The formation of shell fragments in the southern North Sea

D. Eisma and J.J. Hooft

Netherlands Institute for Sea Research

Publications and reports

nr. 1969-3

June 1969

This paper is not to be cited without prior reference to the author.

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D. Eisma and J.J. Hooft
(Netherlands Institute for Sea Research, Den Helder)

Introduction.

Shell fragments may be formed out of whole shells (c.f. Schaeffer 1962) by:

1) direct mechanical action by current, surf or moving sand;
2) mechanical action after weakening of the shell structure by micro-organisms;
3) some fishes and Crustaceae which feed, in part, on bottom mollusks and crack the shell.

In the southern North Sea shell fragments are formed predominantly by fragmentation of the mollusk species with fragile shells (Abra alba, Abra prismatica, Angulus fabula, Angulus tenuis, Ensis spec., and Macoma balthica, which has a somewhat heavier shell but is much consumed by fish). The main mollusk-feeder which cracks shells in this area is the plaice (Pleuronectes platessa). Its abundance indicates that it must be responsible for a large proportion of the shell fragments. Laboratory experiments, however, indicate that shell fragments can also be formed from the fragile shells by direct mechanical action in amounts of the same order of magnitude as by bottom fish, provided the mollusks died intact (Eisma 1968). In fact this probably will not be the case as

predation by the plaice will leave relatively few fragile shells whole.

Whether predation by fish can indeed account for the amounts of shell fragments present in the sand may be tested by comparing the amount of shell fragments present with the amount of shell fragments produced by bottom fish. This is done below for a part of the southern North Sea off the Dutch coast (fig. 1), an area of 14.580 x 10^6 m^2. The calculations are given in Table I; the data were derived as follows.

Calculations.

a) Volume of Holocene sea sands. The surface of the area is 14.580 x 10^6 m^2. The average thickness was estimated from the few data available. In offshore drillings off Hoek van Holland the recent sea sands were found to have a thickness of 5 m (pers. comm. E. Oele). The megaripples in this area have a height up to 6-7 m (Langeraar 1966) so that the minimum thickness of the recent sea sands is about 3.5 m, Off Petten the recent sea sands are about 2 m thick (Report Geological Survey 1959), whereas nearshore off Texel they form a thin veneer of about 0.5 m on Saalian glacial deposits. Further west off Texel Houbolt (1968) suggests a thickness of 10 m on Texel Spur. Between Texel Spur and the coast of Texel-Vlieland -

on the Texel Rough and in the Texel Hole - the recent sea sands contain a large admixture of Saalian fine gravel and Eemian fossils and probably are thin. It follows that the average thickness will be somewhere between 3 and 10 m. It has been taken here as 7 m, giving a volume of 1×10^{11} m^3 for the Holocene sea sands.

b) Volume of recent beach and dune sands. The coast is 150×10^3 m long. The average width of the dune belt is 2.1×10^3 m and was determined by averaging the width's measured at intervals of 1 km. The average height has been estimated as 10 m, but may be up to 20 m, the base of the present dunes being near to present sea level.

c) Volume of older Holocene marine, beach and dune sands (barrier deposits). These extend from south of Den Haag to north of Alkmaar, a distance of about 80×10^3 m. The width of this belt is about 8×10^3 m. The thickness is given by Van Straaten (1963) as 10 m to which a few meters are added because the former barriers are partly covered with dunes of up to 10 m height. Since not all deposits in this area down to 10 m depth are either marine or former beach and dune sands, whereas sands at a deeper level may still be counted as such, the limits of error have been arbitrarily set at 6-15 m.

d) Content of shell fragments in recent sea sands. This was determined in 61 sea sand samples. Shell fragments in these sands are larger than about 250 μ (EISMA 1968) so that they were first sieved through a 250 μ sieve while whole shells were taken out. Then about 10 gr of the fraction > 250 μ was heated for about 15 min. with 6N HCl and subsequently filtered off over a paper filter. The filtrate was diluted to 1 l and neutralised with NaOH to pH 8 indicated by neutral red or phenolphthaleine. Usually fine iron hydroxyde floccules had been formed at that time and the solution was left standing until the floccules had settled. Then an aliquot of the clear supernatant solution was taken and the Ca-content determined by titration with EDTA and murexide as indicator. The standard deviation of the mean ($\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$ where σ is the standard deviation of n observations) was found to be 0,05%. It is assumed that the average amount of shell fragments present in the top 5-10 cm is representative for the whole volume.

e) Content of shell fragments in Holocene coastal sands. Shell fragments accummulate on the beach when the coast is stable or prograding seawards, so that beach and dune sands contain on the average about 4 times as many shell fragments as the adjacent sea sands (Eisma 1968).

f) Total amount of shell fragments in the area of investigation. The weight of 1 cc of sand was found to be 1.7-1 8 gr. This value was determined with dry sand of varying grainsize firmly packed into a measuring glass. Since on the whole the sand was probably less densely packed than on the sea floor, the higher value was used.

g) Average amount of shell fragments produced by plaice. From a number of catches of plaice caught in 1967 in the area of investigation, the intestines were collected, 717 in all. The total weight of shell fragments in there was 48.3 gr., i.e. an average weight of 0.067 gr. per specimen (Hooft, 1968). This is the average production of one day: the plaice feeds at day while during the night the intestines are emptied (de Groot, 1964) and the intestines were collected just before dawn. This implies that there is only a small distance between the place where the food is consumed and the place where the shell fragments are dropped. In 1967 the plaice had eaten relatively large numbers of worms: only 14.6% of the intestines contained shell fragments whereas normally about 75% contains mollusk remains, (Todd 1915, Poulsen 1933, Kühl 1963, Gilis 1966). Comparison of the abundance of mollusks off the Dutch coast in 1967

with the abundance in 1964 indicates that in 1964 10-100 times as may mollusks with fragile shells were present as in 1967 so that the low amount of shell fragments in the intestines is due to a paucity of mollusks. Normally about 5 times as many mollusks shells are consumed as in 1967, so that we may take an average of 0.3 gr. per specimen per day.
During the months of November and December the plaice virtually does not eat (Todd 1914) while in January and February about 50% of the intestines contain food. Taking therefore the average number of days on which shell fragments are produced as 250 the total average production per specimen per year becomes 75 gr.

h) Average number of plaice in the area of investigation.
Fisheries statistics available on the catches of plaice larger than 25 cm in this area during 1959-1966 show that on the average 24 ($\pm$ 5) x 10^6 specimens were caught per year. Usually about 40% of the total number of plaice larger than 25 cm is caught per year. The mortality due to natural causes can be estimated to be 10%.
The total decrease per year thus is 50%. Taking N_o as the number of plaice larger than 25 cm at the beginning of the year, N_1 as the number of plaice at the end, and N_a as the number of plaice caught during the year,

the following relations are valid:

$$N_1 = \frac{5}{4} N_a$$

$$N_o = \frac{10}{4} N_a$$

The average number of plaice > 25 cm must be somewhere between N_o and N_1. The relation between N_o, N_1 and time (t) is given by:

$$N_1 = N_o . e^{-(F+M)t}$$ (Beverton and Holt 1957)

where F is the mortality due to fishing and M the natural mortality.

Substituting N_1/N_o by 0,5 gives

$$F + M = 0.690$$

The average N is thus found to be equal to 0.72 N_o so that

$$N = 0,72 \times \frac{10}{4} N_a$$

The average N for 1959-1966 is thus 4.3 ($\pm$ 0.9) x 10^7 specimens.

Plaice smaller than 14 cm consume only very small amounts of mollusks (Todd 1914). Data available at the Netherlands Institute for Sea Research show that 75% of the plaice longer than 14 cm, but smaller than 25 cm, have consumed mollusks. 14 cm is the minimum length of plaice 2-3 years old (year class II).

Some specimens of this age will already have been caught before the end of the year, whereas some will still be too small at that time to be caught during the next year. Since for at least the last 20 years it can be assumed that the population of plaice has on the average remained constant, the total weight of the plaice $\geq$ 25 cm caught each year is about equal to the total weight of year class II. The average weight of plaice of 25 cm is about 0,070 kg (Beverton and Holt 1957). Thus we can calculate N_1 for the year class II, and N since we may state

$$N_1 = N_o \, e^{-Mt}$$

where $e^{-Mt} = 0.9$ and $M = 0.1$ (natural mortality being 10%), and:

$$N_{14-25} = \frac{95}{90} \times N_1.$$

The plaice of 14-25 cm are mainly concentrated along the Dutch coast and in the German Bight (fig. 2), whereas the larger plaice migrates from here into the other part of the southern North Sea. Therefore for N_o the number of plaice > 25 cm caught in the entire southern North Sea by Dutch fishermen has been taken. About 1/2 to 1/3 of this number was present the year before as plaice of 14-25 cm in the area of investigation, (pers. comm. de Veen). Using Dutch fisheries statistics for 1959-1966 this number was on the average 7 to 17 ($\pm$ 1) x 10^7 specimens. Adding this to the total number of plaice > 25 cm the total becomes 1-2 ($\pm$ 1) x 10^8

specimens.

Extrapolating these data to a period of more than 8000 years involves a calculation of the number of plaice $\geq$ 14 cm which would have been present if there had been no fishing industry. According to Beverton and Holt (1957) the amount of plaice which would be present if the mesh size of the nets was so large that even 15 year old fish could pass through (15 years is about the maximum age of plaice), would be $\frac{6.8}{1.3} \approx 5$ times the present number. Natural mortality, however, would be higher if there were no mortality due to fishery. Doubling this mortality, it is than assumed that before the advent of a fishing industry the number of specimens was about 4 times higher than the present number. The effect of the intense fishery of the last 100 years can be neglected in a period of 8300 years: the error made is in the order of 1%.

i) Amount of shell fragments formed by fish during the Holocene. According to Jelgersma (1961) and Pons et al. (1963) the area of investigation became a sea between about 9000 and 7500 BP so that the area as a whole has been a sea for 8300 years. It has been assumed that on the average the number of plaice has remained constant, i.e. varying roughly between 2 and 20 x 10^8 specimens. This is not altogether unlikely since 8000 years ago temperatures probably have been only slightly lower than

at present, while the plaice can live in a broad temperature range.

Discussion.

The average amount of shell fragments in the area of investigation was found to be 15.6×10^{11} kg with a minimum around 10×10^{11} kg and a maximum of about 50×10^{11} kg. The amount of shell fragments produced by plaice is on the average 3.75×10^{11} kg (2.5 to 5×10^{11} kg) which is about 3 times lower. Although the difference is at most one order of magnitude, it is in fact much smaller because:

1°. There is an admixture of Eemian shell fragments off Hoek van Holland - Noordwijk and especially off Petten - Vlieland which makes the amount of shell fragments too high.

2°. Shell fragments are also formed by crustaceae and by some fish which are comparatively rare at present in the investigated area but may have been more frequent in former times (e.g. the haddock, Gadus anglefinus, and the seawolf, Anarrichas lupus).

3°. For the calculation of the number of plaice only the Dutch fisheries statistics have been used. To this must be added the amount caught by Belgian, English, German and especially Danish fishermen. The statistics given by other

countries do not allow further calculation but the total average number of plaice may be twice as high.

Thus the amount of shell fragments produced by mollusk eating fish during the Holocene in the area of investigation are likely to be of about the same order as the amount of shell fragments present in the sand.

There is an independent way to arrive at this conclusion by starting with the number of mollusks present in the area. In 1964 the number of mollusks specimens with fragile shells that are consumed by bottom fish, was 14×10^{11}. Subsequent sampling in 1965-1967 showed that in these years this number was 10-100 times lower. The average number of specimens each year therefore is somewhere between 5×10^{10} and 5×10^{13} specimens. The average weight of one fragile mollusk shell is about 0.15 gr. so that between 0.75×10^{7} and 0.75×10^{9} kg weight is present each year. Since whole fragile mollusk shells are rarely found intact nearly all shells must have become fragments which, in 8300 years, would give between 6.2×10^{10} and 6×10^{12} kg. The average is 6.2×10^{11} which is very near to the amount produced by plaice as found above.

Conclusion.

In the area of investigation the amounts of shell fragments present, the amount of shell fragments produced

by fish since the area became a sea, and the amount of mollusk shells that may have been consumed by fish since that time differ not more, and probably much less, than one order of magnitude. The uncertainties in the data used, however, prevent a more precise calculation of the amounts involved. It follows that with the information available at present, it cannot be shown beyond doubt that the mollusk consumption by bottom fish is sufficient to account for the total amount of shell fragments formed since the area of investigation became a sea some 8300 years ago, especially since fragmentation by mechanical action (tidal currents) may reach the same order of magnitude. However it is apparent that

1. shell fragment production by fish is quantitatively important in the southern North Sea;
2. as more data will be available on the thickness of the Holocene sea sands, the Holocene history of the area, the uptake of mollusks by plaice, the number of plaice and the amounts of bottom mollusks present during a large number of years, calculations such as the one given above will lead to more precise results.

Acknowledgements.

The authors are much indebted to Mr. J. de Veen, RIVO, IJmuiden, for his advice and to Dr. I.N. McCave for reading the manuscript.

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Table I.

a) volume of sea sands:

$7 \times 14580 \times 10^6$ m3 = 1×10^{11} m3

b) volume of recent beach and dune sands:

$10 \times 150 \times 10^3 \times 2.1 \times 10^3 = 3 \times 10^9$ m3

c) volume of older Holocene marine, beach and dune sands:

$12 \times 8 \times 10^3 \times 80 \times 10^3 = 8 \times 10^9$ m3

d) content of shell fragments in 61 recent sea sands:

$0.59 \pm 0.05\%$

e) content of shell fragments in Holocene coastal sands (old + recent):

$\pm$ 4 x the amount in recent sea sands: $\pm$ 2.4%

f) total amount of shell fragments in the area of investigation during the Holocene:

in sea sands:	10.8×10^{11} kg
in the other sands:	4.8×10^{11} kg
	15.6×10^{11} kg (average)

g) average amount of shell fragments produced by one specimen of plaice per year: 250 x 1.335 gr. = 75 gr.

h) average number of plaice per year present in the area of investigation: 4 to 8 ($\pm$ 1) x 10^8 specimens.

i) amount of shell fragments formed by fish during the Holocene:

8300 x 4 x 10^8 x 83.75 gr = 2.5 x 10^{11} kg (minimum)

8300 x 8 x 10^8 x 83.75 gr = 5.0 x 10^{11} kg (maximum)

average $\underline{3.75 \times 10^{11} \text{ kg}}$

Figures

fig. 1. Location of the investigated area.

fig. 2. Area with large concentration of plaice of year-class II (length 14-25 cm).

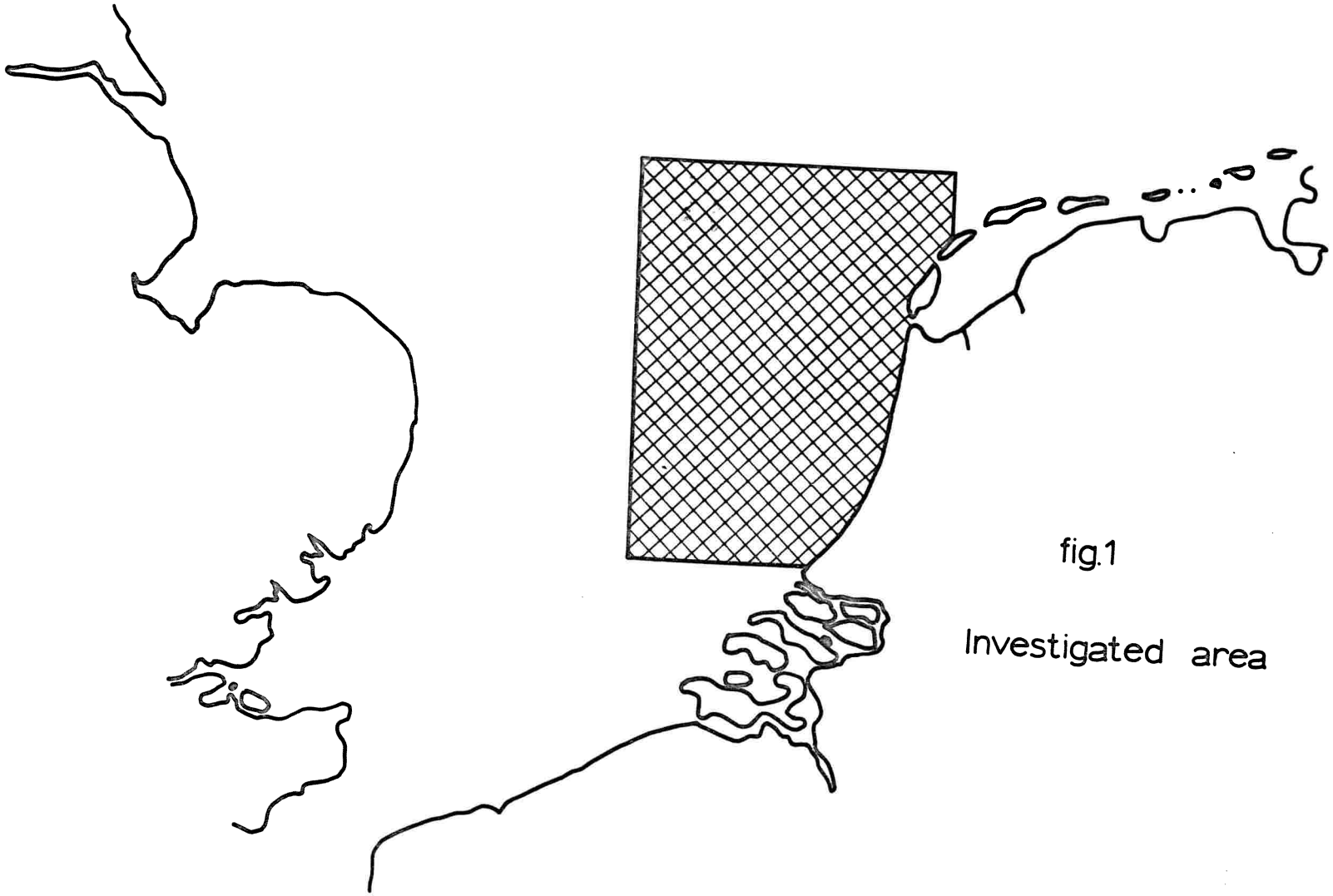

fig.1

Investigated area

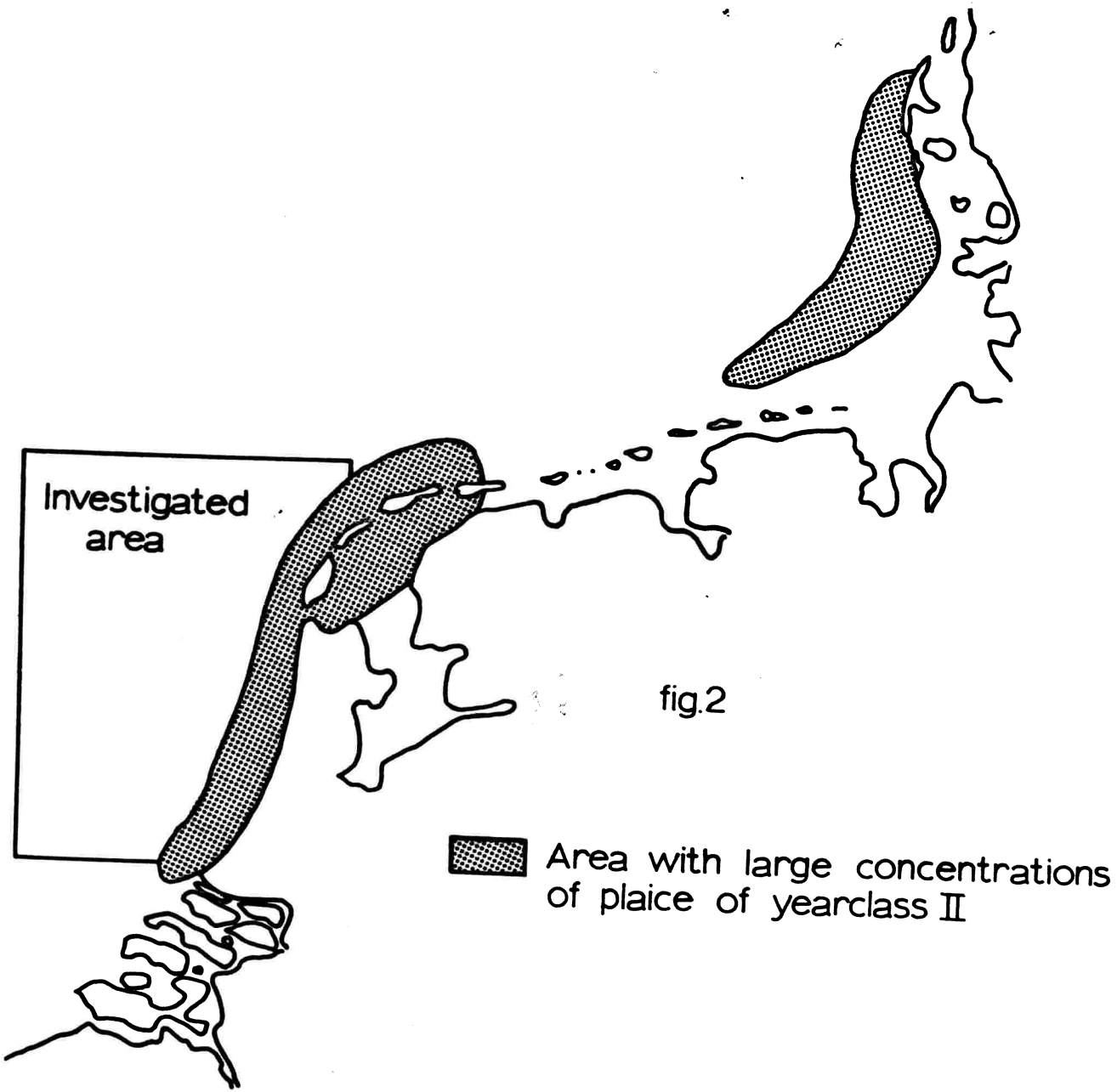
Investigated
area
Area with large concentrations
of plaice of yearclass II

fig.2