On the origin of septarian structure.

(With Plate XI.)

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I. *Historical.*

IN the *Geological Magazine* for 1913 there appeared three papers discussing the origin of the system of cracks in septarian nodules. Dr. A. Morley Davies[1] opened the discussion in a paper where, after a summary of earlier literature, he again put forward an older idea. Without adducing evidence, he considered:

(*a*) that interposition of particles between those of the original matrix caused expansion which set up tensile strain in the growing body;

(*b*) that the cracking of the nodule was due to the relief of those tensile stresses.

J. E. Todd[2] followed, supporting the 'expansion' theory and adducing some evidence in favour of it. Later, T. Crook,[3] upholding the more popular 'contraction' theory, replied to both papers and to some extent disposed of Todd's evidence. He specified, however, that he considered the structure to be due to the shrinkage *on* a solid external shell as the cause, rather than contraction of the whole concretion towards the centre.

On reading these papers it seemed to me that the subject was not sufficiently investigated, and the results of work consequently undertaken are presented below.

II. *The Septarian Structure.*

Septarian structure is commonly stated to consist of radiating cracks uniformly widening towards the centre, with a series of concentric

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[1] A. M. Davies, Geol. Mag., 1913, dec. 5, vol. x, pp. 99–101.

[2] J. E. Todd, ibid., pp. 361–364.

[3] T. Crook, ibid., pp. 514–515.

cracks usually added. This combination would produce a spider-web appearance. This description is, however, inaccurate and misleading. Except at the margin, the 'radial' system is rarely radial, being more usually quite irregular, and the width does not increase uniformly towards the centre; whilst the 'concentric' series, where it can be detected at all, is more irregular still.

On the other hand, a typical septarian nodule such as Plate XI, fig. 1 (kindly lent me by Mr. H. C. Sargent), shows the following structures:

(1) The bulk of the interior is divided up into irregular polygons[1] the sides of which could only be classified into the above two systems very roughly and inexactly. In three dimensions they really correspond to columns of polygonal section which run vertically through the nodule. In some cases the columns are snapped across in the centre; and, when the spaces are filled, the interior of such a nodule then appears to be a mass of calcite. (The large nodule from the Oxford clay in one of the Palaeontological galleries of the British Museum is an example.)

(2) The width of the cracks except in the immediate neighbourhood of the outside boundary is independent of their position in the nodule.

(3) The cracks in the marginal region are radial or rather normal to the boundary. They increase in width for a short distance inwards until they pass between the polygons, but become very fine and die off towards the margin, rarely penetrating to the outside.

(4) Within the nodule there is also a very distinct line (marked *a* in the figure), concentric with the boundary and from a tenth of an inch to several inches within it. This line marks the outward limit beyond which the septarian cracking does not usually extend.

Now, instead of simulating a spider-web, it will be seen that this structure reproduces the appearance of a film of clay allowed to dry, i.e. mud-crack structure (Plate XI, fig. 3).[2] The remarkable resemblance of the cracking system to septarian structure will at once be noticed.

However, there are occasional occurrences where the cracks form a truly radial system, and I have seen examples with a distinct concentric crack (Plate XI, fig. 2). But I do not find a simple relation between the size of the nodule and the system of cracks developed, as Todd claims in the article referred to above. At Bracebridge, Lin-

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[1] A. Geikie (Text-book of Geology, 1903, 4th ed., p. 186) alone describes the cracking as polygonal.

[2] A similar figure of cracks in a dried clay film is given by S. Meunier, La Géologie expérimentale, Paris, 1899, p. 219, fig. 36.

colnshire, the smaller nodules had the typical structure. Moreover, the Museum collections that I have examined do not support Todd's contention. The system developed depends upon a number of factors, among which size is probably included.

III. *Cracks in Timber.*

Timber, particularly when dried or 'seasoned', often develops characteristic systems of cracks which depend upon the nature of the decay that has set in, and the particular kind of tree in question. There are three main types of cracks or 'shakes'.[1]

1. '*Heart Shake*' (fig. 1 *a*).—Cracks converge to the centre and increase in width uniformly towards the centre. This shake is due to incipient decay in the heart, and consequently more rapid drying takes place there. The shrinkage is chiefly circumferential.

2. '*Star Shake*' (fig. 1 *b*).—Radial system of cracks which increase in width outwards; due to the decay and more rapid drying of the outside. The shrinkage is again mainly circumferential, but in this case attains its maximum at the outside surface.

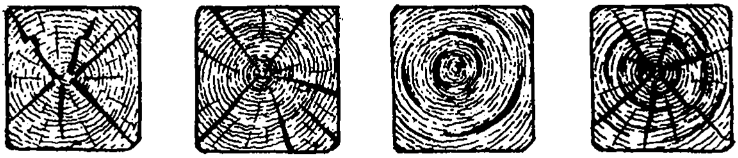

FIG. 1.—Cracks in timber.

a. 'Heart Shake.' *b*. 'Star Shake.' *c*. 'Cup Shake.' *d*. Shakes *a* and *c* combined.

3. '*Cup Shake*' (fig. 1 *c*).—Concentric cracks due to the decay and drying of the inside and its shrinkage towards the centre.

Therefore, in timber, radial and concentric cracks of the types that concern us are produced by the contraction, not expansion, of the inside. It is also interesting to note that when heart and cup shakes are combined (fig. 1 *d*) they produce the spider-web, but not the mud-crack structure.

IV. *Experiments with Clay Balls and Pats.*

In order further to test the type of crack produced by expansion and contraction, I made some balls of wet modelling clay about 2½ inches in

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[1] T. Laslett and H. M. Ward, Timber, 1894, pp. 54-58.

diameter, and surrounded them by a portland cement mixture to act as an indicator of the inside movements. The following observations were made:

Set 1.—Balls dried in air. No cracks at all appeared on the outside. On cutting through, the inside was found to have shrunk away from the outside, leaving a concentric gap. In some cases, where such a break was only partial, an irregular crack or so ran through the body of the clay, very crudely imitating septarian structure.

Set 2.—Similar balls immersed in water. The expansion of the clay inside cracked the outer cement coat, the cracks forming a polygonal system. No cracks of any kind, and no separation of the layers, appeared on cutting through.

Set 3.—Similar balls soaked in concentrated brine. In this case no cracks appeared *outside*, but inside there was a distinct concentric crack partially separating the inner from the outer shell. There was, therefore, *no expansion of the clay, but actual contraction.*

In order to obtain further confirmation of these important results under conditions more favourable for observation, pats of very wet Reading clay were placed on glass squares.

Set 1.—Air dried. The usual polygonal system and desiccation cracks appeared wider at the free surface and diminished towards the glass boundary (Plate XI, fig. 3).

Set 2.—Immersed in distilled water. A cut made in the pat was partially filled up, but otherwise no change occurred.

Set 3.—Immersed in a concentrated solution of calcium chloride. After five minutes there appeared a polygonal series of fine desiccation cracks giving similar polygons to, but smaller in area than, those of Plate XI, fig. 3. After immersion for some days there is no doubt that the clay was slightly firmer and harder.

These experiments and the consideration of timber cracks tend to show:

1. That slight contraction of the inside *on* a solid outside shell combined with strong circumferential contraction would produce radial cracks widening inwards.
2. That expansion of the interior would produce radial cracks widening outwards.
3. That contraction *on* the inside would produce concentric cracks.
4. That either free or chemical desiccation is competent to produce a polygonal system of cracks.

V. *Composition of Septarian Nodules.*

Any contraction theory assumes that the interior of a septarian nodule has a more 'clayey' composition than the outside. Todd, in his papers,[1] states definitely, but without offering much in the way of evidence, that the nodules are of uniform composition throughout. As I was unable to find any investigation of the matter recorded, I made the following partial analyses.

Alumina and the other constituents present in considerable quantity were estimated. It may be remarked that owing to the difficulty of separating the finer calcite veining from the matrix, the values for lime inside a nodule probably come out much too high.

	No. I. Bracebridge.		No. II. Nottinghamshire.			No. III.
	Outside.	Centre.	Outside.	One inch from outside.	Centre.	Typical Clay, Bracebridge.
SiO_2 ...	24·7	13·1	12·8	8·0	4·5	53·1
Al_2O_3 ...	18·6	35·1	trace	2·0	4·0	31·1
Fe_2O_3 ...	34·8	4·7	7·2	3·9	8·5	7·3
CaO ...	—	22·9	36·3	45·8	46·0	—

I, Ironstone Septarium 6 inches diameter, Lower Lias, Bracebridge, Lincolnshire (Plate XI, fig. 2).

II, Limestone Septarium 9 inches diameter, Nottinghamshire (Plate XI, figs. 4, 5, 6).

III, Typical Lower Lias Clay, Bracebridge, Lincolnshire.

An inspection of the above table shows that there is an excess of alumina in the centre, and if alumina may be taken as an index of the 'clayey' matter, there is also an excess of this within the nodule. The filling of the cracks points to subsequent infiltration and no doubt there has been a certain amount of cementation by iron or lime. But whilst the composition of the nodule as found cannot be assumed to be the same as at the time of fracture, still such evidence as there is goes to show that a distinct difference in composition existed between the interior and exterior of a septarian nodule, sufficient to warrant the assumption of the contraction theory.

A comparison of the centre of the Bracebridge nodule with clay (anal. III) from the same pit shows that the former is not an inclusion of this clay. For example, a considerable part of the silica has been removed so that there is not sufficient left to saturate the alumina. The facts

[1] J. E. Todd, loc. cit.; also Bull. Geol. Soc. Amer., 1903, vol. xiv, pp. 358-368.

point to considerable chemical changes in the enclosed clay accompanying the formation of the nodule. This, as mentioned later, may explain the fact that empty cracks do not close again when the nodule becomes saturated with water.

VI. *Causes of Septarian Structure.*

We are now in a position to examine the various theories that have been advanced to account for septarian structure:

(a) *Davies's Expansion Theory.*—Expansion of the nodule during growth by the swelling of any part of the interior through the addition of new material would produce a system of cracks widest on the outside, as shown in the experiments quoted. If expansion is merely the increase in size due to gradual growth, a different set of conditions arises. Dr. Davies points out that he would expect on his theory field evidence of the crowding of the layers immediately surrounding the nodule. As a matter of fact, evidence of this is abundant. At Bracebridge, I noticed that the clay contact-faces were slickensided; that incipient cone-in-cone structure was not uncommon; and I also noticed numerous examples of distortion of the lamination planes in the vicinity of a concretion. Todd, in the papers already quoted, draws attention to the same phenomena in American strata. Moreover, a belt of cone-in-cone clay is noticed surrounding several septarian boulders on a New Zealand beach,[1] although they are apparently not *in situ*.

It would be well to examine the nature of the stresses thus set up, and their competency to produce septarian cracking. The crowding of the strata during growth implies external pressure upon the nodule, and, although this is unknown, it may possibly reach a great magnitude. The case then becomes that of a thick spherical shell subjected to external pressure. An analysis of the stresses is unnecessary, but the general results may be seen in fig. 2.[2] On any element in the shell there is radial pressure depending on the dimensions and the external pressure, and a circumferential or 'hoop' tension. In general the intensity of this hoop tension is greater than the intensity of radial compression. Moreover, judging by the behaviour of building stone, portland cement, and other material resembling the nodules, these will possess greater resistance to compression than tension. In other words, when the limit is reached, the material will be likely to give way by tension along such

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[1] A. Hamilton, Trans. New Zealand Inst., 1901, vol. xxxiv, pp. 447–451. G. A. Mantell, Proc. Geol. Soc., 1850, vol. vi, p. 319 and figure.

[2] For a general analysis see A. Morley, Strength of Materials, London, 1908, pp. 293–297.

a surface as OA. This does not mean that a crack will open along OA—if it did we should expect it to widen outwards where the maximum tension exists. It means rather that the nodule would collapse; cones such as OAB sliding over one another. An interesting nodule shown in Plate XI, figs. 4, 5, 6, is doubtless a case of collapse by pressure.[1] A portion of the surface such as *a* has been forced in, whilst the other portions such as *b* have slipped outwards. With regard to the other phase of the expansion theory as set forth by Todd—namely, that the addition of material to the free surface of a growing nodule sets up internal stresses—I am in agreement with Crook that it is no more competent to do so in a nodule than in a growing crystal.

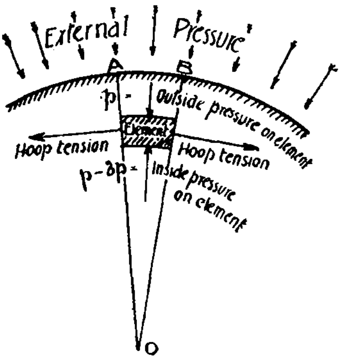

FIG. 2.—Stresses in a thick shell under external pressure.

(b) *Contraction Theories.*—These have been admirably summarized by Dr. Davies in the paper quoted, and whether contraction of the whole towards the centre is emphasized, or shrinkage on a rigid outer shell, they all look to drying as the cause of contraction. Todd[2] has criticized this theory not only on the score of uniform composition of the nodule, which I have already answered, but points out that these nodules often occur in a wet rock and are full of water themselves. Moreover, the presence of the calcite veins points to the presence of solutions since the cracks were formed. In place of the above I suggest *chemical desiccation* as the cause of the structure. This may now be examined.

(c) *Chemical Desiccation Theory.*—I do not regard either contraction

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[1] I have to thank the Rev. A. Thornley and Miss Andrews for bringing this interesting and critical example to my notice.

[2] J. E. Todd, Bull. Geol. Soc. Amer., 1903, vol. xiv, p. 359.

of the interior towards the centre, or its shrinkage on an external shell as a true description, except in a few exceptional and limiting cases. They are both special cases of general desiccation due to the nature of the boundary. The stresses set up in drying are readily understood. There is contraction towards certain centres such as *A*, fig. 3. This produces tension at surfaces such as that of which *BC* is a trace. The contractile force set up in the medium towards *A* is proportional to the volume involved and also probably to the rate and conditions of drying, and depends also on the nature of the medium; whilst the tensile stress is proportional to the area of the surface and, at the fracture point, to the resistance of the medium. The size of the polygons produced is, therefore, dependent on the nature of the medium and the physical conditions of desiccation. At the boundary, the contraction is not balanced, and there results a certain amount of free energy, which, in the case of clay films, results in the bending inwards of the sides (Plate XI, fig. 3).

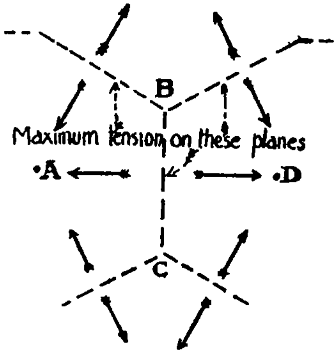

FIG. 3.—Desiccation stresses.

In Meunier's experiments,[1] he states that this force was sufficient to fracture 1 mm. glass. It is possible that this may have been the cause or a contributory factor to the collapse of the nodule just discussed, although the nature of the breakdown suggests that the explanation already given is the more likely. A further example of this contractile force is furnished by some Bracebridge nodules where large enclosed specimens of ammonites (*Amaltheus margaritatus*) are cracked across in the same way as the matrix.

That the cause of the drying may have been physico-chemical is rendered probable not only by the above experiments, but also by the

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[1] S. Meunier, loc. cit.

fact that the existence of the nodule is evidence of the presence of strong and even supersaturated solutions. Under the conditions of temperature and pressure that obtain in a rock, and with a large time factor, chemical desiccation may proceed to limits not attainable in a laboratory. A criticism of Todd's is interesting in this connexion, namely, that the nodule in water does not swell up and close the cracks. It is possible that the colloidal nature of the original rock has been destroyed by the chemical desiccation, and, as in the case of the dried peat, is incapable of recovering that state again. Moreover, I think there has been a certain cementation of the matrix by compounds of iron or lime. This would not merely destroy the colloidal state, but at the same time might cause further contraction; although, as Todd remarks,[1] there are no reliable data on this point. I am also convinced, as mentioned above, that there has been a removal of certain substances in solution, and this might well be a contributory cause to contraction. In discussing this subject Mr. W. E. Howarth remarked to me that the Lias clay at Whitby under the action of sea-water did not break down and become plastic as in quarries inland, but even boulders on the beach remained as hard as rock. I made some inquiries as to the action of sea-water on clay, but, through the lack of opportunity to examine the matter on the spot, I have been unable to arrive at a definite conclusion. Such clays, however, are often badly cracked.

VII. *The Filling of the Cracks.*

The filling of the cracks is undoubtedly subsequent to their formation, as shown by the following facts:

1. Some nodules (good examples can be seen in the Mineral Gallery, British Museum) show the cracks without any infilling or with just a layer of crystals lining the walls. There is every stage from the empty to the completely filled crack.

2. Under the microscope, the structure is that of an ordinary vein—namely, fibrous crystals lining the walls with equidimensional grains filling the centres of wider cracks. In the drusy centres of partially filled spaces the crystals have well-developed faces.

3. The system of cracks in the empty nodules is the same both in size and character as in the completely filled nodule.

4. There is evidence to show that the exterior of the nodules is permeable to diffusing solutions. On the tip heaps at Bracebridge, for example, there is abundant evidence of a passage of iron outwards from

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[1] J. E. Todd, loc. cit., 1903, p. 360.

the centre of the weathered nodules. The dried nodule is also fairly porous, as shown by its soaking up coloured fluid.

The vein material is usually calcite, but pyrites in ironstone nodules is not uncommon, although it rarely fills the larger cracks. This is no doubt deposited by the reaction of organic by-products such as hydrogen sulphide with infiltrating bicarbonate of iron solution. Barytes and other minerals are also occasionally found as vein material.

VIII. *Rhythmic Deposition.*

Field evidence strongly suggests that Liesegang's diffusion theories[1] are, as in the case of flint, applicable to the formation of these concretions. In the first place it may be noted that in accordance with Liesegang's law of form[2] these concretions tend to be spherical or sub-spherical. The sub-spherical form is due to the greater ease either of diffusion or of growth along bedding planes—a fact that has long been recognized.[3] Again septaria occur in definite bands which recur at regular intervals, e.g. at Bracebridge[4] and at Cuffley,[5] as we might expect if the deposition followed a rhythmic law. Strong evidence on this point would be obtained if the distributions of the concretions in any one band could be ascertained, such, for example, as the arrangement of the nodules in concentric circles corresponding to the deposition circles of Liesegang's plates. Unfortunately the quarry rarely exposes a floor of nodules in this way; but, by examining adjacent sections at Bracebridge, I came to the conclusion that an arrangement of this type was possible. Liesegang points out that in depositions of this sort two processes are to be distinguished:[6]

1. The formation of the material precipitated—a chemical process. In this case probably a gradual accumulation of solutions of bicarbonates by the action of the organic by-products on finely disseminated compounds of iron or lime in the rock.

2. The precipitation of the same—in general a physical process. It is to be noted that the solutions may be in the labile state or they may be precipitated by nuclei. It is commonly stated that the nuclei of these concretions are often fossils. This is not, however, borne out by

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[1] For a brief account of these theories see G. A. J. Cole, Geol. Mag., 1917, dec. 6, vol. iv, pp. 64–68.

[2] R. E. Liesegang, Geologische Diffusionen, Dresden and Leipzig, 1913, chap. vi.

[3] J. Geikie, Structural and Field Geology, Edinburgh, 1912, p. 121.

[4] For the section at Bracebridge see A. E. Trueman, Geol. Mag., 1918, dec. 6, vol. v, p. 103.

[5] R. W. Pocock and L. Wells, Proc. Geol. Assoc., 1914, vol. xxv, p. 78.

[6] R. E. Liesegang, loc. cit., chap. x, Rhythmische Fällungen.

careful examination in the field. At Bracebridge, for example, whilst there are some remarkable examples already alluded to where large specimens of *Amaltheus margaritatus*, &c., are included in the nodules, the bulk are without fossils of any kind. Moreover, where fossils such as ammonites, brachiopods, &c., do occur they are rarely central. Their distribution in the nodule is as sporadic as in the rock itself, and they may occur partly included in the nodule and partly in the surrounding clay. Again, one layer of nodules at Bracebridge, which yielded scarcely any fossils, occurred only about three inches above a rich and well-defined fossiliferous band consisting largely of small ammonites. On the whole, I am inclined to think that these depositions are rhythmic and are precipitated from labile or metastable solutions, and that the presence of fossils has had little influence in determining the position of the bands. They do not show concentric lines of growth and are the result of continuous precipitation in a colloidal medium, although in the same quarry at Bracebridge small ironstone concentrations in the Middle Lias have concentric structure and are non-septarian.

Summary.

In this paper an endeavour has been made to establish the following points:

1. That septarian structure consists of a polygonal system of cracks corresponding to a mud desiccation structure.

2. That the cracking of the nodule is due to the desiccation of a colloidal centre by chemical means.

3. That the nodules originated by the rhythmic precipitation of solutions diffusing through a colloid according to Liesegang's laws.

Finally, in addition to acknowledgements made in the text, I beg leave to thank Professors H. H. Swinnerton and C. H. Bulleid for helpful criticism; Mr. H. Preston for placing his collection at my disposal; the chemical staff of University College, Nottingham, for generous assistance; and Dr. G. T. Prior for his kind attention at the British Museum.

EXPLANATION OF PLATE XI.

Fig. 1.—Typical septarian nodule from the Lias of Nottinghamshire, showing a concentric line at *a*. The original 6 inches in diameter (p. 328).

Fig. 2.—Ironstone nodule from Bracebridge, Lincolnshire, showing a large concentric crack. Original 6 inches in diameter (p. 328; analyses of the inner and outer portions on p. 331).

Fig. 3.—Film of Reading clay on glass plate dried in air, showing polygonal cracks, which decrease in width towards the glass boundary where contraction is restrained, and imitating septarian structure (p. 330).

Figs. 4–6.—Collapsed limestone septarian nodule from Nottinghamshire: fig. 5, the nodule viewed from above; fig. 4, vertical section through XX; fig. 6, horizontal section. Size 9 inches in diameter (p. 333; analysis on p. 331).

Fig. 1.

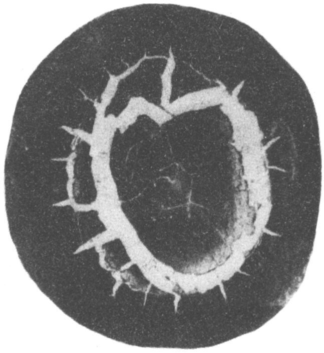

Fig. 2.

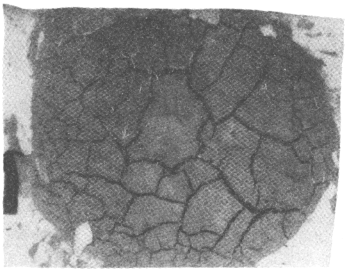

Fig. 3.

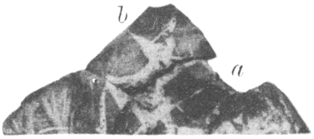

Fig. 4

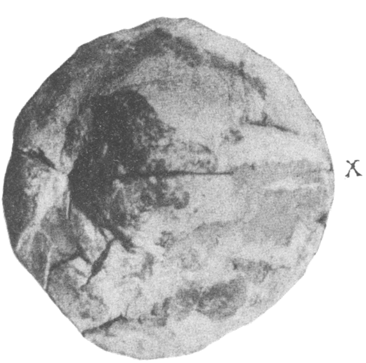

Fig. 5.

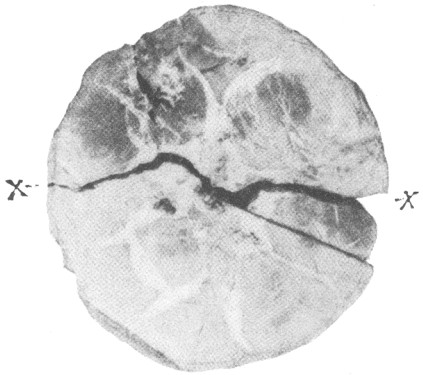

Fig. 6.

W. A. Richardson: Septarian Structure.