

# ORIGIN OF LIFE ON EARTH: SELF-ORGANIZING VESICLE-LIKE STRUCTURES IN CORDIERITE-ROCKS FROM SOTO (ARGENTINA)

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(Manuscript received October 5, 1995; accepted in revised form October 9, 1996)

**Abstract:** At Orcoyana, in the Soto region (Argentina), two types of cordieritic rocks outcrop: a light variety and a dark variety. Both of these contain, in very different quantities, very peculiar structures considered in literature as porphyroblasts. In order to gain insight into their origin, a petrologic and geochemical study was carried out. In the light of the new ordering principle, called "order through fluctuation", we applied the basic principles of self-organization dynamics to the Argentine structures. They appear to have "self-organized" as colloidal dissipative structures which formed in a self-organizing basic fluid. According to us, the origin of the Argentine structures involved a phase separation process ensuing from spontaneous density fluctuations in critical conditions. As the phase separation proceeded the fluid comprised immiscible portions in a state of emulsion. When the segregated phase was very concentrated, the Argentine fluid exhibited three distinguishable phases. From a thermodynamic point of view, there was a three-phase system, like a vesicle, with an interior, barrier and exterior.

**Key words:** Argentina, self-organization, cordierite-rocks, structural characters.

## Introduction

Self-organization is the dynamic principle underlying the emergence of a rich world of forms manifest in various types of structures, for example, biological, geochemical, and geophysical. It characterizes one of the two basic classes of structures which may be distinguished in physical reality, namely, the dissipative structures which are fundamentally different from the equilibrium structures. Dissipative structures exhibit two different types of behaviour: near their equilibrium, order is destroyed (as it is in isolated systems), but far from equilibrium, order is maintained or emerges beyond instability thresholds (see e.g. Prigogine et al. 1972; Nicolis & Prigogine 1977; Helleman 1980; Jantsch 1980; Prigogine & Stengers 1984). As long as dissipative structures exist, they produce entropy. However, this entropy does not accumulate in the system but is part of a continuous energy exchange with the environment. Entropy can also remain at the same level or even decrease in the system. Structures of this kind constitute the simplest case of spontaneous self-organization in open evolution (see e.g. Kauffman 1989; Ortolova 1994).

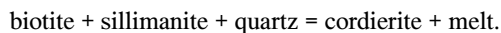
During research carried out on cordierite-rocks of the Soto region (Argentina), very peculiar structures were discovered (Gordillo 1974). The study of these structures and their host-rock appears of considerable interest because it may provide valuable petrogenetic information on self-organization dynamics which closely links together the animate and inanimate realms. By extrapolating from the most basic mechanisms by which non-living organisms produce "complexity", we seek to elucidate chemical mechanisms by which the same fundamental processes could be achieved in living systems. In this paper petrologic, geochemical, and structural

features of the Soto rocks are presented. They show how spontaneous organization worked into originating vesicle-like structures in an Argentine basic colloidal fluid. Following this a comparative analysis with membrane vesicles (protocells) is carried out.

## Petrographic features

The Soto region (Argentina) is part of the extensive Precambrian basement of the Sierra de Cordoba, which is composed of high-grade gneisses, migmatites and intrusive granites. In this region, forming a roof over five small granite hills, occur rocks containing cordierite in considerable and unusual quantity (80-90 %). The country rock, El Pilon granite, is a small pluton, outcropping over an area of ca. 16 km<sup>2</sup>, emplaced within quartz-biotite schists, some of which remain as relicts in the granite and cordierite rocks. Because of their beautiful blue colouring the Soto rocks have been intensively quarried as ornamental stones. The principal outcrops were found at Orcoyana in the quarries of Cerro Negro and Tamain (65°00' W and 30°58' S, 800 m above sea level), 184 km NW of Cordoba City. The rock bodies show evident signs of cataclasis and are more or less lenticular in shape. They vary in length from 40 to 60 m and in thickness from 5 to 10 m. The Argentine rocks are essentially of two kinds: 1) a light variety, which is more abundant in the Tamain quarry and is composed entirely of coarse-grained pale greyish blue cordierite with accessory quantities of biotite, quartz and plagioclase, 2) a dark variety, prevailing in the quarry of Cerro Negro, rich in biotite (15-38 %) with accessories of quartz and plagioclase (Schreyer et al. 1979). In some outcrops the green line in the rock is due to scarce chlorite de-

rived from the alteration of cordierite or biotite. The remaining minor components of the cordieritic rocks are: sillimanite, muscovite, apatite, sporadic tourmaline and rarely epidote of the piemontite type. Under the microscope the cordierite crystals are generally xenoblastic, though idioblastic crystals do occur. Cordierite is generally pure, but in some cases sillimanite, zircon, biotite and quartz occur as inclusions. Its optic axial angle ( $2V\alpha$ ) is  $78^\circ$ . Biotite approaches 1–2 mm in length and occurs as brown lamellae often having fringed ends. In the Cerro Negro rocks biotite is deformed, partially replaced by sillimanite, and in some cases chloritized. Sillimanite occurs in prismatic or fibrous aggregates along with cordierite and biotite; it rarely occurs inside quartz crystals. Interstitial quartz and plagioclase are rare, but they greatly increase in quantity in some neighbouring minor outcrops (Gordillo 1974). According to Gordillo (1974), the Argentine cordierite-rocks owe their origin to a metasomatic process which involved the allochemical addition of Al-Mg-Fe-Mn as a basic front, derived from the granite, to the enveloping quartz-biotite schists. Subsequently, Schreyer et al. (1979) suggested that the cordieritic rocks from Soto originated by anatexis. According to these authors, rocks initially rich in biotite and sillimanite melted by the reaction:



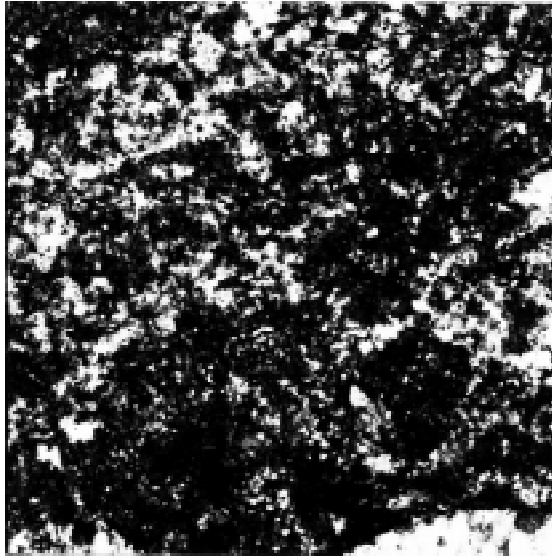
In particular, the cordierite and residual biotite remained as a sort of restite because they were refractory relative to the consequent melt which migrated away and was largely incorporated into the neighbouring granitic magma.

### Textural evidence

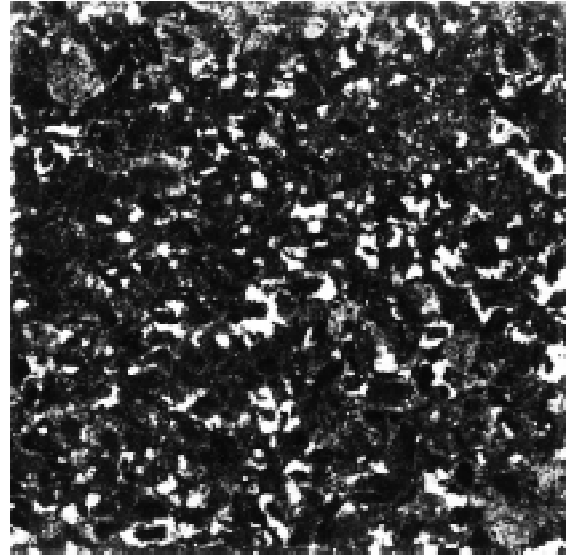
In many outcrops the cordierite occurs as unusual subspheroidal or oviform shapes. Most of these shapes range from 4 to 6 cm, but in some places they reach approximately 20 cm in their greatest dimension (see Fig. 6d as an example). These spheroids are often rimmed by aggregates of biotite. The smaller spheroids are monocrystalline, the larger ones are polycrystalline aggregates in a groundmass rich in quartz and feldspar (Schreyer et al. 1979). In the literature (Gordillo 1974; Schreyer et al. 1979) these structures are considered to be porphyroblasts. However, the following evidence sharply contradicts this view: a) the rock does not have the typical banded structure of a gneiss; b) the rock does not possess the characteristic fabric of a hornfels, c) cordierite is coarse grained (its grains generally measure from 2 to 10 mm) and becomes only rounded by granulation; d) interstitial quartz generally shows the effects of strain, whereas cordierite is rarely affected; e) the fact that spheroids were soft and capable of being deformed (Figs. 5c and 6d) strongly suggest colloidal conditions of formation. In this respect, the study of colloidal fluids as precursors of rocks has become more and more important in any petrogenetic process, whatever the nature of the fluid may be, magma, partial melt, or aqueous solution (Lucido 1993a). Today, the term colloid is indistinctly applied to all systems formed by entities having high specific surfaces independently of the dispersed substance (see e.g. Hiemenz 1986; Hunter 1987; Lyklema 1993). In particular,

silicate colloidal particles can be either lyophilic or lyophobic depending on whether the energy obtained by their net interaction is higher or lower respectively, than the sum of their attraction energy and the repulsion energy of the silicate fluid. This net interaction is dependent on temperature, electrolyte concentration, interparticle distance and the size and shape of the particles making up the fluid (for further information on silicate colloidal dispersions, the reader is urged to see Elliston 1984; Lucido & Triolo 1989; and Lucido 1993a,b).

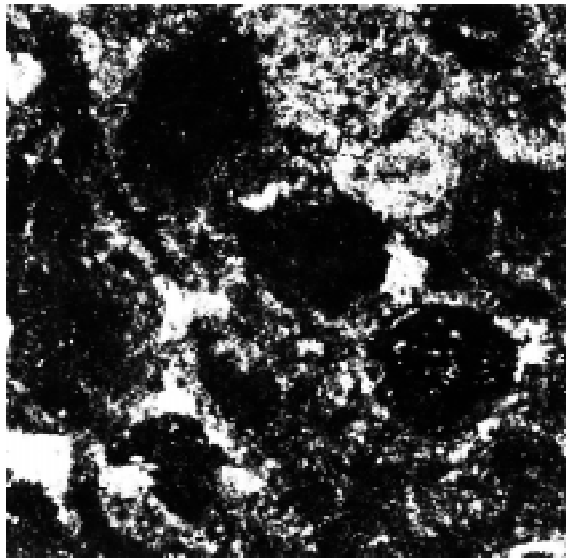
In order to gain insight into the origin of the above spheroids, several Argentine rocks were sectioned. Fig. 1 shows an incipient phase separation process producing light "micellar" (micelle is a colloid particle in suspension obtained by the reversible association of a large number of amphiphilic molecules under the effect of the solvent) acidic particles in the Argentine basic fluid. The chemical and physical properties of this fluid are similar to those indicated for a mud flow. In particular, the solid phases comprising the body of the material are the same: essentially hydrated aluminosilicates, silica gels, and hydrous ferromagnesian minerals. The only difference could be the temperature which is largely dependent on burial depth. The melt from which spheroid develop is of necessity, therefore, a colloidal system of mixed hydrosilicates. The unique properties reside in the large surface to volume ratio of the dispersed phase, such that the surface energy becomes an important component of the total energy of the fluid. In this respect, in fact, the acidic particles form a strong contrast to the black basic portion and indicate colloid formation; in the most general terms they are coacervate-like particles, and essentially are cordieritic in composition. Clearly visible are primary plate-like particles (platelets), subspherical flocs and clusters of flocs. Organic structures of this type have been suggested as being significant in biogenesis (e.g. Oparin 1924; Haldane 1929; Bernal 1954). Fig. 2 exhibits an emulsion-like structure. This textural relationship indicates liquid immiscibility between the acidic and basic portions. Liquid immiscibility occurs when the positive enthalpy of mixing outweighs the entropy of mixing term so that the free energy of mixing is positive (Ryerson & Hess 1978). In practice, each element distributes itself between the two liquids in such a way as to achieve a minimum energy state. This implies that the structural characteristics of basic melts more readily permit stable coordination of cations by oxygen (Watson 1976). Therefore, the elements normally forming framework structures are concentrated in the acidic portions, whereas the less polymerizing ones are partitioned into the basic portions (Hess 1971). The dimensions of these portions suggest that the unmixing phenomenon is not related to an early stage of evolution. The immiscible lighter portions scattered in the black basic fraction of Fig. 2 have a quartz-feldspathic composition. Fig. 3 shows a well-developed spotted texture. Fe-Mg rich basic spots (or spherules) are dispersed in a clearer Al-Si rich phase. The spotted texture is inverted if compared with the texture showed in Fig. 1. The latter shows light acidic particles scattered in the basic matrix, whereas the spotted texture has basic spots dispersed in the acidic fraction. Card-house texture is incipient all around the basic spots. Further textural evidence of the



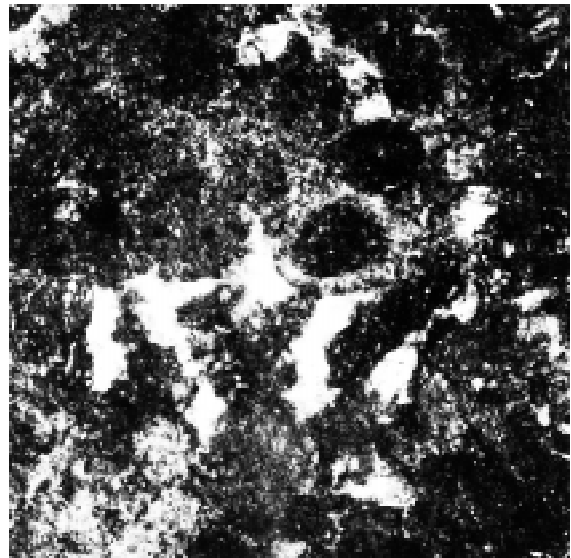
**Fig. 1.** Phase separation in the Argentine basic fluid. "Micellar" cordieritic particles: platelets, flocs and clusters of flocs. Width of figure is 10 cm.



**Fig. 2.** Emulsion-like texture from an Argentine rock-sample. Basic and acidic immiscible portions showing lobate margins. Width of figure is 60 cm.



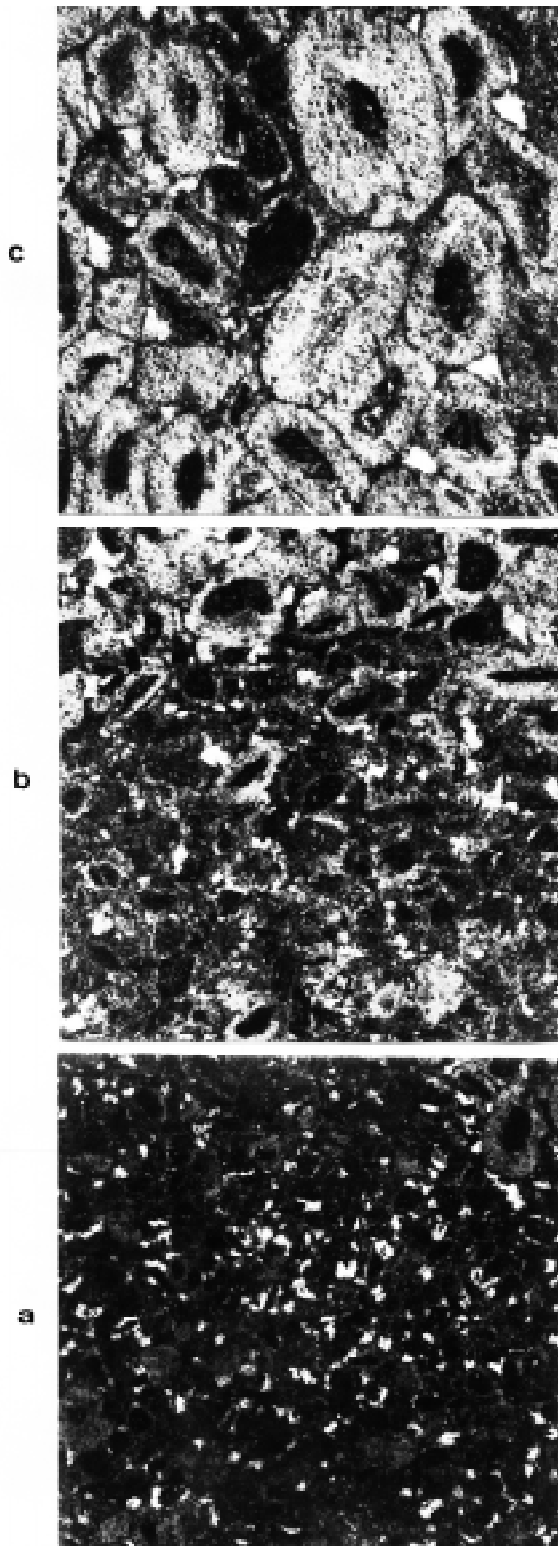
**Fig. 3.** Detail of Argentine rock showing reverse colloidal phases forming spotted texture. Evident basic spots (or spherules) are scattered in the light acidic portion. These spots are the future nuclei of the Argentine spheroids. Width of figure is 12 cm.



**Fig. 4.** Detail of Argentine rock exhibiting "reverse or inverted micelles"-type blobs. Note the radial organization of the light cordieritic chains all around the basic polar portion. Width of figure is 13 cm.

process forming colloidal aggregates in the Argentine basic fluid is shown in Fig. 4. This figure exhibits blobs conceptually similar to "reverse" micelles. They consist of a cordieritic non-polar lyophobic portion (straight chain) attached to a basic lyophilic polar portion. These reverse colloidal phases originated when high concentrations of cordieritic material was reached, because the basic polar portion is characterized by the tendency to associate with itself rather than to remain in close proximity to the cordieritic chain. Sometimes, in both Cerro Negro and Tamain quarries, the dark basic and the light cordieritic rock outcrop in continuity. Fig. 5 shows

the transition between the dark variety and the light variety. More specifically, at the outcrop scale, Fig. 5 illustrates the evolution (from bottom to top) of the phase separation process which led to the formation of the subspheroidal structures. In particular, Fig. 5a exhibits incipient subspheroidal structures. Fig. 5b represents a nucleation process all around the basic spots: spheroids at different stages of growth are evident. Finally, Fig. 5c shows well-developed oviform structures always having a basic nucleus inside. From all the above-reported data and from the geochemical and petrological research that we have carried out (Lucido 1981, 1983a,



**Fig. 5.** Three different stages showing the evolution in time (from bottom to top) of the formation process of the Argentine structures. **a** — (initial stage) — immiscibility at a late stage of its evolution. Note that in the right upper part of the photograph there is a first well-developed subspheroidal structure. **b** — (intermediate stage) — cordieritic material nucleating all around the basic spots. **c** — (final stage) — well developed subspheroidal or oviform structures. Note that spheroids were soft and capable of being deformed. Width of figure is 60 cm.

1990, 1993a,b; Lucido & Triolo 1983, 1984, 1989; Lucido et al. 1994), the following genetic model appears explain all features of the Argentine structures.

### The genetic model

#### *Phase separation and critical fluctuations*

Under certain circumstances an immiscible new fluid phase originates in the Argentine cooling basic melt (Fig. 1). This new liquid phase has a more silic composition than the neighbouring basic melt. As the cooling fluid reaches the critical consolution temperature ( $T_c$ ), immiscible portions of cordieritic composition in a state of dispersion form (see Fig. 2). This results from density fluctuations in the basic fluid at this temperature. The fluctuations involving high surface charge ions (e.g. Fe, Mg, Ca, Mn, Ti, P) will be more effectively dampened than the others, resulting in a tendency of the fluid to split into two portions, one enriched in high charge ions and the other enriched in low charge ions (e.g. Si, Al, Na, K). As the phase separation proceeds the fluid will behave more like a fluid with short range correlations (see Lucido & Triolo 1983, 1984). The effect of decreasing the temperature is also to decrease the fluctuations that characterize the critical behaviour. These space and time dependent fluctuations are small for temperatures far above the critical,  $T \gg T_c$ , and grow in size near  $T_c$ .

In the unstable regime of phase separation, the linear theory of spinodal decomposition holds initially. The ultimate limit of metastability is reached when the nucleation barrier is no longer small,  $\Delta F^*/T_c$  ( $\Delta F^*$  is the nucleation Helmholtz free energy barrier) is in the order unity (Binder 1984). At this stage one can observe a smearing of the transition between nucleation and spinodal decomposition in this finite regime (Lucido et al. 1994). This smearing is small in the mean-field critical regime, but it becomes large when approaching unity, at the crossover region to the non-mean-field critical regime. For a time smaller than the crossover time ( $t < t_{cr}$ ), very weak fluctuations will grow, but the wavelength does not change i.e., the fluctuations "compactify" (Heermann & Klein 1983) but do not coarsen. For  $t > t_{cr}$ , one enters a basically nonlinear regime where the inhomogeneous structure coarsens. Under these conditions, a closely related new phase appears in the melt, that is similar in density to a liquid. The densities of the liquids are different and the interfacial free surface energy is high. However, decrease in the magnitude of the interfacial free surface energy as the result of cooling and/or coalescence of the differentiated particles is not negligible. As a consequence, we find spots of dark (Fe-Mg rich) phase dispersed in a clearer phase richer in elements forming framework structures, particularly Al and Si (see e.g. Fig. 3).

#### *Colloid formation near the metastable state*

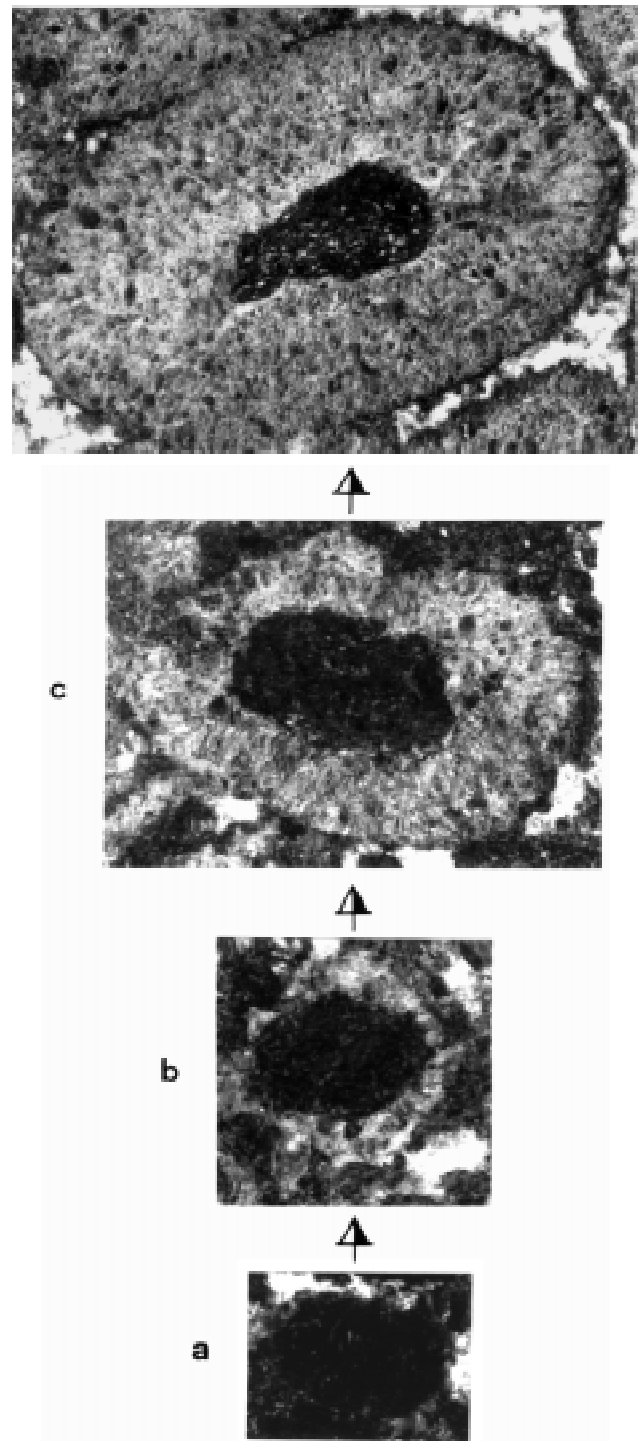
If temperature and pressure are sufficiently high, any fluid consists of a single liquid phase, that is, the small condensed species which form the liquid contain a small number of at-

oms. On cooling, however, when a given portion of fluid contains a few hundred atoms or more, and the structural order of atoms in the species has a longer range than is normal in liquid, it must be regarded as a separate immiscible phase and the system will be colloidal. In this manner, the formation of a colloidal system leads to inhomogeneities in the chemical composition. In particular, during the dispersion of the Argentine cordieritic material C in the basic fluid B, supersaturation conditions are created in which molecular and ionic units combine to form assemblies similar to micelles. Fig. 1 shows three types of "micellar" cordieritic particles: a) platelets, namely, primary plate-like dispersed particles, b) subspherical particles or flocs, and c) clusters of flocs. The interaction between platelets may result in three different modes of particle associations: 1) edge-to-edge, 2) edge-to-face, and 3) face-to-face. The edge-to-face and edge-to-edge associations lead to three-dimensional voluminous card-house textures that generate flocs (see Lucido & Triolo 1989). Otherwise, the thicker and larger particles which result from face-to-face associations are tactoids.

As long as the temperature of the fluid remains near the critical consolution temperature, the colloidal dispersion is metastable. A metastable state is characterized by an affinity which is not zero, but has a zero velocity of reaction (De Donder & Van Risselberghe 1936). Metastable states may thus persist over great lengths of time. Moreover, during liquid immiscibility, surfaces of a C cordieritic particle may be solvated to form C-B interfaces (see stage 2 of Fig. 8). So, if  $\Delta G_{cc}$  is the free energy of association of C molecules and  $\Delta G_{bb}$  is the free energy of association of B molecules,  $\Delta G_{cb}$  will be the free energy of sorption of molecules C onto the surfaces of B with the formation of an interface C-B. In the metastable dispersion, C will be a lyophobic colloid and  $2\Delta G_{cb} > \Delta G_{cc} + \Delta G_{bb}$  (Lucido & Triolo 1989). That is, the lyophobic colloid C has a characteristic property, a true interface with a defined surface tension, which exists between the disperse particles and the dispersing medium. As we shall see in the next section, the formation of this interface is the clue to account for the self-organization of the Argentine structures.

### Self-organization of Argentine structures

During phase separation, cordieritic platelets gradually emerge in the cooling Argentine fluid (Fig. 1). When the fluid reaches the critical temperature, basic spots (or spherules) in a bidispersed metastable state are obtained. In particular, a migration of cordieritic platelets from fluid to basic spots comes about (Figs. 2 and 3). Cooling damps the thermic motion of the fluid and generates in it ordered structures. In this regard, Fig. 4 shows structures conceptually similar to "reverse or inverted micelles". As a matter of fact, cordieritic particles are specifically absorbed by an acidic - basic interface. Considering the chemical properties of the two liquid portions, it is inferred that the particle charges have the same sign but the potentials of the individual particles are different. In such a case, the magnitude of the repulsion energy is determined by the particles with the lower potentials (Yariv



**Fig. 6.** Four different stages showing the formation of a single Argentine spheroid. **a** — photograph showing the initial stage: single basic spot or spherule having nothing or very little cordieritic material around it; width of figure is 3.5 cm. **b** — the increased accretion around the entire basic spot forms a cordieritic corona (block-house structure); width of figure is 4.5 cm. **c** — the further accretion of cordieritic material around a basic spot forming well-developed spheroid; width of figure is 12.5 cm. **d** — photograph showing the final stage: a big cordieritic spheroid showing a biotitic basic nucleus inside and a thin border having the same composition on the outside. Note light phases within the nucleus; width of figure is 19 cm.

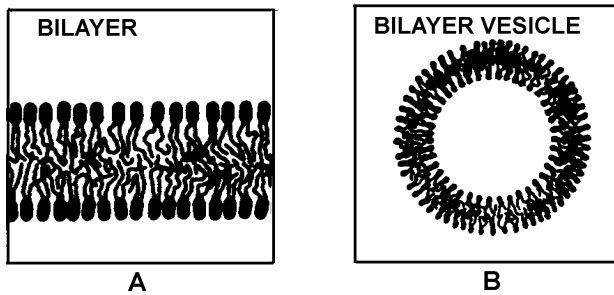


Fig. 7. Micellar colloidal structures. **A** — A biomolecular leaflet of amphiphiles, or bilayer; the black dots represent lyophilic polar heads and wavy lines represent lyophobic tails. **B** — Bilayer vesicle (after Yariv & Cross 1979).

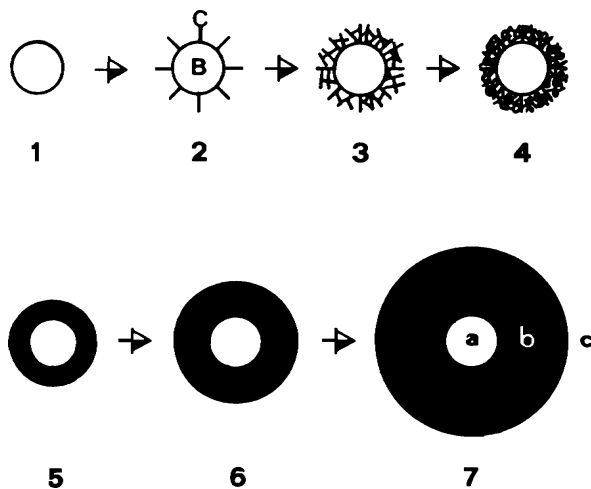


Fig. 8. Schematic illustration of the formation of a single spheroid. **1** — Origin of a basic spot in the Argentine fluid; **2** — formation of a reverse micelle-like structure, after separation of cordieritic particles; **3** — card-house structure around the basic spot; **4** — block-house structure around the basic spot; **5** — continuous layer origin around the basic spot; **6** — layer thickening; **7** — origin of a thin exterior border.

& Cross 1979), that is, by the cordieritic liquid particles. Furthermore, the higher potential of the basic polar group can change the radius but not the strength of the interacting force (e.g. Sonntag & Strenge 1972). Thus, since the cordieritic material is nonpolar, bonds between cordieritic and basic components are weak and the interaction energy occurring at the interface is low. In this manner, subject to available energy flows on or near the Earth's surface, matter organizes itself toward those states we regard as central to life.

It is obvious that on the surface of a basic spot (see Fig. 6a) all sites are equally susceptible to sorption, and therefore the maximum possible value of the number of particles absorbed per unit of area corresponds to the state when the entire surface is occupied by the absorbed particles, and is determined by the surface area occupied by the sorbed particles. In the case of particles having a highly elongated shape, as for example the cordieritic chains, the area they occupy on the basic spot surface depends on their position, whether they are horizontal or vertical, the latter orientation giving a greater density of absorbed particles (Lucido & Tri-

olo 1989). As a consequence, the maximum possible number of particles absorbed per unit area is not constant, but increases with concentration. In a first stage, card-house texture is formed around the basic spot. Successively, as sorption on the basic surface increases, block-house texture is formed (Fig. 6b). As the mean separation of cordieritic sorbed particles further increases, dense packing is attained, resulting in interaction between neighbouring sorbed particles (Fig. 6c). This interaction brings about the closure of the cordieritic layer into a vesicle-like structure. There is a decrease of Gibbs free energy accompanying the formation of this structure; more specifically, it represents a local free-energy minimum. In other words, this interaction results in a greater tendency for cordieritic particles to be sorbed onto the basic spot surfaces. In fact, the surface-absorbed particles are compacted in continuous layers (coronas) in which lyophobic bonding occurs. Subsequently, these layers coarsen and form thick layers of finite extent all around the basic spot. In practice, the basic spots act as nucleation centers. They are the loci around which, antagonistically, the segregated phases place themselves. Field-relationships indicate that the growth (acidic accretion) of a single spheroid with time is in accord with the general evolution of the rocks from basic to acidic (see Fig. 5). Evidently, as single spheroids grow the light variety of the outcropping rock increases. In some cases, the accretion towards the basic spots occurs at a lower rate. In this event, to obtain the same amount of material against the dark spots, a longer accretion period may be necessary. Thus, depending on circumstances, accretion may occur more or less quickly, generating in time, different-textured zones. They are due to variation in the rates of growth and nucleation during the evolution of the fluid. These textural variations represent modifications in the distribution of kinetic energy and therefore suggest a fluctuation of the fluid cooling conditions. Finally, with time, we may even expect to see a well defined biotitic border (see Fig. 6d) separating the neighbouring matrix from the thick cordieritic layer. At this stage of the process (ripening) the vesicle-like structure is completed. The interior fluid, at first, reflects closely the composition of the environment at the time of spheroid closure. There are, in fact, two basic fluid phases, the inner and outer, separated by the cordieritic layer.

Summing up, the above structure provides in one sweep for: (1) the partition of the world into interior and exterior, and (2) a three-phase system enabling transborder couplings. This three-phase system consists of a polar interior (corresponding to **a** in Fig. 8), a nonpolar intermediate zone (corresponding to **b** in Fig. 8) and a polar exterior (corresponding to **c** in Fig. 8) — the environment. We think that this abrupt transition may have led also to the directed chemistry or vectorial chemistry necessary for the origin of life.

## Comparison with membrane vesicles

### *The Morowitz model*

Very recently, Morowitz (1992) presented a radically new model of the origin of life on Earth 4 billion years ago. He

postulated that core metabolic processes have not changed with time. We can thus use a study of modern biochemistry to advance our knowledge about the chemical processes of the earliest prokaryotes<sup>1</sup>. According to Morowitz (1992), events of a purely statistical order from disorder occurred in the primitive chemical domain giving rise to identifiable, distinguishable, and persistent structures. These structures must by their very nature have been nonequilibrium entities and likely far from equilibrium on some time scale. All non-equilibrium structures are subject to thermal decay, hence the necessity of processing matter and energy to preserve a pattern following the second law of thermodynamics. Persistence of a far-from-equilibrium entity can occur only by a reprieve from the degradation wrought by random thermal motion. Persistence of a pattern can occur by replication, and as long as the pattern gives rise on average to more than one similar pattern, that pattern will exponentially increase. However, once matter and energy become necessary for persistence, the entities are in competition for molecules and energy source from the environment. The systemic forces leading to speciation exist as long as there is any memory at all, memory being implied in the notion of persistence. The synthesis requires a flow of energy from a source, and this energy eventually leaves the system.

Morowitz (1992) developed a model in which cells originate first, proteins follow, and genes evolve last. He proposed that the first step toward the origin of life was the spontaneous condensation of amphiphilic bilayers (Fig. 7). The bilayers are not linear structures but are sheets which easily may fold to form a closed vesicle, or protocell. Because the vesicle emerges with such unique properties, it is important to reiterate that it is a spontaneously forming structure representing local minimum free energy. Following vesicle formation two phases are present in the system, the inner and the outer, separated by the amphiphilic bilayer. Since the lyophobic portion of the bilayer has a very low solubility for polar compounds, the inner and outer phases can maintain different chemical compositions. Moreover, a bilayer has a very high electrical capacitance so that a small charge separation can lead to substantial transbilayer voltages. Another property of the vesicle is that it forms surfaces and opens the possibility of heterogeneous phase catalysis. Again, vesicle allows for pH differences, and oxidation-reduction differences between the two phases. The above differences open up the possibility of electrochemical and protonchemical reactions. Life on Earth as we know it must have been associated with liquid water (Lucido 1982, 1983b, 1989a) since its beginning. Nonaqueous life forms have been suggested, but the principle of continuity and the evidence from petrology and geochemistry (Lucido 1989a,b, 1990) demand that biogenesis be considered as a series of events occurring in a watery milieu. Water is an essential metabolite as well as a solvent; it is also the source of protons in membrane protonchemistry. As before mentioned, the vesicle forms a local free-energy minimum for certain classes of amphiphilic molecules in an aqueous environment.

The interior solution, at first, reflects closely the composition of the environment at the time of vesicle closure. Fol-

lowing this, vesicles can grow by the insertion of slightly water-soluble amphiphiles into the existing membrane. At this stage cellular life began, and also the origin of species started. This model fulfills the principle of continuity and has the distinct advantage of being testable. It is also supported by evidence from biology, biochemistry and biophysics.

## Conclusions

Comparing the rock-structures occurring in the Argentine outcrops with membrane-vesicles, it is possible to distinguish the following important analogies.

1 — Membrane-vesicles and Argentine structures are a simple case of spontaneous self-organization.

2 — Phase separation phenomena are in both cases responsible for the origin of the primary particles from the environment.

3 — In both cases, from a physico-chemical point of view, the genetic environment was a colloidal one.

4 — In both, order is processed from disorder, a characteristics of the transition from a homogeneous chemical domain to a heterogeneous one.

5 — The lyophobic or lyophilic character of matter is in both cases absolutely central to its structure and function.

6 — The formation of the Argentine structures and membrane-vesicles involved an abrupt transition forming a three-phase system: interior, barrier, and exterior (see a, b and c in Fig. 8).

7 — As a result, in both cases, increased amounts of particles are segregated, and these cause the growth of the individual structures, by addition to the existing layers.

On the basis of the above-mentioned analogies and considering the foregoing results the following is proposed.

a — The Argentine spheroidal or oviform structures are not porphyroblasts.

b — The Argentine structures and membrane-vesicles are formed by means of a unique mechanism.

c — The sequence of the events which in time led to the formation of a single spheroid is: 1) basic spot origin 2) reverse micelle-like 3) card-house structure 4) block-house structure 5) continuous layer origin 6) layer thickening 7) exterior border origin. This sequence is schematically indicated on Fig. 8.

d — In agreement with Morowitz (1992), our genetic model defines the characteristics of the simplest distinct autotrophic system that might have developed prebiotically.

**Acknowledgements:** The author would like to express his sincere appreciation to Prof. J. V. Gonzales Segura and Prof. N. A. Hillar Puxeddu of the Cordoba University (Argentina), Mr. Nunzio Di Matteo and Mr. Benito Pennisi of the A.R.L. co-operative society, Sicilistoro (Palermo), for their interest, kindness and assistance in providing him with rock-specimens. The writer is also extremely grateful to the two anonymous referees. This work has been supported by M.U.R.S.T. (Ministero dell'Università della Ricerca Scientifica e Tecnologica) and by C.N.R. (Consiglio Nazionale delle Ricerche).

<sup>1</sup>Prokaryotes are characterized by the absence of membrane-bounded organelles and have a genome that consists in the minimum case of a single, doubled-stranded, closed loop of DNA, a single molecule of nucleic acid.

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