Proper Oscillations of Lake-shelves

By

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I. Introduction

We have previously shown[1] that the long-period surface oscillations (of one to two hours) on the open coasts, which have hitherto been unexplainable as seiches of neighbouring bays, must be attributed to the proper oscillations of the continental-shelf-sea. We proved also theoretically[2] that the oscillations of the shelf-sea can be dealt with in a manner similar to the way in which the oscillations of the bay are treated. We may expect that in the lake also, at the portion where the shelf is fully developed, oscillations of the same kind will occur. Actually, oscillations of about 5 min. period (Fig. 4) recorded during the Muroto typhoon by the limnogram installed on the Imazu coast of Lake Biwa, can not been explained by any usual oscillating area forming a bay. One of the writers (Nomitsu) has suggested in another paper[3] that they are oscillations of the neighbouring lake-shelf. According to this suggestion, the present work has been done. We describe herein the results of our own limnological observations and minute soundings over the well-developed shelves at Imazu and Ômizo in Lake Biwa and examine whether the observed periods coincide with those calculated for the corresponding lake-shelves.

II. Sounding

When we look at the depth map[4] of Lake Biwa drawn by the Kôbe Marine Observatory, we find that shelves develope in the north-western portion of the lake, most remarkably in the neighbourhood

1. T. Nomitsu and K. Habu: Proper Oscillations of the Sea of Continental Shelf. These Memoirs, A, **18**, 247 (1935).

2. T. Nomitsu: A Theory of Tunamis and Seiches produced by Wind and Barometric Gradient. These Memoirs, A, **18**, 213 (1935).

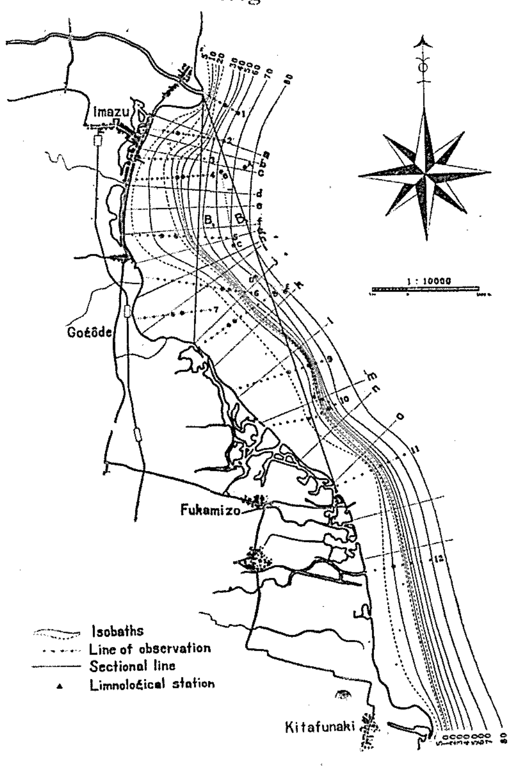
3. T. Nomitsu: Surface Fluctuations of Lake Biwa caused by the Muroto Typhoon. These Memoirs, A, **18**, 227 (1935).

4. 海洋氣象臺彙報 **8**, (1926). Its reproduction is given in these memoirs, A, **18**, 223 (1935).

of Imazu and Ômizo and next in the vicinity of Kaizu. But since, in this map, there are almost no soundings in the lake-shelf, and the observing points about the shelf margin are very few, we had to make for ourselves soundings sufficiently minute for our present purpose.

The soundings in the neighbourhood of Imazu are shown in Fig. 1.

Fig. 1



We established 12 sounding lines from the shore, and one line perpendicularly to them in the off-shore. Whenever possible we chose for the origin of the observation lines such points as the end of piers or the mouth of a river, points which are definitely indicated on the map issued by the Land Survey Department and can be easily found from the off-shore. Where no such landmarks were available, we indicated the starting points by flag-staffs. For the depth measurement, a sounding rope with lead and a modified Lucas machine were prepared, and for the determination of the observing station we prepared a sextant, a simple telemeter and a 100 m. measuring rope (to which were attached many small floats in order that it could be stretched over the water in a line as nearly straight as possible), and many rubber toy-balloons.

To secure our soundings, we used two Japanese junks which we rowed in a straight course by fixing our eyes on a definite object such as a point of a mountain or an island situated far on the other shore. When we had rowed about 100 m. (a few times only 70 m.), we stopped the boats, dropped the anchor, floated one of the rubber toy-balloons with lead sinker as a bouy, and measured the distance between the balloons with the measuring rope, and the distance from the shore by the simple telemeter for reference. Further, using the sextant we determined the positions of a few points (marked ⊙ in Fig. 1) on each observation line, the direction of which thus were known by these points and the points of origin.

The depth at each station was measured by both the Lucas machine and the sounding rope, taking the mean of the two as the real depth there. But as there were no great differences between them, sometimes we used only the sounding rope, mainly to save our labor and time. The results are tabulated in Table 1.

Table 1

Result of soundings near Imazu.

I-line

Station No.	Depth (m)	Distance from the shore (m)
1	10.5	50
2	23.5	100
3	28.7	200
⊙ 4	30.7	300
5	55.2	400
⊙ 6	62.4	500

II-line

Station No.	Depth (m)	Distance from the shore (m)
1	5.5	180
2	8.4	250
3	11.1	320
⊙ 4	12.2	390
5	13.4	460
6	15.1	530
7	17.1	600
8	20.6	670
9	21.8	740
10	33.0	810
11	49.7	880
12	57.2	950
⊙ 13	60.5	1020

III-line

Station No.	Depth (m)	Distance from the shore (m)
1	8.6	148
2	10.5	240
3	15.1	370
4	17.9	463
5	27.4	
6	29.8	685
7	55.6	926

IV-line

Station No.	Depth (m)	Distance from the shore (m)
1	6.8	70
2	8.1	140
3	9.2	210
4	10.8	280
5	12.4	350
6	14.6	420
7	16.9	490
8	20.4	560
⊙ 9	25.6	630
⊙ 10	32.4	700
11	39.5	770
12	43.6	840
13	46.6	910
14	48.7	980
15	50.5	1050

V-line

Station No.	Depth (m)	Distance from the shore (m)
1	4.7	100
2	6.2	200
3	8.4	300
4	10.4	400
⊙ 5	11.4	500
6	12.5	600
⊙ 7	14.2	700
8	16.0	800
9	32.0	900
10	47.6	1000
11	49.3	1100
12	57.3	1200
13	59.1	1300
14	63.0	

VI-line

Station No.	Depth (m)	Distance from the shore (m)
1	2.1	200
2	2.0	300
3	2.0	400
4	2.0	500
5	2.0	600
6	2.8	700
7	2.8	800
8	3.8	900
9	6.5	1000
⊙ 10	9.3	1100
⊙ 11	13.4	1200
12	15.0	1300
13	41.3	1400
14	53.3	1500

VII-line

Station No.	Depth (m)	Distance from the shore (m)
1	2.4	130
2	2.4	260
3	2.6	390
⊙ 4	2.6	520
⊙ 5	2.9	650
6	3.2	780
7	2.9	910
8	2.5	1040

VIII-line

Station No.	Depth (m)	Distance from the shore (m)
1	2.1	0
2	2.5	100
3	2.9	200
4	2.3	300
⊙ 5	2.2	400
⊙ 6	3.0	500
7	3.8	600
8	5.3	700
9	6.2	800
10	22.0	900
11	43.0	1000
12	54.5	1100
13	60.3	1200

IX-line

Station No.	Depth (m)	Distance from the shore (m)
1	1.5	130
2	2.5	260
3	2.9	390
4	2.9	520
5	3.4	650
6	3.9	780
7	4.6	910
⊙ 8	5.3	1040
9	6.0	1170
10	7.1	1300
⊙ 11	13.5	1430
12	59.1	1560
13	66.0	1690

X-line

Station No.	Depth (m)	Distance from the shore (m)
1	1.8	100
2	2.1	200
3	2.8	300
4	3.5	400
5	3.5	500
⊙ 6	5.5	600
7	8.2	700
8	13.0	800
⊙ 9	42.4	900
10	65.0	1000
11	51.3	1100
12	32.0	1200
⊙ 13	13.5	1300

XI-line

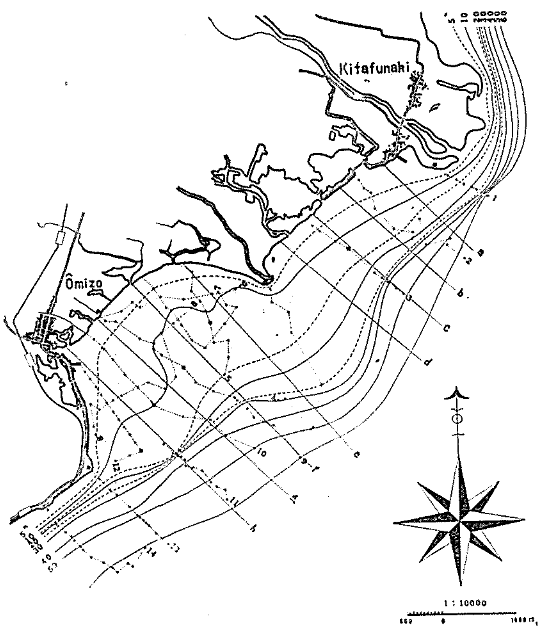
Station No.	Depth (m)	Distance from the shore (m)
1	0.65	37.6
2	1.9	167.6
3	3.2	297.6
4	3.6	427.6
5	3.9	557.6
6	32.0	687.6
7	57.8	817.6
8	68.2	947.6
9	75.0	1077.6

XII-line

Station No.	Depth (m)	Distance from the shore (m)
1	1.1	0
2	2.0	130
3	5.0	260
⊙ 4	10.3	390
5	13.5	520
6	36.9	650
⊙ 7	60.0	780
8	68.4	910

Next, *the soundings in the neighbourhood of Ômizo* were taken along 14 observation lines, as shown in Fig. 2. First we observed the mouth line of the bay and set 4 bouys of wooden frame with lead sinker, intending to make convenient further observations in the bay.

Fig. 2



This time, the position of each observation point was decided by "the two theodolites method," the theodolites being set on the ■-marks in Fig. 2, and the depth was measured only with the sounding rope. The irregularity of arrangement of the observation points is due to the fact that the two theodolites method made us so easy as we were not so precise in fixing the ship's course, and worked on no anchoring, the ship thus drifting by the lake current. The results are given in Table 2.

As for *the neighbourhood of Kaizu*, we did not sound ourselves, because there are many points sounded by the Kôbe Marine Observatory, up to fairly near the shore.

Table 2

Result of soundings near Ômizo. (Angles are measured from the base line connecting the two theodolites.)

I-line

Station No.	Depth (m)	Angle read at	
		H-station	E′-station
1	8.8		
2	13.9		
3	16.2		
4	20.7		75° 01′
5	21.8		74 20
6	49.4		76 51
7	72.1		77 18

II-line

Station No.	Depth (m)	Angle read at	
		H-station	E′-station
1	1.0		50° 49′
2	2.6		54 05
3	3.4	253° 19′	59 04
4	5.5	243 08	64 19
5	12.1	216 54	78 30
6	18.9	202 39	81 19
7	20.0	192 53	79 09
8	33.1	200 05	83 49
9	38.6	190 33	87 30
10	52.0	175 50	88 46
11	51.7	173 05	69 40
12	62.0	167 35	75 10

III-line

Station No.	Depth (m)	Angle read at	
		H-station	E′-station
1	2.5		46° 52′
2	6.0		55 09
3	10.0		67 21
⊙ 4	10.5	230° 48′	81 22
5	23.8	215 09	
6	23.6	211 19	
7	38.0	227 41	
8	43.2	204 53	
9	48.2	200 54	

IV-line

Station No.	Depth (m)	Angle read at	
		A-station	E-station
1	8.0	39° 31′	127° 09′
2	12.0	42 46	142 40
3	13.0	46 15	147 20
4	13.6	51 02	154 55
5	24.4	59 44	154 31
6	47.0	73 01	186 23
7	54.0	75 11	184 30
8	27.7	62 51	177 47
9	27.7	55 09	201 27

V-line

Station No.	Depth (m)	Angle read at	
		A-station	E-station
1	3.1	21° 04′	280° 37′
2	6.0	23 41	271 44
3	8.0	26 48	261 09
4	9.7	30 55	248 27
⊙ 5	11.0	(at C.) 111 04	232 12
6	12.0	40 03	222 24
7	12.7	43 44	216 29
8	13.0	47 57	210 05
9	15.0	50 40	206 32

VI-line

Station No.	Depth (m)
1	3.7
2	4.5
3	6.0
4	8.0
5	8.5
6	9.2
7	10.5
8	8.5

VII-line

Station No.	Depth (m)	Angle read at	
		C-station	E-station
1	11.2	04° 24′	257° 05′
2	11.5	97 29	232 20
3	11.2	106 13	228 06
4	11.5		
⊙ 5	11.0	121 52	235 31
6	10.5		
7	10.0		
8	8.8		
9	5.0		

VIII-line

Station No.	Depth (m)	Angle read at	
		C-station	E-station
1	10.0		
2	10.2		
3	10.0		
4	10.1	154° 34′	228° 40′
5	10.0	165 49	228 21
6	9.1		
7	8.8		
8	8.7		
9	6.2		
10	2.4		
11	3.7		
12	4.9		

IX-line

Station No.	Depth (m)	Angle read at	
		A-station	E-station
1	2.8		
2	4.0	5° 12′	259° 52′
3	9.0	16 08	
4	10.2		
5	10.0		243 51
6	10.5		235 13
⊙ 7	11.1	139 21 (at C.)	228 13
8	11.5		219 31
9	15.5		207 50
10	22.5	59 10	198 40
11	38.0	63 51	194 20
12	39.0	68 52	190 21
13	42.5	71 46	182 16
14	60.0	82 36	174 06

X-line

Station No.	Depth (m)	Angle read at	
		A-station	E-station
1	3.5		
2	6.0		
3	8.5		
4	9.0		
5	10.0		
⊙ 6	10.0		
7	10.0	(at C.) 143° 51′	228° 04′
8	12.0	38 00	
9	21.8	44 17	
10	40.7	56 29	
11	50.5	57 30	

XI-line

Station No.	Depth (m)	Angle read at	
		A-station	E-station
1	10.6		
2	11.0		220° 07′
3	11.4	66° 02′	216 49
4	13.8	73 30	213 12
5	30.5	76 23	211 19
6	35.8	78 06	210 12
7	36.6	79 48	209 02
8	43.3	85 04	205 33
9	45.0	86 13	
10	46.3	86 52	203 37
11	51.9	91 21	200 18
12	53.6	94 01	196 53
13	55.1	95 15	195 30
14	55.1	98 14	194 55

XII-line

Station No.	Depth (m)	Angle read at	
		C-station	E-station
1	2.1		
2	4.1		
3	3.7		
4	6.7		
5	7.5		
6	8.9		
7	9.6		
8	10.4		
9	10.8		
10	10.9		
⊙ 11	12.0	173° 01′	223° 19′
12	11.2		
13	11.8	182 32	

XIII-line

Station No.	Depth (m)	Angle read at	
			E-station
1	12.6		224° 21′
2	24.2		220 32
3	29.7		219 02
4	37.6		215 19
5	43.5		211 39
6	54.6		213 15
7	55.0		211 37
8	55.4		210 46
9	55.9		209 47
10	58.0		207 54
11	60.0		206 20
12	60.6		205 04

XIV-line

Station No.	Depth (m)	Angle read at	
		A-station	E-station
1	2.3		
2	23.6	206° 55′	
3	34.1	196 41	224° 20′
4	38.4	191 57	222 06
5	44.1	187 40	
6	50.9	182 11	
7	53.9	179 32	218 39
8	56.0	175 34	217 08
9	59.4	167 50	214 36
10	60.1	163 54	212 58
11	61.8	161 29	211 50
12	60.6	154 42	210 34
13	61.0	152 06	209 55
14	60.4		

III. The records of the seiches

This autumn, at Imazu, Ômizo, Kaizu and other places we established non-reducing limnimeters of the bouy-type made in our own workshop, and made many records of the seiches. We show only some examples in Figs. 3–4. We reproduce also the Imazu record of the Muroto typhoon obtained by the Section of Public Works of Siga Prefecture, for the record is an apt illustration for the present purpose. In these records special attention must be paid to the undulations of the 5 min. period at Imazu and the 15 min. period at Ômizo. That these two are certainly the oscillations of the lake shelf is proved in the following articles, and can not be explained by any other oscillating area. Beside these, several other periods can be found in our own records, the aforementioned Bulletin of the Kôbe Marine Observatory and the report of Dr. S. Nakamura and Dr. K. Honda.[1] At Imazu the seiches of period of about 9 min. and 30 min. occur

Table 3.

Observed periods (Thin type means weak rare occurrence)

Location	Observed period (in min)				
Imazu	**5**	**9**	**30**	22	71
Ômizo	**15**	**8–9**	**12**	17–18	
Kaizu	9	11–12	**30**		

1. S. Nakamura and K. Honda: Seiches in some Lakes of Japan. Jour. Coll. Sci. Imp. Univ. Tokyo, Vol. **28**, Art. 5 (1911).

Fig. 3

Limnograms at Ômizo (Yanagawa, Dezaike)

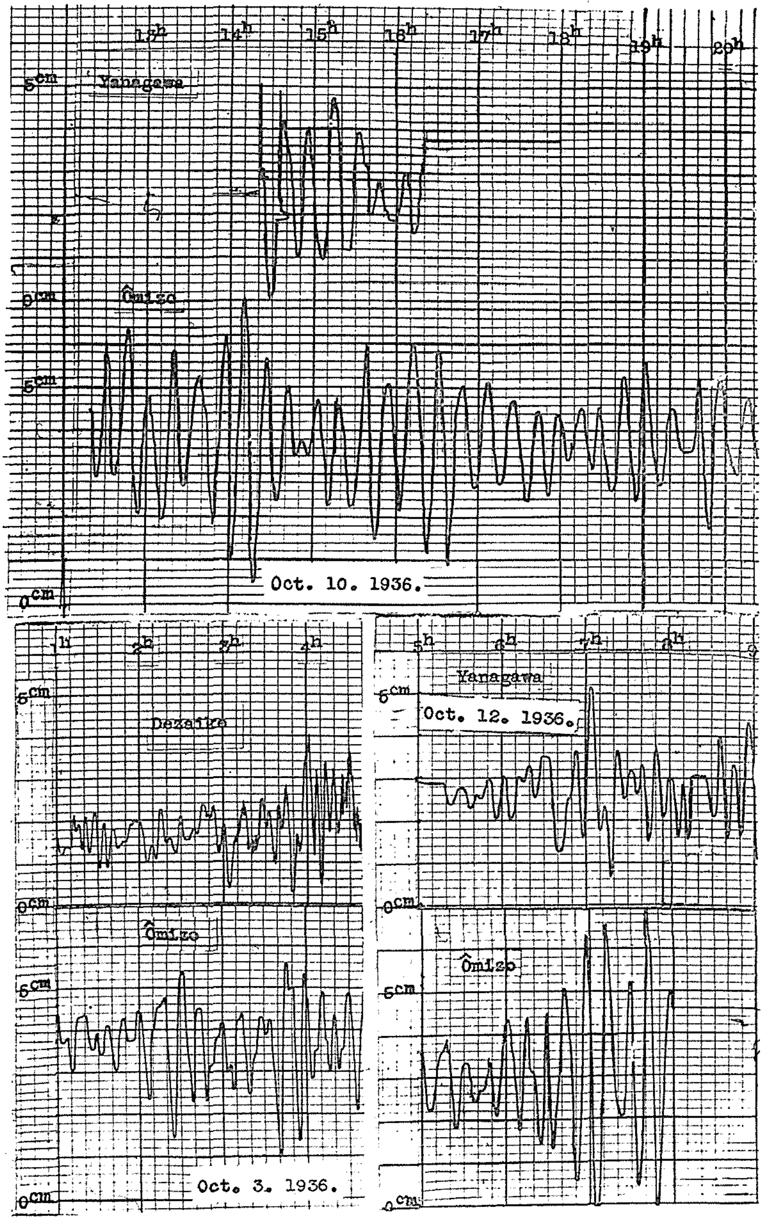
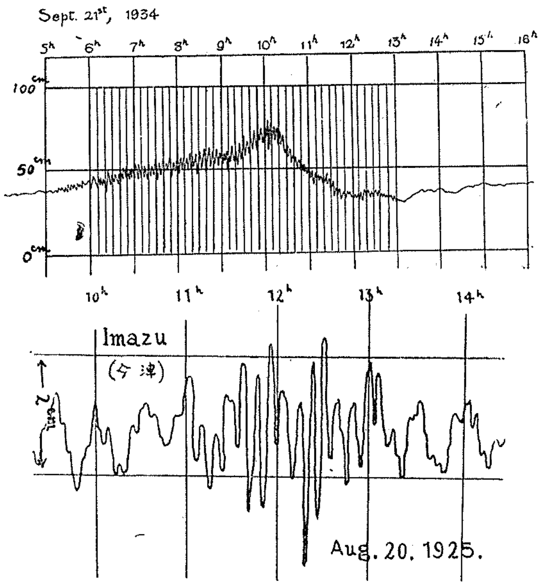


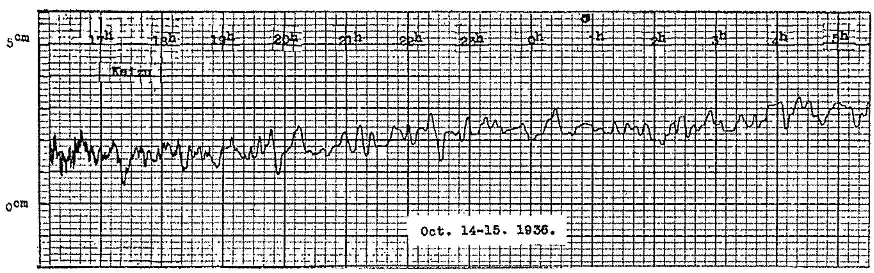
Fig. 4

Limnograms at Imazu and Kaizu.

(A) Imazu



(B) Kaizu



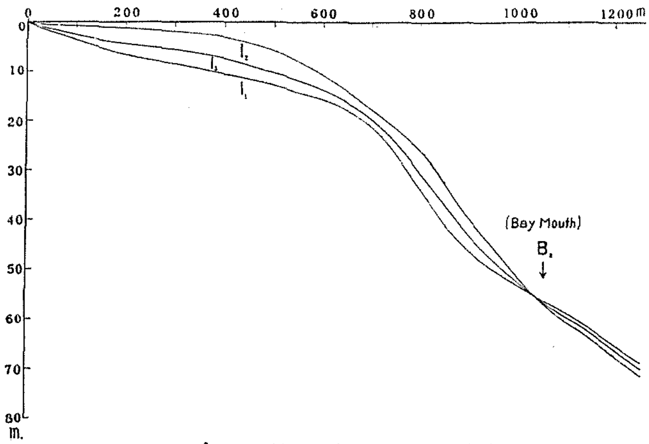
frequently and slight oscillations of 22 min. and 71 min. occur rarely. At Ômizo the strong seiches of 8–9 min. and 12 min. often appear and sometimes about 18 min. in slight intensity. At Kaizu about 30 min. is the habitual period and 9–12 min. seiches are not rare. Table 3 gives the summary of the above described.

IV. The lake-shelves and other oscillating areas

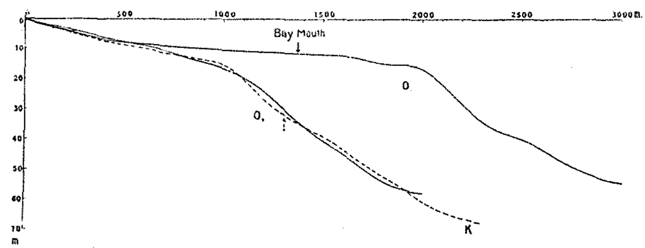
If we draw cross sections of the lake bottom according to the data given in Chap. 1, we see the distinct formation of the lake shelf (Fig. 5 & Table 4). Especially at Ômizo the shelf is much more conspicuous, and at Imazu it is a little narrower and more gentle, than we would expect judging from the map prepared by the Kôbe Marine Observatory.

First, *for the neighbourhood of Imazu*, I_1 gives the mean of the nine cross sections corresponding to lines a to i which are drawn orthogonally to the contour lines (cf. Fig. 1). Similarly I_2 is the mean of the cross sections from j-line to o-line, and I_3 represents the mean

Fig. 5
Cross sections of lake bottom.
(A) Imazu.



(B) Ômizo (O_1, O_2) and Kaizu (K).



of all cross sections from a-line to o-line. The lake shelf against the inlet from Imazu to Gogôde is I_1, and the lake shelf south of it is I_2, while I_3 is the mean shelf covering the whole region whose center is situated at Gogôde.

Now let T_1, T_2, T_3 denote the corresponding periods of the proper oscillations of each

Table 4
Mean cross section of the lake bottom.

Distance from the shore	I_1 Depth	I_2 Depth	I_3 Depth	Distance from the shore	O_1 Depth	O_2 Depth
62.5 m.	2.5 m.	0.4 m.	1.7 m.	200 m.	3.5 m.	3.1 m.
125.0	4.6	0.8	3.1	400	6.9	6.3
187.5	6.3	1.2	4.2	600	8.2	9.1
250.0	7.5	1.6	5.1	800	9.6	12.8
312.5	8.9	2.0	6.1	1000	10.3	16.4
375.0	10.0	2.5	7.1	1200	11.2	24.2
437.5	11.3	3.6	8.2	1400	11.5	36.0
500.0	12.6	5.4	10.0	1600	12.3	45.0
562.5	14.4	8.7	12.1	1800	14.6	54.2
625.0	16.8	12.2	14.8	2000	16.4	58.0
687.5	20.1	16.4	18.6	2200	28.3	
750.0	26.3	21.5	24.4	2400	37.8	
812.5	35.7	27.1	32.2	2600	43.1	
875.0	43.8	36.1	40.7	2800	50.3	
937.5	49.0	43.5	46.7	3000	54.4	
1000.0	53.1	51.8	52.8	3200	59.4	
1125.0	60.3	62.2	61.1			
1250.0	68.8	71.7	70.0			

shelf I_1, I_2, I_3 respectively, and calculate them by the formula

$$T = \frac{4L}{\sqrt{g\bar{h}}} = 4\int \frac{dL}{\sqrt{gh}}, \qquad L: \text{ The breadth} \quad h: \text{ The depth,}$$

then we get the following table. The upper values in the table are obtained by using the usual mean (arithmetical) as the mean depth $\bar{h}$, and the lower by using the integral mean of $dL/\sqrt{gh}$ for every 100 m. of dL. In any case, it is evident that the lake shelf about Imazu (I_1 or I_3) has a period of about 5 min.

Table 5

Calculated periods for the shelf near Imazu.

T_1	T_2	T_3
4.5 min.	7.5 min.	4.9 min.
5.8	8.7	5.6

Besides the shelf, what area including Imazu may generate the seiches shown in Table 3? There is the main body of Lake Biwa north of Katada, having a period of about 70 min., and the rectangular water basin between Imazu, Siraisi-jima, Take-jima, Hikone, Nagahama, and Kaizu. The Kôbe Marine Observatory[1] and one[2] of the writers (Nomitsu) have reported that the latter basin should have a period of 30 min. for the longitudinal oscillation and 22 min. for the transversal. The remaining region conceivable as another oscillating area is only the inlet having the mouth at B_1 or B_2 line shown in Fig. 1. In order to find the corresponding period, the mean depth of the bay is calculated by measuring the area between the contour lines, and the mouth correction is obtained by exterpolating the usual formula established when the ratio of breadth to length is less than unity. The result is given as follows.

Table 6.

Calculated periods of the Imazu Bay.

Mouth line	Length	Breadth	Coefficient of mouth correction	Mean depth	Period
B_1	1600 m	5600 m	1.37	19.8 m	10.5 min
B_2	1050	3500	1.37	11.8	8.9
			(Transversal oscillation)		10.9

Thus the seiches of the period of 8–9 min. which often actually occur at Imazu are the oscillations of this bay.

1. loc. cit.
2. These Memoirs, A, **18**, 227 (1935).

Second, for *the neighbourhood of Ômizo*, we calculated the periods assuming the region as a shelf on the one hand and as the bay on the other. In Fig. 5, O_1 is the mean of the cross-sections e, f, g, h shown in Fig. 4, and represents the shelf of Ômizo proper. O_2 is the mean of the cross sections a, b, c, d thus representing the shelf on the north of O_1 at about Funaki. The calculated periods corresponding to these shelves are given below.

Table 7

Calculated periods for the shelf near Ômizo.

T_1	T_2
14.4 min	7.9 min
15.0	8.8

From this we see that the 15 min. seiches continually occurring at Ômizo are the proper oscillations of the well-developed lake shelf O_1 there. It may be here noticed that when this kind of seiche occurs at Ômizo, the resembling seiche occurs on the opposite shore (Yanagawa and Dezaike). Comparing the simultaneous records, however, we note that the phases are not always the reverse of each other, and that the periods at the opposite side are always a little longer than at Ômizo, attaining 16–18 min. (cf. Fig. 3). Now, calculating the period of transversal oscillation of the middle part of Lake Biwa, we get 18.7 min. and the report of the Imperial Marine Observatory[1] gives 16.7 min. for the same oscillation. At any rate, this is the same as the faint oscillation of 18 min. period which occasionally occurs at Ômizo. Since this is comparatively near the period of the shelf-seiches at Ômizo, it seems that the former is the exciter of the latter. The lake is far deeper at the Ômizo-side than at the Yanagawa-side. Hence, if the seiche oscillates between them, the amplitude at Yanagawa and Dezaike should be far greater than at Ômizo, but the actual seiches of ca. 15 min. period at Ômizo are always a few times larger and more frequent and of longer duration than at the others.

Next if we calculate the period for the Ômizo inlet as a bay, we get the following value, which explains the actual seiche of 12 min.

Table 8.

Calculated period of Ômizo bay.

Length	Breadth	Coefficient of mouth correction	Mean depth	Period
1300 m	3400 m	1.36	7.90 m	13.3 min

1. loc. cit.

The occasionally found period of 8–9 min. is either the oscillation which is propagated from the aforementioned oscillation of the O_2-shelf, or the harmonics of the transversal oscillation of 17–19 min. between Ômizo and the opposite shore.

Last, for *the neighbourhood of Kaizu*, we did not take special sounding ourselves. But utilising the data in the report of the Kôbe Marine Observatory we get the K-curve in Fig. 5 (B) as the mean cross section of the region. Here also we certainly perceive a shelf, though it is not so good in development and is rather narrow in breadth, so that oscillations of remarkable amplitude may not be expected. From the view-point as a bay, however, the length is longer than the breadth of the shelf, and therefore the bay-oscillation can have a longer period and a larger amplitude according to circumstances. At any rate, we calculated the periods of both the bay- and the shelf-oscillations as before, and obtained the following results.

Table 9

Calculated period for Kaizu region.

Oscillating region	Length	Breadth	Mean depth	Period
Bay	1300 m	3100 m	10.8 m	11.1 min
Shelf	1000		7.12 (Integral mean used)	8.0 (8.7)

The table shows that the seiche of 11–12 min. often observed at Kaizu is perhaps the bay-oscillation and that the 9 min. period is that of the shelf-oscillation. The report[1] of the Kôbe Marine Observatory gives an oscillating area (the *enclosed*, not the bay-type) of a 10.5 min. period in front of Kaizu and Imazu, but we can not understand it. It will be, indeed, altogether absurd to suppose that an oscillating region of the *enclosed* type has one of its sides in the deepest portion (about 90 m.) of the lake.

Finally the seiche of 30 min. period occurring most frequently at Kaizu must be the same as the oscillation of the identical period at Imazu.

V. Conclusion

Summarizing the chief points stated above, we see that:

1) The oscillations of the lake-shelves certainly exist, and that they have comparatively short periods among the lake-seiches.

1. loc. cit. Fig. 43, Map of Oscillating Areas.

In the ocean, as we have seen previously,[1] rather long periods among the secondary undulations belong to the shelf-seas, because there are no oscillations of the whole ocean except the tide, and because the shelf-seas are usually larger than the neighbouring bays. On the contrary, in a lake, any shelf is narrower than the whole breadth of the lake, so the shelf-oscillations commonly have comparatively short periods among the seiches.

2) Even in the bay of which the breadth is larger than the length, oscillations seem to occur beyond our expectation; especially so when the bay is fan-shaped. The amplitudes, however, are naturally small in any case.

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1. These Memoirs, A, **18**, 213 (1935).