MAGNETIC ANISOTROPY OF NATURALLY OCCURRING SUBSTANCES.

II. Molluscan Shells.

BY P. NILAKANTAN.
(*From the Department of Physics, Indian Institute of Science, Bangalore.*)

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1. *Introduction.*

IN a previous communication,[1] the author has described how the determination of the magnetic anisotropy of the nacre of iridescent shells enables us to gain information regarding its inner architecture. The results also seemed to indicate that the cementing medium conchyolin itself has most probably got a quasi-crystalline structure. The method thus proved itself to be fruitful, and in the present investigation it has been extended to a more general study of the structure of molluscan shells.[2] These have been extensively studied by means of the polarising microscope and the contributions of W. J. Schmidt[3] and O. Boggild are of special interest. While Schmidt confined himself to a detailed examination of some typical shells of the various classes of molluscs, O. Boggild has made an exhaustive and systematic study of them. The present work is concerned with the shells of *Placuna placenta, Pinna bicolor, Meretrix casta, Mactra lurida, Mactra hebbalensis, Vulsella rugosa* and *Turbinella pirum* (Indian *Chank*). A minute structural examination of these shells bringing out all the peculiarities of arrangement and constitution of the elementary crystals is not possible by the magnetic method. But the presence of magnetic anisotropy can definitely establish the crystalline character of the elements that go to build up the shell, as well as give a general indication of the most probable orientations ; and in some favourable cases such as *Placuna placenta,* it is possible to get significant information concerning the elementary crystals themselves, as will be shown later.

2. *Description of the Shells.*

Placuna placenta is the well-known species of window-pane oyster found in the Indian Ocean. The shell has got a pearly lustre, is faintly iridescent, and consists exclusively of calcite. It cleaves into thin leaves like mica, and the structure has been described by Boggild as foliated. When examined under the microscope numerous fine lines (*streifen*) can be seen on the foliæ, parallel to one another the surface resembling a fibre mat. The leaves easily break into small strips in the direction of these lines. By examination under the polarising microscope, W. J. Schmidt has found that the thin laminæ show extinction in the direction of the fine lines. Conoscopically examined, they always gave a negative uniaxial eccentric interference pattern. This indicates that the optical axes of the elementary crystals are inclined to the plane of the laminæ. Schmidt has also found that the smallest elements of the shell are extremely thin leaf-like structures, about 1μ thick, 5μ wide and 100μ long. They are arranged with their lengths parallel to the fine lines on the laminæ. Their accurate crystallographic determination was not, however, found to be possible. Boggild also has mentioned the inclination of the optic axes of the crystals to the laminar plane.

The shell of *Pinna bicolor* consists of two layers, an upper prismatic calcitic layer, and a lower aragonite nacreous one. The nacreous layer, which shows bright iridescent colours, can be easily chipped off and is usually very thin. Schmidt has isolated the tiny prisms of calcite in the upper layer and has found that the optic axis coincides with the prism axis. Each prism is a single crystal of calcite arranged in the shell with its axis normal to the shell surface. It has also been found that there is very little difference between the different species of *Pinna*.

The common feature of the shells of the *Mactra* sp., according to Boggild, is the crossed lamellar concentrical layer. This is however in many cases irregular. *Mactra lurida* is a white aragonite shell with a violet coloured patch in the middle. The lowest porcellanous layer was taken for examination from both the white as well as the coloured portions. The shell of *Mactra hebbalensis* is dark in colour and very brittle.

Vulsella rugosa has got a very thin and fragile shell. It consists of an upper prismatic calcitic layer and an extremely thin nacreous layer below. The shell of *Meretrix casta* is hard and porcellanous in appearance. The "*Chank*" is very well known in South India.[5] The shell is white and chalky in appearance and consists of several calcitic layers. These were found to break easily along a particular direction in a somewhat similar manner as the cleaving of crystals. Only the lowest layer, which appeared to be translucent, was taken up for examination.

3. *Magnetic Anisotropy of Calcitic Shells.*

It is convenient from the experimental standpoint, to determine the anisotropy of the shells, firstly in the plane of the shell layer, and then in the two perpendicular planes determined by the directions of maximum and minimum susceptibility in the shell plane. In the case of the nacreous layer, where we have got a normal orientation of the aragonite crystals, the orientations could be deduced from the results in a simple and straightforward manner. But when inclined orientation of the crystals is present, as in the calcitic shell, *Placuna placenta*, the orientations may be deduced from the following considerations.

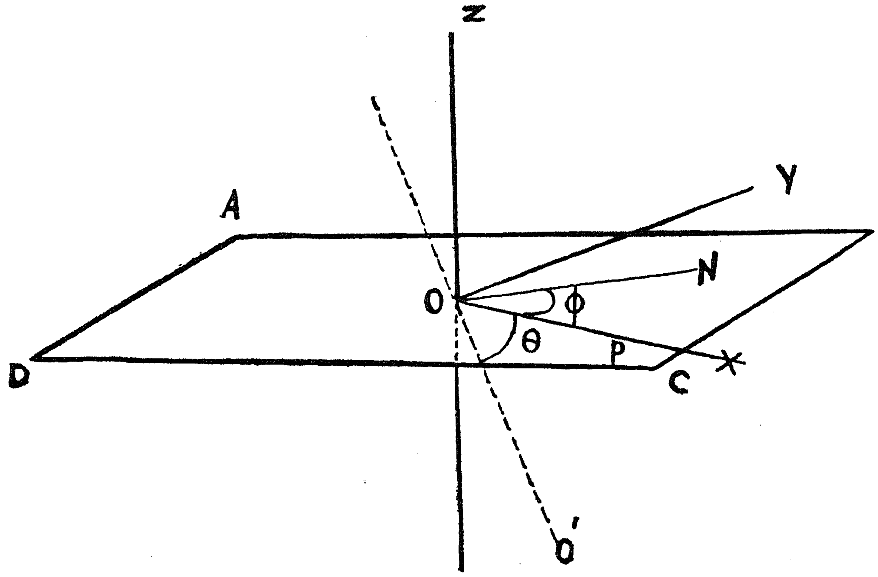

FIG. 1.

Let ABCD (Fig. 1) represent the plane of the folia and let OO′ be the direction of the trigonal axis of the calcite crystals inclined at an angle to the plane—Let a rectangular co-ordinate system be chosen such that the direction of the projection of OO′ on the plane is the X-axis. OY in the plane represents the Y-axis. If K_1 and K_2 are the magnetic susceptibilities along and perpendicular to the trigonal axis respectively and if ON is any arbitrary direction in the plane making an angle θ with OX,

$$\chi_{ON} = K_1 \cos^2\theta \cos^2\phi + K_2 (\sin^2\theta \cos^2\phi + \sin^2\phi)$$

$$\frac{d\chi}{d\phi} = (K_2 - K_1) \sin 2\phi \cos^2\theta.$$

This will be zero when $\phi = 0$ or $90°$.

χ is maximum when $\phi = 0$

and equals $\chi_1 = K_1 \cos^2\theta + K_2 \sin^2\theta$.

The minimum value of $\chi = \chi_2 = K_2$

when $\phi = 90°$.

OX and OY are thus the directions of maximum and minimum diamagnetic susceptibility in the plane. The magnetic anisotropy

$$\Delta\chi = (K_1 - K_2) \cos^2\theta.$$

The directions OX and OY can be easily located by suspending the shell with the plane horizontal in a uniform magnetic field and observing the orientation. When the piece of shell is suspended with the OX direction vertical, the orientation will be with the plane parallel to the field.

$$\text{and } \Delta\chi = (K_1 - K_2) \sin^2 \theta.$$

When, however, it is suspended with the OY direction vertical, the plane will make an angle $(90° - \theta)$ with the field.

Hence, θ can be known.

$$\text{and } \Delta\chi \text{ will be } = (K_1 - K_2).$$

4. *Experimental.*

Both Krishnan's[6] oscillation as well as torsional methods were employed, for the determination of anisotropy according to convenience. The oscillation method has already been described in the previous communication by the author. Here, the torsional method will be briefly described.

The chief advantage of this method is that very small pieces can be employed for examination, and this is desirable in the case of shells for obvious reasons. The principle of the method is as follows :—If an anisotropic body is freely suspended in a uniform magnetic field, it will orientate itself such that the directions of maximum and minimum (algebraic) susceptibility in the plane of oscillation about the axis of suspension, will be along and perpendicular to the field respectively. If the torsion of the fibre is zero in this position, and if the torsion-head is turned slowly until at a critical point the body swings round suddenly, then the anisotropy in the plane is given by

$$\Delta\chi = \frac{2\,(\alpha_c - 45°)\,\pi}{180°} \cdot \frac{c}{mH^2}$$

where

α_c = The angle through which the torsion-head has been turned.

c = modulus of torsion of the fibre.

m = Mass of the body.

H = Field strength.

At the critical position the body will make an angle of 45° with its initial position. However, in the case of some of the shells it was observed that this angle was considerably greater. This may be attributed to the presence of an irregularity in the orientation of the crystals which, so to speak, blunts the critical point. The oscillation method also was tried in such cases to check up.

The anisotropy was determined as usual, for three modes of suspension ; firstly, with the plane horizontal—from the orientation the directions of maximum and minimum susceptibility in the plane are known ; then with these directions vertical respectively.

TABLE I.

$\chi_1' > \chi_2' > \chi_3'$ *Algebraically.*

Shell	Class	Mode of suspension	Orientation	Specific anisotropy $\times 10^8$ E.M.U.	Remarks
Placuna placenta ..	Bivalve	(A) Plane of the shell folia horizontal	Direction of the fine lines $\perp^r$ to the field	$\chi_1'-\chi_2'=0 \cdot 8$	The optic axes of the crystals make an angle of 64° with the laminar plane and are inclined in the direction of the fine *streifen*
		(B) χ_1' axis vertical	Plane made an angle of 26° with the field	$\chi_2'-\chi_3'=5 \cdot 2$	
		(C) χ_2' ,,	Plane $\|^l$ to the field	$\chi_1'-\chi_3'=4 \cdot 6$	
Pinna bicolor (calcitic layer)	,,	(A) ,,	Indefinite	$0 \cdot 0_6$	optic axis $\perp^r$ to the shell plane
		(B)	Plane $\|^l$ to the field	,, $5 \cdot 6$	
		(C)	,,	$5 \cdot 8$	
Pinna bicolor (nacreous layer) ..		(A)	Line of growth $\|^l$ to the field	$0 \cdot 3$	*c* axes of the aragonite crystals normal to the laminar plane. *a* axes probably $\perp^r$ to the line growth
		(B) ,,	Plane $\|^l$ to the field	,, $7 \cdot 0$	
		(C)	,,	$7 \cdot 2$	
Meretrix casta ..	,,	(A)	..	$0 \cdot 0_5$	Trigonal axis of the crystallites of calcite $\perp^r$ to the shell plane
		(B) ,,	Plane $\|^l$ to the field	,, $5 \cdot 7$	
		(C)	,,	$5 \cdot 8$	
Mactra lurida ..		(A)	..	$0 \cdot 0_7$	Trigonal axis of the crystallites $\perp^r$ to the plane
		(B) ,,	Plane nearly $\|^l$ to the field	,, $5 \cdot 7$	
		(C)	,,	$5 \cdot 7$	
Mactra hebbalensis ..	,,	(A)	Line of growth nearly $\|^l$ to the field	$1 \cdot 7$	The values obtained with different specimens differed considerably. Those given are only approximate
		(B) ,,	Plane made an angle of about 15° with field	,, $6 \cdot 2$	
		(C)	Plane nearly parallel to the field	$5 \cdot 0$	

Vulsella rugosa (nacreous layer) ..	,,	(A)		..		0·1	The cokes of the aragonite crystals normal to the laminar plane
		(B)	,,	Plane parallel to the field	,,	7·2	
		(C)		,,		7·4	
Vulsella rugosa (calcitic layer) ..		(A)		..		0·1	Trigonal axis of the crystals $\perp^r$ to the shell plane.
		(B)	,,	Plane parallel to the field	,,	6·2	
		(C)		,,		6·4	
Turbinella pirum ..	Gastropod	(A)		Line of cleavage $\|^l$ to the field ..		0·4	Here also the values for different specimens differed by more than 15% and the orientation by about 10°
		(B)	,,	Plane made an angle of about 20° with field ..	,,	5·3	
		(C)		Plane nearly parallel to the field ..		4·7	

TABLE II.

	Mode of suspension	Orientation	Specific anisotropy $\times 10^8$ E.M.U.
Calcite	Trigonal axis horizontal	Trigonal axis normal to the field	4·0

For each mode of suspension, there are however two ways of suspending the piece ; the second being with the shell piece turned upside down. This gives an accurate method of determining the orientation in the field. We have only to take the mean of the two orientations of the piece corresponding to the two ways of suspending it.

In the author's earlier communication, it was mentioned that for determining the modulus of torsion of the fibre, a rectangular glass plate was employed. This cannot give accurate values, and therefore here, a circular disc suspended at its centre with its plane horizontal, was used. The field strength was determined with the help of the Grassot Fluxmeter. The other experimental details have been described in the earlier paper of the author.

The results are entered in Table I. Table II gives the values for a single crystal of calcite. In the notation adopted χ_1' and χ_2' are the maximum and minimum susceptibilities in the plane of the shell (algebraically) along mutually perpendicular directions. χ_3' is that normal to the plane of the shell.

The shells were all found to be diamagnetic.

5. *Discussion.*

It is easily evident from the results that the shell elements are crystalline, and regularly arranged to a greater or less extent.

In the case of *Placuna placenta* significant conclusions can be drawn since consistent results were obtained with several specimens. The behaviour of the shell in a uniform magnetic field corresponds exactly with the case dealt with theoretically, thereby indicating inclined orientation of the trigonal axes of the calcite crystals to the shell plane. The optical axis of the small crystals are inclined to the laminar plane at an angle of 64° and the inclination is in the direction of the fine lines seen on the thin foliæ. A simple calculation shows that the trigonal axis in a single crystal of calcite makes almost the same angle (63°, 48′) with faces of the form {110}. This evidently means that the long leaf-like elementary crystals of calcite have the direction of a crystal axis (which may be denoted the a_3-axis) lying along their lengths, the (110) planes being parallel to the laminar plane. These crystals themselves are arranged with their lengths parallel to the direction of the fine lines on the foliæ.

It is very likely, in view of the extreme thinness of the elements, that the (110) and $(\bar{1}\bar{1}0)$ faces are well-developed in them and this peculiar crystal *habit* then accounts for the foliated structure of the shell also.

We know that the prisms of calcite are orientated in the upper layer of *Pinna* with the prism axis normal to the shell surface. The anisotropy determinations show that the trigonal axes of the crystals are normal to the shell surface: which means that the optical axes of the prisms coincide with the prism axes. This agrees with the observations of Boggild. In the nacreous layer it is seen that the *c*-axes of the aragonite crystals are orientated normal to the laminar plane. As regards the orientation of the *a*- and *b*-axes, one cannot speak with certainty in view of the complications already discussed in the earlier communication of the author. It may, however, be tentatively inferred that the *a*-axes of the crystals are probably orientated perpendicular to the line of growth.

With *Mactra hebbalensis* no consistent results could be obtained. This is most probably due to considerable irregularity of structure. The *c*-axes of the aragonite crystals in this case seem to be inclined to the shell surface. In *Mactra lurida*, the probable orientation of the aragonite crystals is with the *c*-axes normal to the shell surface. No great difference was found in the anisotropies of the white and coloured portions of this shell.

In the calcitic layers of the shells of *Meretrix casta* and *Vulsella rugosa*, the crystals are evidently orientated with the optical axes more or less normal to the shell plane. In *Chank*, however, an inclined orientation is present.

It may be noted that in the case of the calcitic layers of all the shells investigated the values of the magnetic anisotropy are nearly the same as that of calcite. But in view of the irregularity in the arrangement of the crystals which we should expect, the values ought to be lower, but actually they are some 20% higher. The reason is not quite clear. It is probable that here also, the cementing medium makes a contribution to the anisotropy due to a quasi-crystalline structure as suggested in a previous communication by the author. Further investigation is necessary to elucidate this point. The magnetic anisotropy of the nacre of *Vulsella rugosa* and *Pinna bicolor* is seen to be higher than that of the respective calcitic layers below. This is evidently due to the greater regularity of arrangement of the crystallites in the former in layers, a characteristic feature of all nacre.

In conclusion, the author wishes to express his thanks to Sir C. V. Raman, Kt., F.R.S., N.L., for the kind interest shown during the progress of the work, and for helpful suggestions and criticism.

Summary.

The magnetic anisotropy of the shells of *Placuna placenta*, *Pinna bicolor*, *Meretrix casta*, *Vulsella rugosa*, *Mactra* sp., and *Turbinella perium*, have been determined. In all cases, the crystalline character of the elements as

well as their regularity of arrangement have been established and the probable orientations deduced. In the case of *Placuna placenta* information regarding the character and *habit* of the crystalline elements has been obtained.

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