings a deep, rumbling noice was heard and in the country it seems somewhere to have been heard to great distances. In Aarhus most people who were indoors felt the shock strongly and there was a rattling of windows and doors and a creaking of walls. In the streets, no one seems to have heard or felt anything.

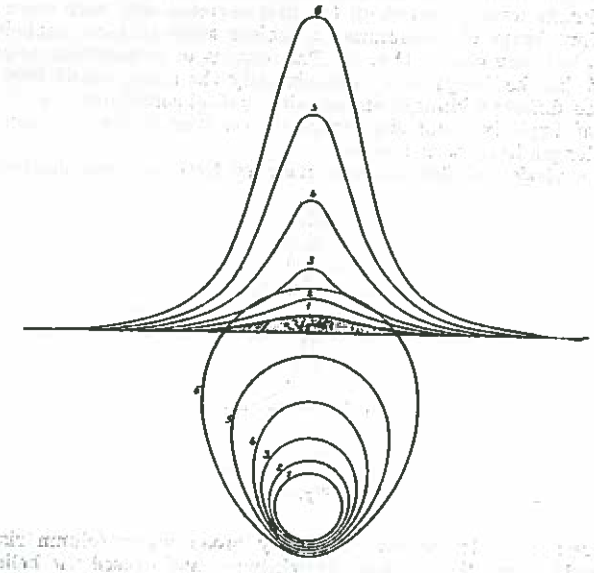

Fig. 8

As a result of the inquiries made by K. Olesen it was found that a circle of radius 22 km could roughly be taken as the boundary line of the macroseismic area. There were a few instances of the shock having been felt at slightly greater distances by persons who were at rest.

The shock of Sept. 20.1946 was felt all along the North coast of Sjælland. In the parts nearest the explosion point the houses were severely shaken. Those who were still asleep were awakened and ran out to see what was happening. The maximum intensity seems to have been about 6 on the international scale. Trustworthy reports were received of the shock having been felt at a distance of about 40 km.

Owing to the scantiness of macroseismic evidence and to the difference in the conditions under which the observations were made no conclusive result can be arrived at when the strength of the shocks is compared. However, the first shock was observed at a distance of 40 km and in spite of careful inquiries the macroseismic area of the second could not be extended beyond about 25 km. The first shock, therefore, is likely to have been the stronger, and since the explosions took place at about equal depth and on seabottoms of similar structure, i. e. chalk covered by a thin layer of sand, the first explosion was probably the stronger.

Some confirmation of this result is obtained from the fact that two water columns were observed on the first occasion and only one on the second. Two heaps of ammunition therefore seem to have exploded on Sept. 20., but only one on Oct. 22. The amount of ammunition originally contained in the heaps was approximately the same, about 1000 tons, there were different kinds of ammunition, not all containing the same but amount of explosive, and after more than a year in the sea some of it may no longer have been active.

The explosion of Oct. 22. was observed from so close quarters that

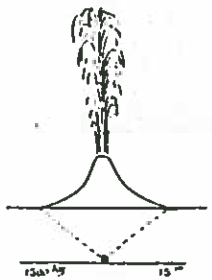

Fig. 9

the impression made by the excessively broad water column rising to great height above the sea was overwhelming and caused the belief that the total amount of ammunition sunk in these waters had exploded. This, however, is quite out of the question. It was, as mentioned previously, laid out on two lines. Each of the nine heaps of one line were marked by buoys that were all there after the explosion. On the other line the end-points only were marked. The explosion point as determined in this paper is close to the middle point of this line. The explosion took place at a depth of about 15 m. A single mine exploded at this depth gives rise to a broad water column as illustrated in Fig. 8 [(9), p. 174] where successive stages in its development are indicated. Sometimes it breaks and a Geysir is formed as seen in Fig. 9 [(9), p. 236]. The ammunition contained in a heap would necessarily be spread over an area of some extension. It is therefore easily understood that the water column would be very broad. The estimates of the height of the water column observed vary greatly; about 500 m. is a probable value.

Comparison of the Göttingen records of the two shocks gives support to the conclusion that the first shock was the stronger. The record of the first shock was weak, but that of the second so weak as to be hardly readable. The distances were very nearly the same, but that of the last explosion slightly smaller than that of the second.

It might be attempted to evaluate the seismic energy of the shocks of Sept. 20. and Oct. 22. and compare with the results for earthquakes. There are various ways of doing so, but they all give very uncertain results.

The amount of ammunition that exploded on Sept. 20. was probably about 2000 tons. According to a personal communication by Professor E. C. Bullard its content of explosives may have been anything between 200 t. and 1500 t. It seems to have been mixed ammunition, and if the amount of explosives is taken to be 700 t., the energy released would be about 10^{19} erg. Very little seems to be known about how great a proportion of this goes into elastic waves. Results of some accuracy have been obtained with floating mines (11), but they are hardly applicable here. It is well known from seismic prospecting that the surroundings of the explosive greatly influence the energy of the elastic waves generated.

It has been attempted to evaluate the total kinetic energy released by an explosion in the sea by means of the height of the water column raised (9), but the results have great uncertainty.

The energy of a shock has often been calculated from seismic records, but I shall refrain from doing this for the following reasons. The Benioff records cannot be used since the movement was too fast for clear recording. Besides, there are no horizontal component records, only a vertical one. The Wiechert records are available, but the magnified records in parts show just a blurr in which lines cannot be separated, and, where comparison with the Benioff records is possible, it is seen that the Wiechert seismograph failed to record the very fast movement recorded by the Benioff seismograph. The Galitzin instruments naturally failed to record the short-period movement. It is therefore believed that the records are not complete enough even for a rough evaluation of the energy of the movement at the Köbenhavn station. The difficulty of evaluating the total energy of the shock by means of that of the movement at a single point is clearly recognized when the records of Lund and Köbenhavn are compared. On Sept. 20. the distance to Lund was 86 km, that to Köbenhavn only 57 km, but nevertheless the records of Lund are the stronger.

As mentioned above, it is not known how great a proportion of the energy released by an explosion goes into elastic waves, but when the explosion takes place on the bottom of the sea, the proportion is known to be greater than when it takes place on the ground. Evidence of this was obtained during the War; mines exploded on the ground were not recorded whereas mines exploded on the bottom of the sea at much greater distances were recorded by the Benioff Z seismograph at Köbenhavn. The bombardement of the ship-yard Burmeister and Wain in Köbenhavn on Jan. 27. 1943 gave a particularly convincing proof. The bombs dropped were all of the same weight, 500 lb. Two very large explosions took place during the bombardement, both caused by several bombs bursting simultaneously. During the following two days and nights, several single bombs burst, in the harbour, on the ground or on the floors of houses. Two of these explosions gave rise to clear and equally big records on the Benioff Z seismograph, a third was faintly recorded. Since the times and places of all the explosions were observed, it was possible to ascertain that the two that gave good records had taken place on the bottom of the harbour and the one that gave a faint record was due to a bomb that was hanging half way down on the bulwark. The other explosions were heard over the greater part of the town and caused considerable damage, but they were not recorded.

C. S. Robinson (12) gives a list of all the large explosions known to have occurred up till 1944 and there are only a few of these that are larger than the Danish explosions. The Oppau explosion of Sept. 21. 1921, so well known to seismologists, involved a larger amount of explosives, 4000 tons according to Robinson, but a comparison of the records (2) with those of the Danish explosions indicates that the energy of the shock was smaller. This of course will be due to its having taken place on the ground. There were several seismological stations near enough to record the shock.

On Nov. 27. 1944 there was an explosion near Burton-on-Trend in England of burried explosives. The shock was recorded by several seismological stations up to a distance of 956 km (Zürich). It would seem, therefore, as if the energy of the ground motion were greater than in the Danish explosion of September 20. that was so faintly recorded by the 17 tons seismograph at Göttingen at a distance of 531 km and not traceable on the Zürich records at a distance of 1012 km. H. Jeffreys [(3), p. 104] calculated the energy fron the Stonyhurst record and arrived at the contradictory result that it was about the same as that of the Oppau explosion. The total energy released by the explosion was of the order of 13 $\times 10^{19}$ ergs.

H. Jeffreys found that Pn of the Burton-on-Trend explosion was 4^s early when compared with his tables and the Heligoland explosion results confirmed that Pn travels faster to small distances than previously supposed. The travel times of the Danish explosions agree with those of the other explosions.

My thanks are due to Mr. K. Olesen for valuable assistance.

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