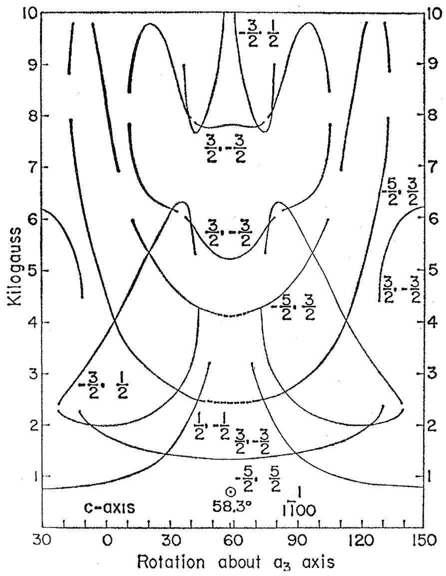

Fig. 1. Angular variation of electron paramagnetic resonance spectrum at 20°C (9.501 Gc) for Fe^{+3} centers in amethyst (dashed lines were not observed).

ated by natural ionizing radiation from precursor centers which arise from substitution of Fe^{+3} at silicon sites. The same Fe^{+3} centers are responsible for the dominant features of the electron paramagnetic resonance (EPR) spectrum of amethyst. The substituent Fe^{+3} is not distributed equally among the equivalent sites in natural crystals.

The color of amethyst is bleached by heat treatment in air at 400°C, but it is restored by x- or γ-radiation. Amethyst is markedly pleochroic, and Pancharatnam (*1*) has shown that there are three principal color directions, namely, along one twofold axis, and two directions perpendicular to this axis. Moreover amethyst is optically biaxial with the acute bisectrix containing this same twofold axis. Both of these facts are in direct conflict with the trigonal symmetry of α-quartz. Laue x-ray photographs of the optically biaxial amethyst crystals show only very minor distortions from holotrigonal symmetry.

Using an X-band paramagnetic-resonance spectrometer, we have identified the transitions of Fe^{+3} centers in sites having the twofold axes of α-quartz. The angular variation of the spectrum (Fig. 1, for rotation about the a_3-axis) indicates that the center is strongly anisotropic, with an axial distortion along the twofold axis, but with a still stronger orthorhombic distortion. The anisotropy of the center could be caused by a charge-compensating ion on the twofold axis. This model is supported by a barely resolvable four-line hyperfine structure of one of the transitions, indicating an interaction with a nuclear spin of 3/2, which could be an alkali or alkaline-earth cation acting as charge compensator.

A most important feature of the electron paramagnetic resonance spectrum is that, although three sets of spectra from the three equivalent sites in the crystal are observable, these are of greatly unequal intensity, in the order 10.0 : 1.2 : 0.8 in the most studied crystal. The twofold axis corresponding to the center of highest concentration is the same as that for the color and the optical biaxiality. The intensity of the electron paramagnetic resonance centers is increased slightly by the heat treatment at 400°C that destroys the color; hence, the electron paramagnetic resonance center is not identical with the color center, but appears to be directly related to it as a precursor which can be converted to the color center by radiation. Further evidence for this relationship comes from the heat treatment at 650°C which equalizes the intensities of the equivalent electron paramagnetic resonances, removes the optical biaxiality, and also removes the pleochroism of a basal section in a specimen recolored by x-rays.

Although the three sites are equivalent in the crystal structure, they can be markedly distinguished relative to developing faces during the growth of the crystal. We have observed that the electron paramagnetic resonance centers occur only in those regions of a synthetic crystal that contain Fe^{+3} that can be subsequently colored amethyst by x- or γ-radiation. These regions lie below the positive rhombohedral faces of the crystal, as do the colored regions in natural crystals. Relative to these faces, the silicon sites have quite dissimilar positions, and the difference in population of Fe^{+3} substituted in these sites can readily arise during the hydrothermal growth of the crystal. Thus, quantitative study of the incorporation of Fe^{+3} in synthetic crystals should provide a basis for geochemical conclusions concerning the conditions of natural growth. The proposed mechanism also serves to rationalize the observations of Melankholin and Tsinober (*2*) on synthetic quartz containing Fe^{+3}.

The optical biaxiality of amethyst is a direct consequence of the unequal occupation of crystallographically equivalent sites by the color centers, the concentrations of which are too low to distort the x-ray symmetry of the crystal as a whole.

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Fossil Microorganisms: Possible Presence in Precambrian Shield of Western Australia

Abstract. *A quartzite believed to be at least 2700 million years old contains pockets of minute red or yellow objects presumably composed of hematite and goethite, respectively. The size and morphology of the objects suggests that most of them may be the remains of microorganisms of at least two species.*

In the vicinity of Southern Cross, Western Australia, a fine-grained quartzite is associated with a banded-iron formation in a belt of "greenstone", which has been intruded by granite and lithium-bearing pegmatites; the latter have been dated by rubidium-strontium and potassium-argon methods and are estimated to be about 2700 million years old (*1*). By the uranium-lead method of dating, galena from an auriferous lode in the same zone of banded-iron formation in greenstone at Bullfinch, 35 km north of Southern Cross, was estimated to be about 2340 million years old; this is taken as the age of the mineralization which brought in the gold, and is assumed to be associated with a later period of granite intrusion (*1*). As it therefore appears that the age of the greenstones and associated banded-iron formations and quartzites is not less than 2700 million years, it was with some surprise that one of us (C.G.A.M.) discovered, within a sample of the quartzite from near Southern

Cross (2), objects which appeared to be of biological origin.

In hand specimens the quartzite has a rather vitreous lustre, with irregular maroon and yellow-brown patches up to about 5 mm across. Microscopic examination of thin sections of the rock showed that it consists mainly of quartz grains which have a slightly undulose extinction and are very angular, with no signs of rounding or corrosion; their average diameter is about 0.15 mm. The grains are imbedded in a colorless, transparent, nonfibrous cement which has a fairly high negative relief with respect to the quartz. The veinlets of the cement are, on the average, about 7 μ thick; but their dimensions vary considerably because of the irregularity of the quartz grains. As there is always quartz above or below the cement, even in thin sections, its optical characteristics are obscured. But tests on pulverized material revealed that the cement is apparently isotropic, with a refractive index above 1.435 and probably nearly 1.440; the balance of evidence therefore suggests that it is opal.

Scattered throughout the cement veinlets are myriads of minute brick-red or lemon-yellow bodies which, presumably, consist of hematite and goethite, respectively. It is the occurrence of these bodies, in pockets consisting almost entirely of one type or the other, which gives the color to the maroon and yellow-brown patches seen in hand specimens. The bodies differ not only in color and composition but also in morphology, and there is complete correlation between color and morphological type. The two commonest types, the R (red) and Y (yellow) series, account for almost all the colored material in the sections, and each exhibits a range of forms that can easily be interpreted as successive developmental stages in hypothetical "life-cycles." In the descriptions of these bodies we have, for the sake of clarity, arranged the various observed forms of the R and Y series in the order of such plausible developmental sequences. A third type, the M (mixed red and yellow) series, is relatively rare, but its members appear to be aggregates of objects of the R series around a yellow core of objects belonging to the Y series.

In the R series (Fig. 1, *a–f* and *h*) the simplest forms are spheres of diameter about 2.3 μ which seemingly elongated to give bacilliform objects about 2.3×3.1 μ. Further elongation was accompanied by progressive central constriction in a plane at right angles to the long axis, producing objects with the appearance of a figure eight; at this stage the two near-spheres occasionally appear to be separated by a distinct "cell wall," and a dark spot may be visible inside one or both of them. Possibly, the objects might then have sometimes completely separated from each other, but it seems that they more commonly remained attached and proceeded to extend along axes roughly at right angles to the previous axis of extension, and again underwent constriction. Repetition of such processes would have led ultimately to the more or less equidimensional closely-packed aggregates of spheres seen in the sections; the occasional separation of "viable" spheres from the aggregates could have completed the cycle. Two striking attributes of the R series are the relative constancy of the diameters of the spheres and bacilliform objects, and the fact that virtually all the red objects clearly consist of singlets, doublets, triplets or larger groups of units with the same diameter. One hundred single spheres and bacilliform objects were chosen at random and measured after projection at a magnification of 10^4; their diameters fell within the range 1.9 to 2.6 μ with a mean and S.D. of 2.3 ± 0.15 μ. Similar measurements of the "lobes" of more complex R aggregates fell within the range 1.7 to 2.9 μ, with a mean and S.D. of 2.25 $\pm$ 0.25 μ.

The Y series (Fig. 1, *i–u*) shows a type of morphological development in which a strange "double-budding" procedure apparently took place, giving rise to distinctive forms unlike those of any extant microorganisms with which we are acquainted. The simplest object has a pyriform or peg-top shape, measuring about 2×1 μ, which seemingly developed into a rod with clubbed ends, either before or subsequently to its developing a pair of lateral buds on one side. In either case, the result was a

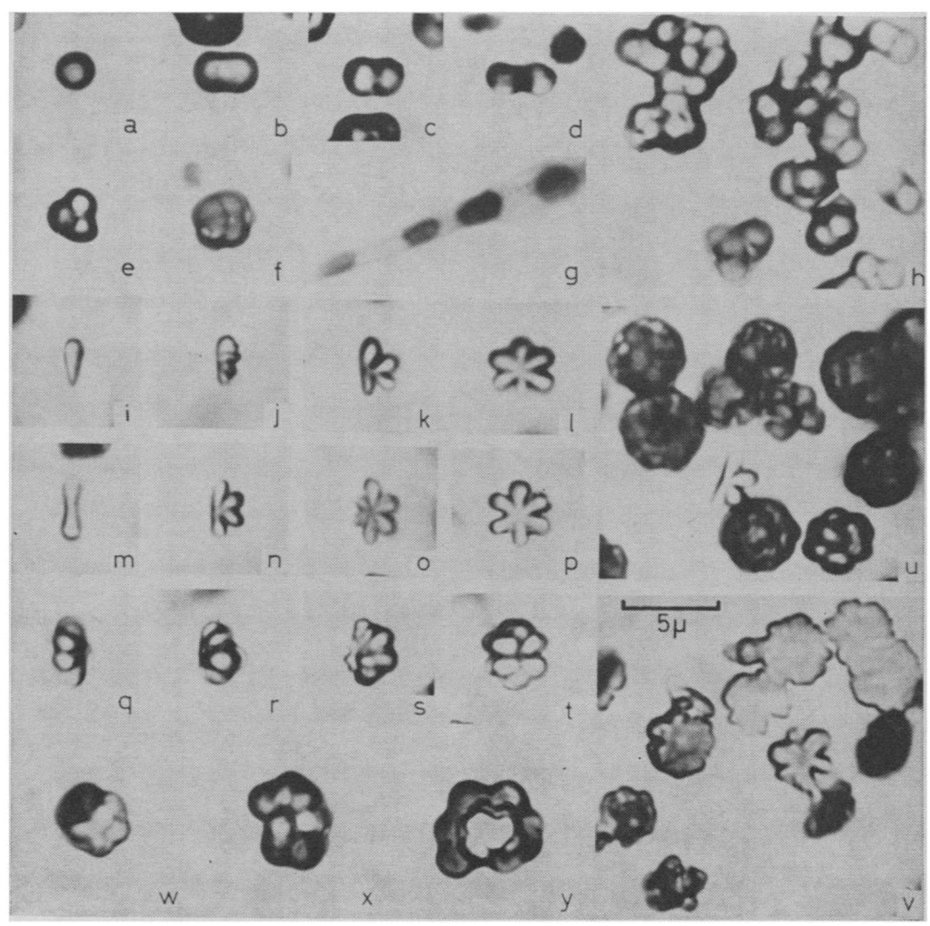

Fig. 1. (*a* to *f*) Typical R forms; (*g*) R forms distorted by entry into a narrow veinlet of cement; (*h*) general view of R-form aggregates; (*i* to *t*) typical Y forms; (*u*) general view of "mature" Y forms; (*w*, *x*, and *y*) typical M forms; (*v*) some Y forms squashed between adjacent quartz granules. All reproductions are to the same scale, which is shown in (*v*).

planar K-shaped tetrad of pyriform lobes. The formation of two more buds on the opposite side produced a symmetrical planar hexad; double-budding next occurred in a plane at right-angles to that of the hexad giving octads and then decads. Beyond the decad stage the lobes are so closely packed that we are unable to follow the hypothetical developmental sequence in detail; but it seems clear that they passed through this multi-lobed stage, measuring about 4 μ in diameter, to a final stage in which the clear outlines of the individual lobes are almost obscured and the objects are roughly spherical, about 4.2 μ in diameter, with a raspberry-like surface. The occasional detachment of single viable pyriform lobes or more complex aggregates could have completed the cycle. It appears that less regular developmental sequences, often involving the retarded "maturation" of one or more buds, must have been common.

The proportion of yellow objects in pockets of the Y series which cannot easily be interpreted as stages in the described developmental sequence is small. However, some of the yellow material occurs as minute, roughly equidimensional, angular granules scattered singly or in groups throughout the rock sections. Their size varies considerably, but is generally up to about 0.6 μ. We assume at present that the granules do not belong (in the developmental sense) to the Y series, because of their irregular shape and size, and the fact that they are more common in the red than in the yellow pockets, but we have no suggestions to make about their origin or significance.

We are also unable to say much about the relatively rare objects of the M series (Fig. 1, *w*, *x*, and *y*) which are up to about 8 μ across. They consist of a yellow core often lacking the symmetrical lobulate structure of advanced stages of the Y series, partially surrounded, and sometimes more or less enclosed, by typical objects of the R series. But they are not the invariable consequence of the mixing of objects of the R and Y series, because members of those two series are sometimes found to be freely intermingled at the junctions of red and yellow pockets without the formation of any M objects.

No carbon has been detected in the quartzite, and we have no direct evidence for supposing the colored objects to be of biological origin; nor can we prove that the orders in which we have described the various R and Y forms actually correspond to temporally-successive stages of development. Indeed, some of the forms occur rather less frequently than we would have expected if our proposed sequences were completely correct. On the other hand, we are unable to conceive of any inorganic processes which would give rise to series of minute, rounded, and seemingly noncrystalline objects of such constant dimensions, assembled into such markedly lifelike patterns as these just described. It might be argued, however, that the most complex objects in the R and Y series are really the remains of relatively resistant "fruiting bodies" composed of masses of the "spores" of higher organisms whose vegetative structures have completely disappeared; and that we are merely observing stages in the disaggregation of the spore masses into their constituent units. But such an interpretation would not account satisfactorily for the bacilliform and figure-eight objects in the R series, or for the partially-formed buds in the Y series. We therefore feel that although our reconstructions of the "life-cycles" may be confused or incomplete, they do at least have the arrow of time pointing in the right direction.

It seems that the microorganisms, if such they were, could have been either iron-oxidizers during life, or that the oxides were formed as the result of secondary changes after death. The occurrence of objects of the R series which have been distorted by entry into exceptionally narrow veinlets (Fig. 1*g*) or of the Y series which have been squashed flat between adjacent quartz grains (Fig. 1*v*) suggests that they were plastic at some stage.

The most intractable aspect of the problem is the assessment of the age of the objects. They cannot be younger than the interstitial cement in which they are imbedded, but the date of the silicification producing that cement is at present unknown; it might have occurred at any time later than the Archaeozoic. If the cement is in fact opal, it seems probable that it must have been formed more recently than the Precambrian and fairly near to the surface rather than at great depth. But the objects could have been present in the rock long before the period of silicification. Thus, at present it can only be said that the objects of the R and Y series are apparently fossilized microorganisms of two new species and that, if they are contemporaneous with the sediments in which they occur, they are possibly at least 700 million years older than the oldest structurally preserved organisms previously described (*3*).

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Solar Neutrons and the Earth's Radiation Belts

Abstract. *The intensity and spectrum of solar neutrons in the vicinity of the earth are calculated on the assumption that the low-energy protons recently detected in balloon and satellite flights are products of solar neutron decay. The solar-neutron flux thus obtained exceeds the global average cosmic-ray neutron leakage above 10 Mev, indicating that it may be an important source of both the inner and outer radiation belts. Neutron measurements in the atmosphere are reviewed and several features of the data are found to be consistent with the estimated solar neutron spectrum.*

In a recent communication Simpson suggested (*1*) that the continuous flux of protons below 200 Mev observed in balloons in the upper atmosphere (*2*) and on the earth satellite Explorer XII (*3*) may be the decay product of neutrons emitted by the sun. We consider here the energy spectrum and intensity of the solar-neutron flux required to produce the observed low-energy pro-