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Morphogenesis of Biomineral and Morphosynthesis of Biomimetic Forms

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> Truly painting is a science, the true-born child of nature. To be more correct we should call it the grandchild of nature, since all visible things were brought forth by nature and, these her children, have given birth to painting.
>
> Leonardo da Vinci

Introduction

In this Account of our recent research on inorganic morphosynthesis and the insight that it provides into the morphogenesis of biomineral forms in nature, I will describe how we have recently learned how to synthesize hierarchical inorganic structures that resemble complete diatom and radiolaria microskeletal structures. This is a feat usually reserved for nature's biominerals and is an area of inorganic materials synthesis where chemists have been rather outclassed by nature.

Our story begins with the naturalist Ernst Haeckel, who in his 1887 *Challenger Monograph*, marveled at the extraordinary delicacy and complexity of the lace-like microskeletons of the unicellular marine organisms known as the diatoms and radioaria.[1] Haeckel's article catalogues the multiplicity of forms consisting of 4314 species in 739 genera. The origin and function of their geometrically regular shapes and elaborate patterns have been an enigma and a delight to scientists of many disciplines.

During the course of our research on inorganic morphosynthesis, we became aware of the creative experimentation of Professor Pieter Harting,[2] who, at the end of the 19th century, took the first steps in the field that we now call biomimetic inorganic chemistry, Figure 1. Harting's imaginative synthetic work focused attention on the nucleation and growth of biologically relevant calcareous morphologies in naturally occurring complex organic media. This work led to the first recorded examples of microskeletal facsimiles before the development of the fields of biochemistry, genetics, and crystal growth kinetics. Harting marveled over images of his synthetic morphologies through the glass eye of an early optical microscope and in a spectacular amalgamation of science and art created delicate hand drawings and sensitively colored renditions of his visual imagery, Figure 2. Harting's aspirations to synthesize complete skeletal forms were not realized until our work on vesicle templating[3] led to the discovery of organic-mediated synthetic pathways to hierarchical inorganic materials. The elaborate morphologies and ornate surface patterns of these materials resembled the microskeletons of certain single-cell organisms.

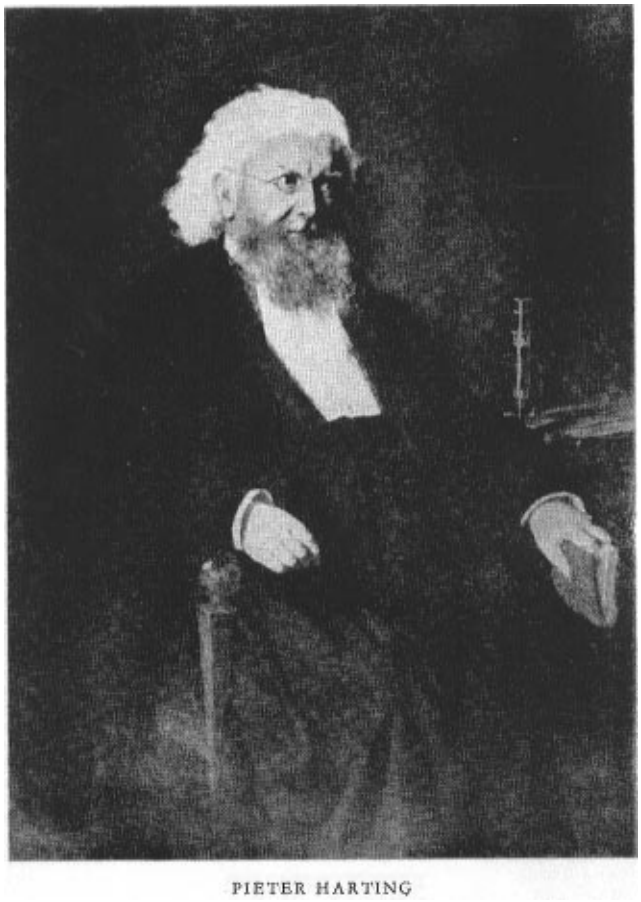

FIGURE 1. Professor Pieter Harting in 1872 took the first steps in the field that we now call biomimetic inorganic chemistry.[2]

The first geometrical description of structure in nature appears in Plato's *Timaeus*, which provides an inventory of four of the regular solids and their association with the four elements: fire with the tetrahedron, earth with the cube, air with the octahedron, and water with the icosahedron. Plato considered the dodecahedron to be the shape that encompasses the entire universe. These five regular polyhedra became known as the Platonic solids.

This geometrical theme is embodied in Sir D'Arcy Thompson's classic 1917 text *On Growth and Form*.[4] He proposed a physicogeometrical hypothesis of causation to explain the theory of formation of many beautiful protozoan agglutinated forms. In this text, he invoked the

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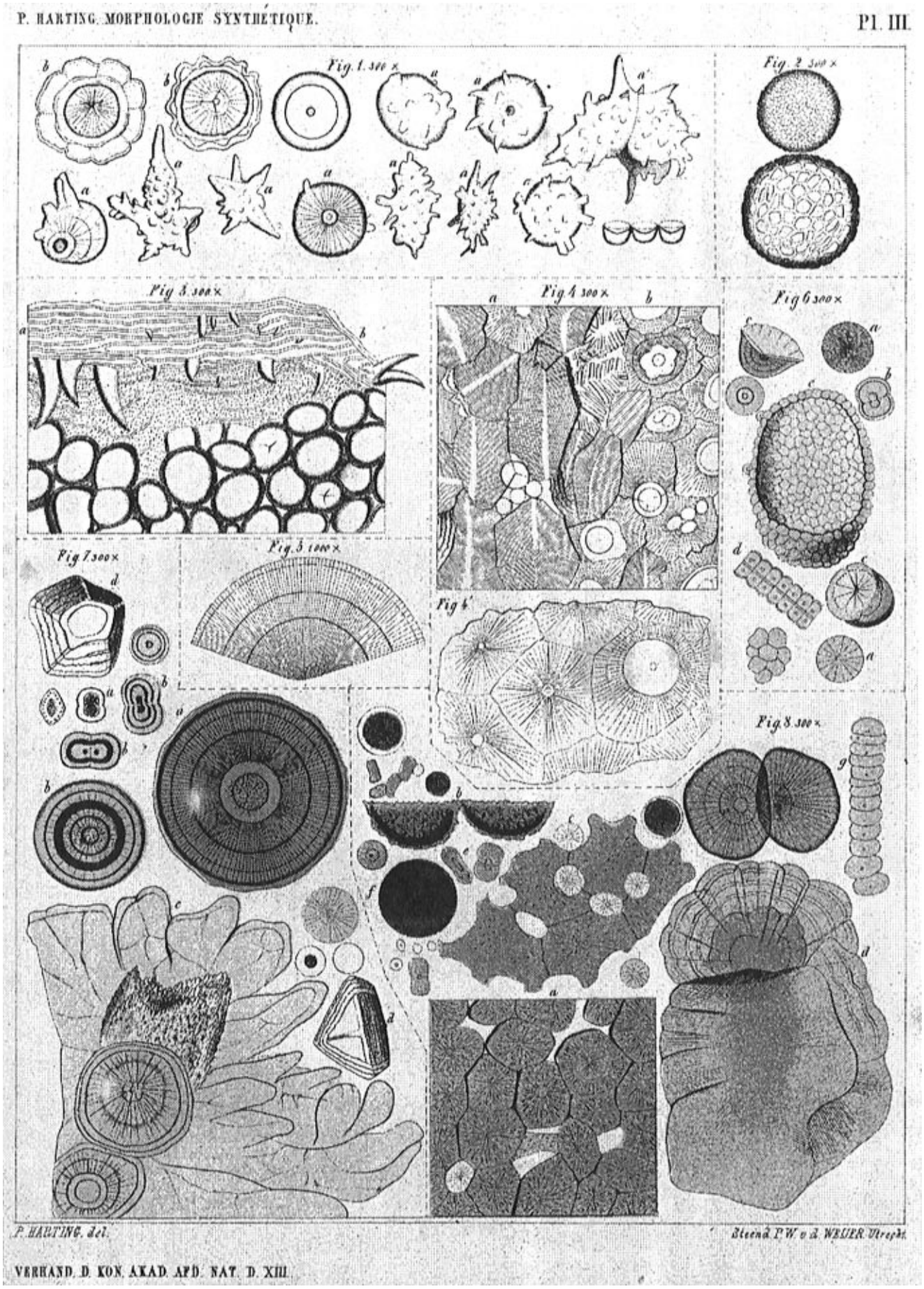

FIGURE 2. Professor Pieter Harting's original 1872 hand drawings of his calcareous synthetic morphologies.[2]

basic laws of close-packing and surface energy minimization of cellular assemblies, subjected to intra- and intermolecular force fields, to explain the occurrence of a variety of single-cell microskeletons. The physicomathematical laws and theorems that govern the arrangements and surface tension forces of groupings of cells appeared to somehow control the adsorption−deposition of inorganics into complex patterns and led to the large number of microskeletal forms in biological systems.

D'Arcy Thompson noted how protoplasmic organisms exploited surface energy minimization to localize and arrest solid particles as an agglutinated shell.[4] He considered the sequestration, confinement, and ordering of inorganic particles to a position of equilibrium within a protoplasmic surface boundary layer to be a general phenomenon of considerable biological significance. In the particular case of the multitude of diatom and radiolaria microskeletons, he visualized a protoplasmic froth of contiguous alveoli or vacuoles as the polygonal organic meshwork that directed the silicification process. Localization and deposition of siliceous precursors into the boundary regions between the associated cells or vesicles in such a close-packed protoplasmic froth was imagined to lead to a delicately patterned perforated silica replica. This model pleasingly rationalized the origin of, for instance, the delicate spheroidal hexagonal network skeleton of Haeckel's radiolaria *Aulonia hexagona*, Figure 3.

Although tremendous strides have been made in the fields of biomineralization and biomimetics since the work of D'Arcy Thompson, his basic paradigm for the growth and form of silica and calcareous microskeletons, through spatially directed mineralization of inorganic material in a living organism, has essentially withstood the test of time. The form of the organism controls the aggregation of a population of vesicles and the symmetry of surface tension forces. The localization of inorganic adsorption and deposition events to the manifold of surfaces, interfaces, and spaces in the system of vesicles provides an appealing physicogeometric explanation of the origin and morphologies of many biomineral structures, especially the microskeletons of the diatoms and radiolaria.

Haeckel's radiolaria skeletons are nature's expression of the most economical structural solution to a given recipe of growth conditions. This exquisite portrayal of natural symmetry and form led the French architect Le Ricolais, in 1940, to propose structural designs based on the triangulated networks of the radiolaria. In 1948 Buckminster Fuller, similarly aroused by the breathtaking beauty of the sculpted radiolaria skeleton, created the geodesic dome. It is interesting to note that, within the context of the modern idiom of buckminsterfullerene, C_{60}, Haeckel's *A. hexagona* first brought to light that no system of hexagons could enclose space, and a few pentagonal facets are to be found among the hexagons.

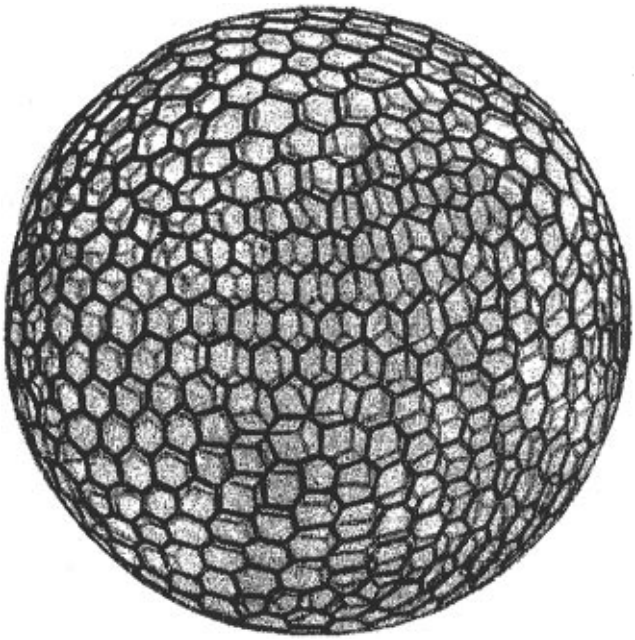

FIGURE 3. Delicate spheroidal hexagonal network skeleton of Haeckel's radiolaria *A. hexagona*.[1,4] Reprinted with permission from ref 4b. Copyright 1992 Dover Publications.

It was a conscious awareness of the work of D'Arcy Thompson, Charles Eames, Konrad Wacsmann, and Buckminster Fuller in harmony with a love for geometrical forms in the natural world that inspired Peter Pearce's classic "synestructics" architectural work based on the paradigm that "structure in nature is a strategy for design".[5] Many "geometrical" educational toys, games, and playground equipment and a large number of building projects are the gifts to society that have emerged from Pearce's work on "universal structure" and his appreciation of the scale-independent physicogeometric expression of form throughout science, art, and nature. It is also to D'Arcy Thompson that one can look for the "biotic sources of material sculpture".[6]

Morphogenesis of Biomineral Forms to Morphosynthesis of Biomimetic Structures

Why did it take so long to make materials with shapes and length scales that mimic those of microskeletal structures in nature? Our 1995 papers were the first to report on the synthesis of artificial radiolaria and diatom microskeletal forms.[3] In hindsight, all of the modern chemistry clues were obvious for synthesizing such microskeletal facsimiles. Paradigms in the burgeoning fields of supramolecular, biophysical, materials, colloidal, and biomimetic chemistry along with rapidly developing concepts in molecular recognition, self-assembly, template synthesis, and hierarchical structures provided all of the guiding principles for the synthesis of inorganic materials with complex form based on biological design principles.[7]

(1) Haeckel, E. *Challenger Monograph*; 1887.
(2) Harting, P. *Natuurkd. Verh. Koninkl. Acad.* **1873**, *13*, 1.
(3) (a) Oliver, S.; Kuperman, A.; Coombs, N.; Lough, A.; Ozin, G. A. *Nature* (*London*) **1995**, *378*, 47. (b) Oliver, S.; Ozin, G. A. *Adv. Mater.* (*Weinheim, Ger.*) **1995**, *7*, 943. (c) Oliver, S.; Coombs, N.; Ozin, G. A. *Adv. Mater.* (*Weinheim, Ger.*) **1995**, *7*, 931. (d) Oliver, S.; Ozin, G. A.; Ozin, L. A. *Adv. Mater.* (*Weinheim, Ger.*) **1995**, *7*, 948. (e) Oliver, S.; Khushalani, D. Kuperman, A.; Ozin, G. A. Hierarchical Inorganic Materials, Stealing Nature's Best Ideas: Modular Chemistry Over Three Length Scales. In *NATO Advanced Research Workshop Proceedings, Modular Chemistry*, Aspen, CO, September 1995; Michl, J., Ed.
(4) (a) Thompson, D. W. *On Growth and Form*; Cambridge University Press: Cambridge, 1917. (b) Thompson, D. W. *On Growth and Form*, complete revised edition; Dover Publications: New York, 1992; p 708.
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(6) Burnham, J. *Beyond Modern Sculpture*; Braziller Inc.: New York 1968.

Particularly relevant to our discovery of microskeleton mimicry was half of a century of research on the synergistic assembly of small organic molecules and inorganics, to create the nanoscale patterns of zeolites.[8] The general consensus of zeolite chemists is that the organic plays a templating function through the spatially controlled assembly of inorganic building blocks.[8] It is believed that the organic serves to fill space, direct the structure, and balance the charge of the resulting inorganic open-framework material. Another vital clue emerged from the work of Kresge and co-workers at Mobil.[9] They discovered that supramolecular assemblies of amphiphilic molecules, in the form of micelles, lamellae, and bicontinuous phases, are able to cooperatively assemble with inorganics, like silica, to form mesostructured inorganic replica materials. In essence, the supramolecular inorganic−organic co-assembly is turned into "stoney forms", that is, a type of "Medusa chemistry".

We realized that the next level in the hierarchy of complexity and scale would involve the use of vesicles to sculpt inorganic shapes and patterns that span length scales, such as those found in nature. This seemed to be the way to synthesize inorganic materials with complex form and could possibly provide a new insight into the genesis of biomineralized skeletal forms in nature. These were the thoughts that led to our discovery of a vesicle-based synthesis of inorganic materials that resemble complete radiolaria and diatom microskeletal structures, Figure 4.[3] It is often difficult to distinguish the natural from the artificial radiolaria and diatoms, Figure 5A−F. This synthetic accomplishment showed that vesicles can sculpt impressive macroscopic forms and surface patterns. We proposed a cellular type of synthesis model, inspired by biological design principles, that was consistent with most of our observations at the time.[3] Our synthesis strategy utilizes a solution of surface-patterned vesicles. The patterning has its origin in the thermodynamically driven phase separation of mixed surfactant−cosurfactant vesicles into domains.[3] The nucleation and growth of the inorganic phase, in specific regions of contiguous aggregations of these vesicles, creates mineralized facscimiles of the overall form and surface patterns of the composite macroscopic co-assembly.

There were numerous precedents in the phospholipid- and amphiphile-based vesicle literature that accounted for our observations. For instance, Ringsdorf's work demonstrated that binary phospholipid vesicles containing a polymerizable component can phase-separate to create surface-patterned spheroidal structures.[10] Similarly, Sternberg's recent work showed that mixed nonionic−ionic surfactant-based vesicles can spontaneously demix to create spectacularly-surface-patterned geodesic-like structures.[11] Menger's work illustrated how simple inorganic ions can form the "glue" that holds together vesicle agglomerations.[12] On the basis of the literature, we could envisage how the formation of inorganic replicas of groupings of these surface-imprinted vesicles could lead to artificial skeletons of radiolaria and diatoms in the laboratory.

The breakthrough in our laboratory came when my graduate student Scott Oliver showed me a scanning electron microscopy image of an aluminophosphate-based macroscopic honeycomb morphology that he had synthesized in the course of his work using amphiphilic alkylamines in glycol−water-based solvents. The resemblance of the micrometer-sized hexagonal-shaped imprints to those found in certain classes of diatoms and radiolaria was, to us, quite amazing. The inorganic portion of the honeycomb was established to be a well-ordered mesolamellar aluminophosphate with an Al:P ratio of about 1:2 and an organic content of 40−50 wt %. The inorganic and organic lamellae themselves lacked long-range order, which was a significant observation as, in this respect, the synthetic system paralleled that found for amorphous silicified structures in biology. We managed to grow single crystals of the surfactant assembly that we believed to be responsible for templating this honeycomb morphology. The single-crystal X-ray diffraction structure was solved and revealed the chemical and architectural aesthetics of this supramolecular template, Figure 6. It had a network of interdigitated single-tailed decylammonium cations, arranged orthogonally and intricately hydrogen-bonded to a layer of dihydrogen phosphate counteranions.[3]

The observation of millimeter-sized inorganic forms (e.g., spheroids, hollow shells) bearing micrometer-dimension surface patterns (e.g., pores, bowls, curvilinear tesselations, star dodecahedra, platelets, posts) suggested to us that vesicles were somehow involved in the templating process. A crude kind of combinatorial approach was designed to establish the synthetic parameters required for this type of templating process. Initial targets included the effects of surfactant head group, length of the alkylammonium chain, degree of oligomerization of the glycol, the amount of water in the reaction, pH, temperature, and time. It became clear that the morphology and patterning of the inorganic structures only occurred for a specific choice of reagents and reaction conditions. Not surprisingly, we were dealing with the control of the structure and templating behavior of surfactant−cosurfactant-based supramolecular assemblies in different regions of composition−phase space. In these exploratory experiments we used tetraethylene glycol (TEG) for manipulating decylamine and undecylamine surfactants. The choice of glycol and the amount of water in the synthesis mixture were crucial. Higher or lower molecular weight glycols, or too much or too little water, failed to produce macroscopic inorganic forms and patterns. A self-assembling amphiphile with $n \geq 8$ appeared to be a prerequisite for vesicle templating.

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(12) Menger, F. M.; Gabrielson, K. D. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2091.
(13) Oliver, S.; Shen, G.; Ozin, G. A. Unpublished work.

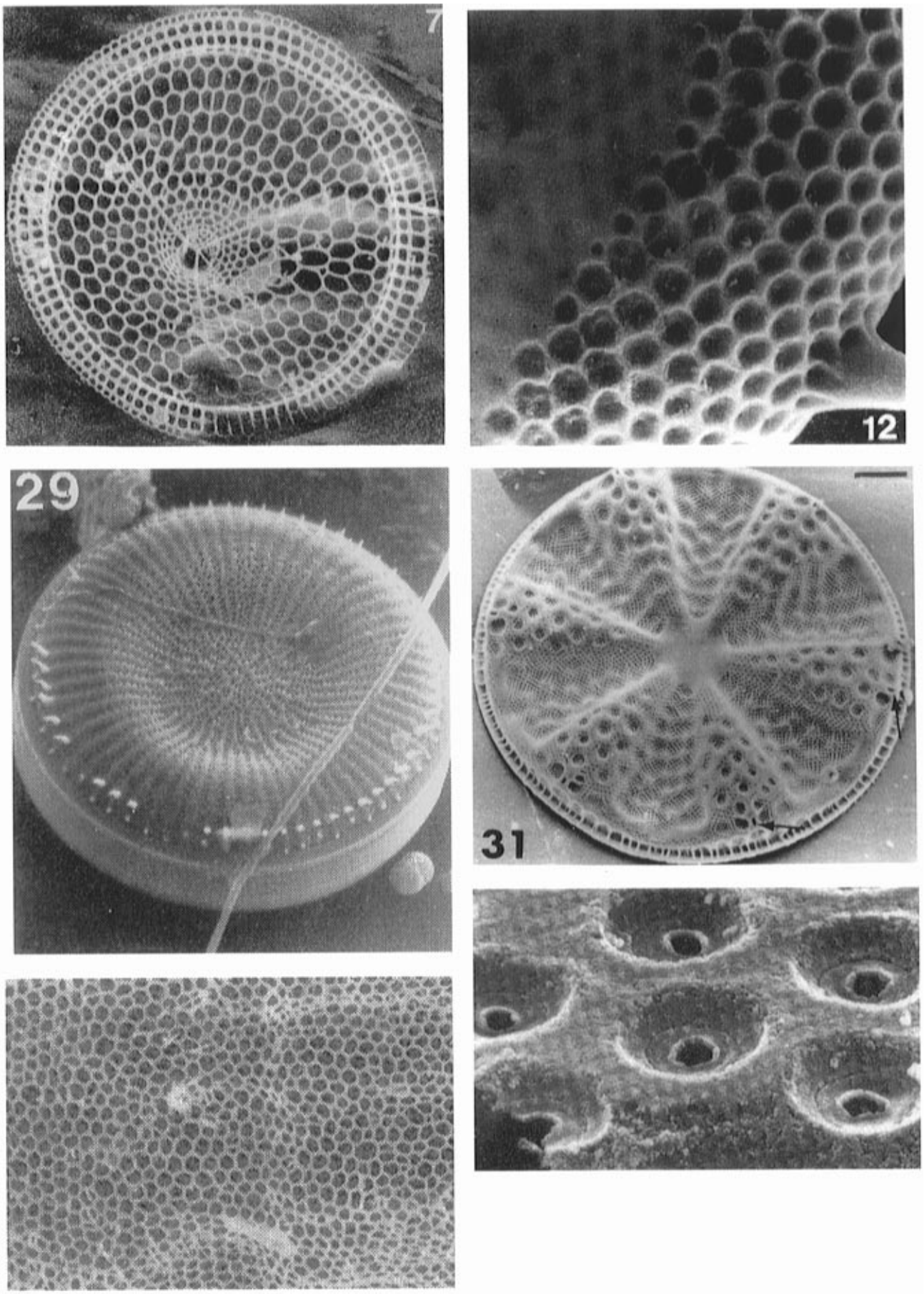
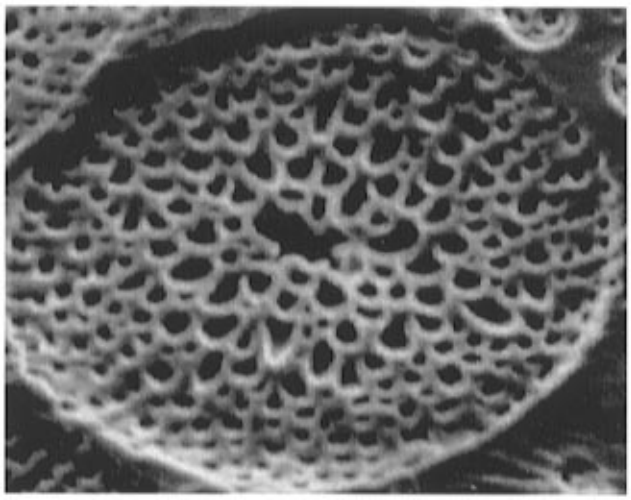
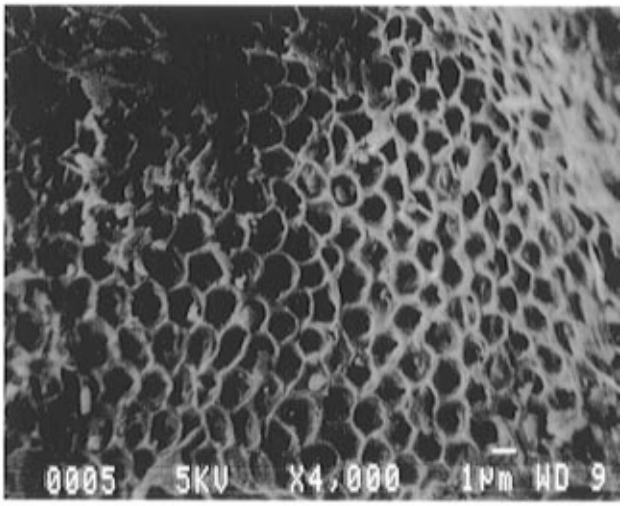


FIGURE 4. Natural microskeletons: (A, top left) radiolaria concentric mesh, (B, top right) radiolaria honeycomb, (C, middle left) disk-shaped diatom, (D, middle right) disk-shaped diatom, (E, bottom left) radiolaria extended mesh, (F, bottom right) radiolaria surface bowls. Panels A, B, E, and F are reprinted with permission from ref 17. Copyright 1991 Kozo Takahashi. Panel C is reprinted with permission from ref 18. Copyright 1990 Koeltz Scientific Books. Panel D is reprinted with permission from ref 19. Copyright 1981 Springer-Verlag.

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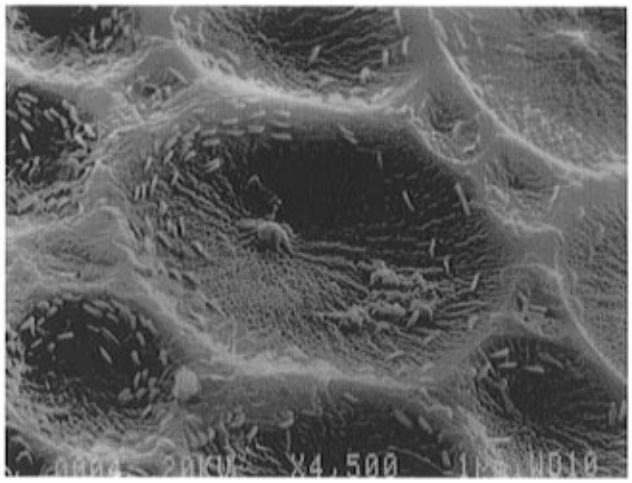

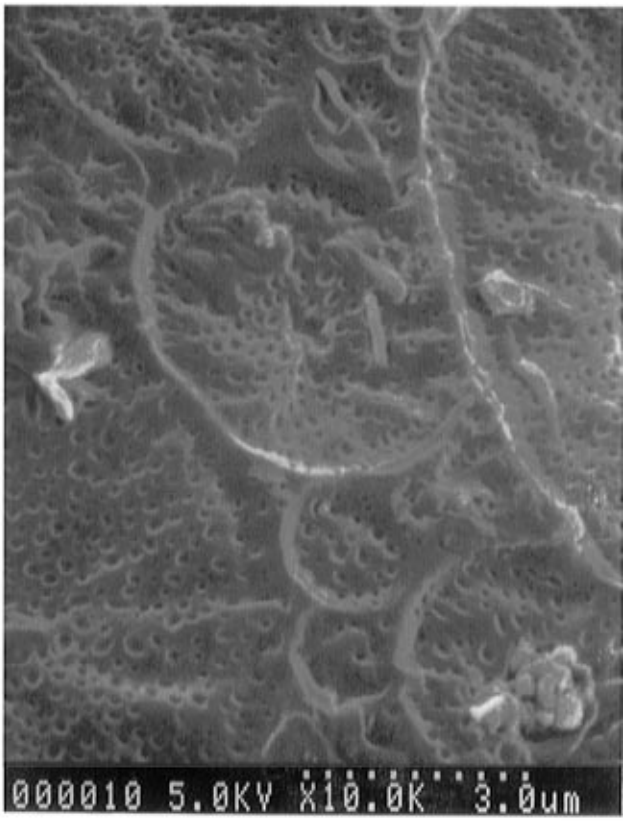
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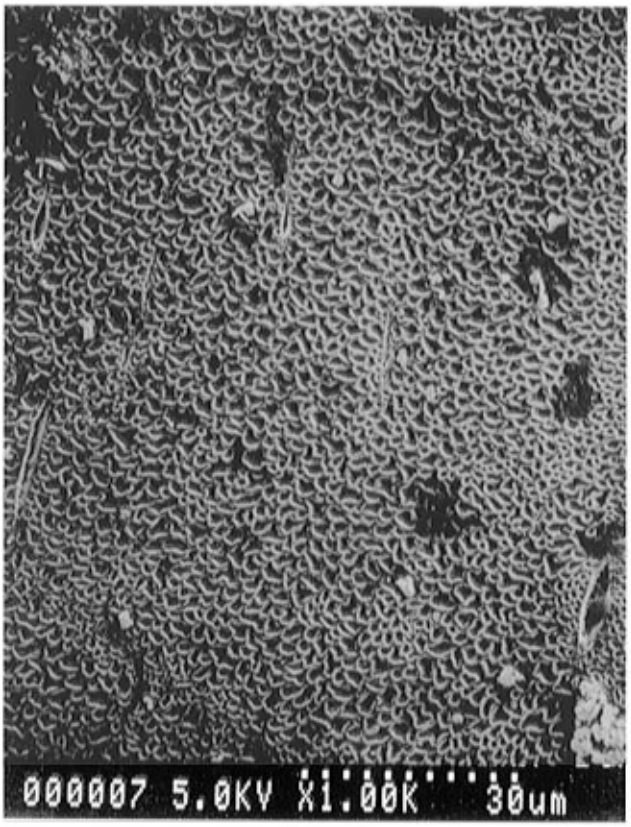
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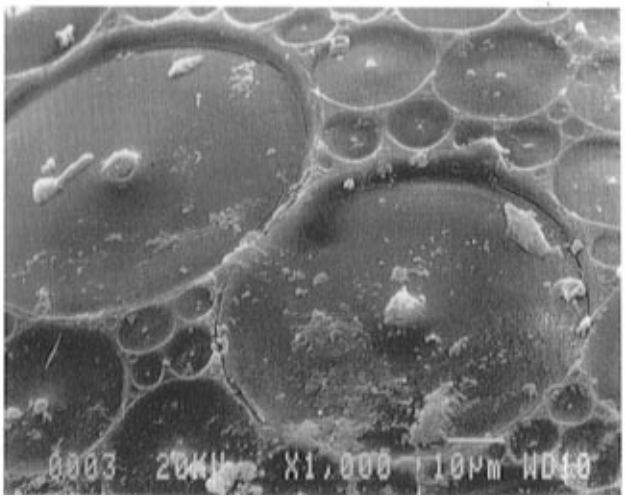
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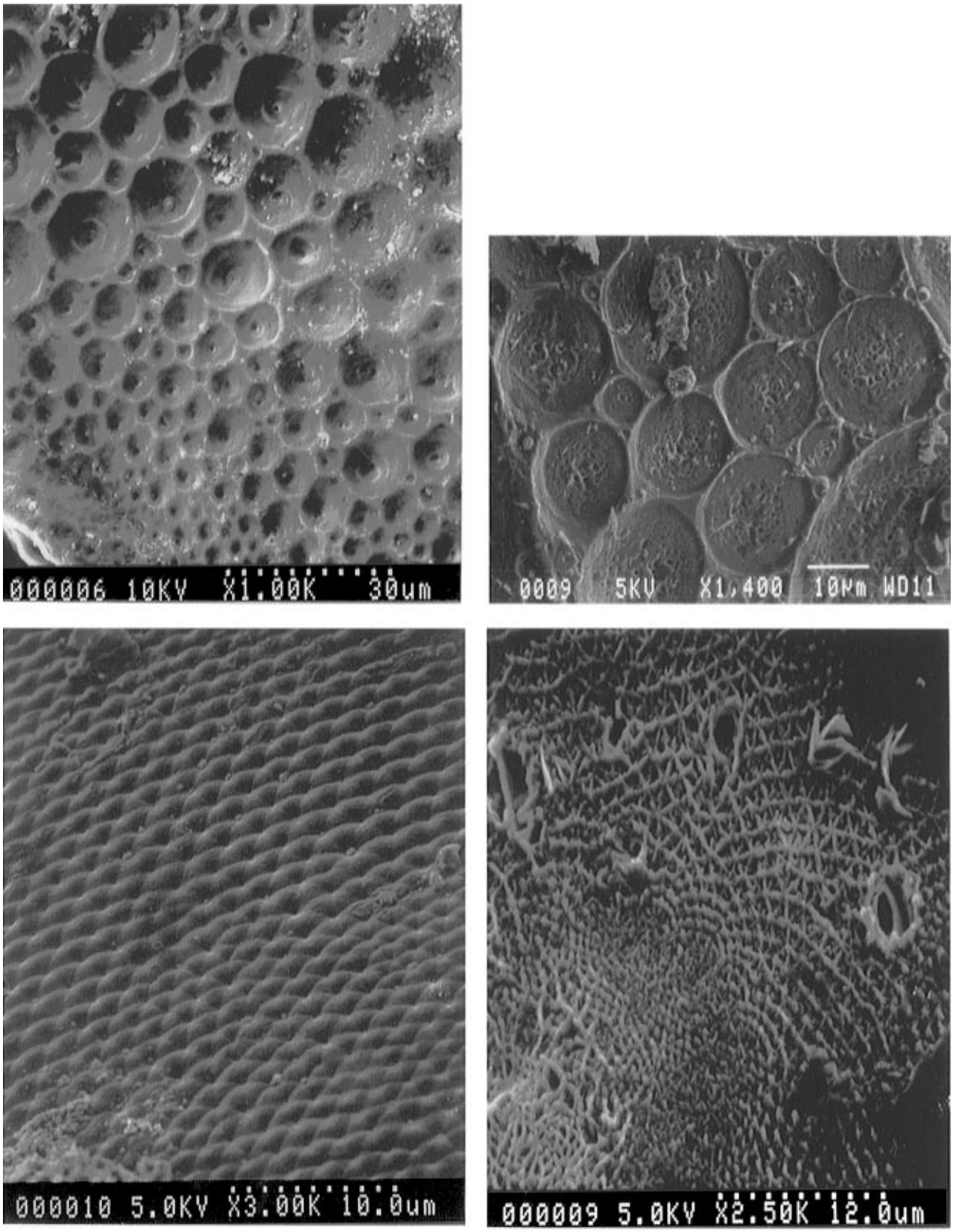

FIGURE 5. Biomimetic forms: ((A)−(F) are shown on the preceding page, and (G)−(J) are shown above) (A, top left) concentric mesh, (B, top right) honeycomb, (C, middle left) diatom facsimile, (D, middle right) diatom facsimile, (E, bottom left) extended mesh, (F, bottom right) surface bowls, (G, top left) gradient, (H, top right) polydispersion, (I, bottom left) shear, (J, bottom right) shrink. Panels A and D are reprinted with permission from ref 3b. Copyright 1995 VCH Publishers. Panels B, C, and F are reprinted with permission from ref 3a. Copyright 1995 Nature.

At this point in the project, we began to categorize the classes of macroscopic morphologies, pores, and surface patterns that we were synthesizing. The product yields were essentially quantitative, and the materials were phase pure. The inorganic fabric was exclusively a mesolamellar aluminophosphate, "molded" into spectacular macroscopic forms and "sculpted" into fine patterns. At first sight we thought the macroscopic templating was out of

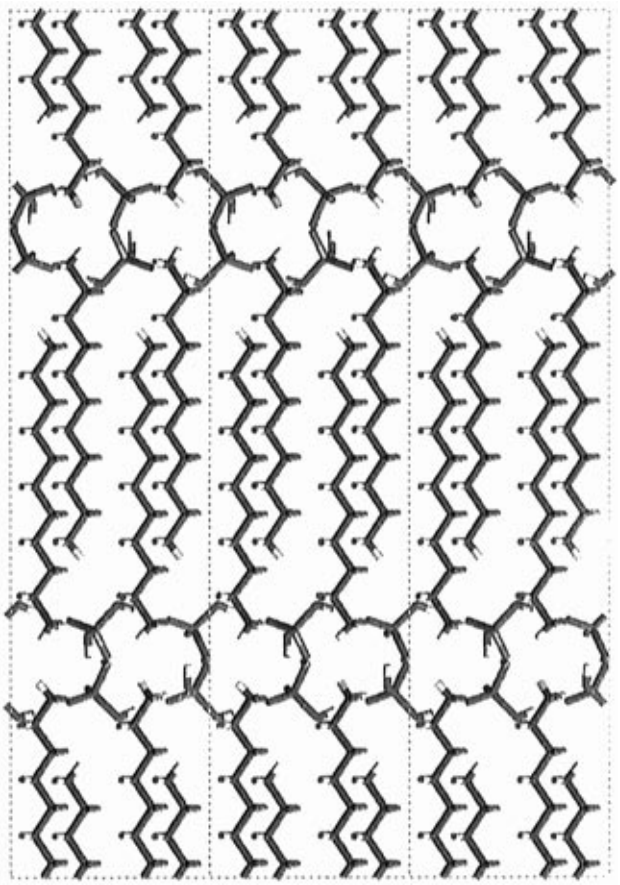

FIGURE 6. Projection from the single-crystal X-ray structure analysis of the decylammonium dihydrogen phosphate bilayer template, illustrating the intricate hydrogen-bonded network of interdigitated single-tailed decylammonium cations arranged orthogonally to a layer of dihydrogen phosphate counteranions.[3]

control and was leading to unrelated morphologies and ornamentations. This turned out not to be the case! The synthesis reproducibly yielded only two surface-patterned shapes, that is, solid spheroids and hollow shells. We could not help but notice the resemblance of these synthetic morphologies to some biomineral forms in nature. It did make us wonder whether nature could be that simple. Of course it is not, and we still have a great deal to learn about genetic control and regulation in the morphogenesis of biomineral forms as well as the details of the assembly processes.

Synthetic Shape: Templating Model

The origin of these synthetic shapes initially seemed to be an enigma. However, recognition of the points sketched below provided us with an insight into the origin of the morphologies and surface patterns observed in the TEG−alkylammonium dihydrogen phosphate−alumina system. These include (A) *the multifunctional role of TEG* (i) as a *solvent* to enable the self-assembly of the vesicle template, (ii) for *viscosity and chemical control* of the rates of mineralization, transport, polymerization, and deposition of the aluminophosphate regions of the structure, (iii) as a *polydentate ligand* to form "controlled-release" (TEG)-Al(III) complexes, (iv) as a *cosurfactant* for the control of bilayer curvature, (v) as a *demixing agent* to promote surfactant−TEG phase separation (domains) and patterning of vesicles, (vi) as *artificial ion channels* to facilitate the transport of (TEG)Al(III) ionophores through vesicle bilayers, (vii) for *polymerization deposition* of (TEG)Al(III) at reactive dihydrogen phosphate sites, and (viii) for *nucleation and growth* of the mesolamellar aluminophosphate and (B) *cellular-type processing events* that ensue during the adhesion, fusion, fission, reshaping, and collapse of vesicles, which facilitate the sculpting of the macroscopic forms and direct the surface patterning of the mesolamellar aluminophosphate fabric.[3]

Subsequently, Scott Oliver discovered that the amphiphilic alkylammonium dihydrogen phosphates used in his work displayed thermotropic liquid crystal properties at the temperatures required to template his biomimetic materials. With this knowledge, Dr. Guo Shen in my laboratory investigated TEG/water/phosphoric acid/alkylamine synthesis mixtures using the variable temperature hot stage of an optical microscope. He made the *in situ* and direct observation that surface-patterned vesicles spontaneously assemble under the same reaction conditions that led Scott Oliver to his biomimetic structures. This discovery has provided us with the missing link in our proposed vesicle-templating mechanism.[3]

The "naturalness" of our synthesis system was most pleasing. Our cellular type of synthesis model[3] served to explain the origin of the aluminophosphate morphologies and surface patterns in the TEG−alkylammonium dihydrogen phosphate−alumina system. We realized that, just as small-molecule organics and surfactant-based micelles could co-assemble with inorganics to form composite materials with microscopic and mesoscopic imprinted patterns, our research demonstrated that vesicles could sculpt impressive forms and carve-out surface designs at an even higher rung up the hierarchical ladder of scale. Each of these scales opens up a range of industrial applications; the smallest patterns provide materials useful for selective organic transformations, small-molecule separations, and chemical sensing, while the largest ones afford materials that could be useful for particle sieving, biomolecule purifications, and biomedical uses, such as bone replacement, augmentation, and repair.

Pattern Formation

The pervasive theme throughout the classic works of D'Arcy Thompson[4] and Peter Pearce[5] in the contemporary idiom is that the response of a cellular system to intrinsic (e.g., hydrophobic, electrostatic, steric, hydration) and extrinsic (e.g., surface tension, shear, osmotic pressure, gravity) force fields creates cellular structures according to the topological rules governing the shape and size of the constituent cells and the requirement of minimum potential energy. In nature, these forces tend to be hierarchical and their description depends on scale. A variety of natural and synthetic cells may be used for organizing inorganics into elaborate patterns. Examples include foams, froths, bubbles, vacuoles, alveoli, vesicles, and droplet microemulsions. They may be monodispersed or polydispersed, and the resulting cellular structures will depend on their relative sizes and abundance.

In an isotropic cellular system, packing and minimum energy requirements provide the driving force for hex-

agonal symmetry patterns. One must also take into account, however, the effect of anisotropic forces on a hexagonal array, as they can dramatically influence the final arrangement. For instance, substrate effects (e.g., planar, curved, adhesion), boundary effects (e.g., edge, surface), and differential growth effects (e.g., shear, shrinkage) can all result in characteristic hexagonal distortion patterns. Demixing of amphiphiles in such cellular structures can also lead to finer decorations. We have found that vesicle-templating of inorganics can produce patterns similar to those found in natures' cellular structures.

Hexagonal Patterns

An example of a hexagonal mesh that is formed in our synthesis system is shown in Figure 5B. This pattern shows a morphological resemblance to the hexagonal cellular structures found in the skeletons of some diatoms and radiolarians. Throughout biological morphology, the most common arrangement of cellular monodispersions is the hexagonal pattern. When equal tensions exist in all contact faces, the cellular array will equilibrate to one where all shared faces meet at angles of 120° and all vertices are joined equally at angles of 109°28′. In Thompson's description of the origin of diatom and radiolaria hexagonal structures, he proposes a layer of roughly-equal-sized cells (i.e., a protoplasmic froth) fashioned through their mutual tensions into a regular meshwork of hexagons. This serves as a mold for the deposition of silica into the intercellular spaces.

Gradient Patterns

There exist numerous natural systems that benefit from the use of graded structures, such as tendon, articular cartilage, wood, bamboo, and bone. A growing number of engineered functionally gradient materials (FGMs) are being designed to attempt to emulate these natural structures in various applications.[14] The interest in FGMs is driven by their position-sensitive physical and mechanical properties arising from spatially inhomogeneous compositions and microstructures. A synthetic approach to FGMs is most desirable.

A variety of gradient patterns are obtained in our decylamine- and undecylamine-based synthesis systems, Figure 5G. They show interesting similarities to some natural gradient patterns found in biogenic iridescent opal, as well as hemispherical and circular biosilicified diatom frustules. One can conjecture that, in our synthesis system, it is the deposition of the aluminophosphate fabric onto an assembly of polydispersed vesicles that yields the more permanent gradient patterns.

Polydispersion Patterns

Thompson and Pearce give many examples of patterns that can arise from the packing of unequal-sized cells.[4,5] Depending on their relative dimensions and populations, close-packing and minimum energy requirements create different patterns. These include progressive decreases in cell size, as found in the patterns of spheres and pores in the opaline and diatom structures. Synthetic patterns which illustrate the efficiency of packing in a polydisperse assemblage of aluminophosphate-coated vesicles are shown in Figure 5H.

(14) Functionally Gradient Materials. *MRS Bull.* **1995**, *20*, 14.

Shear Patterns

An example of an aluminophosphate eiderdown pattern formed in the decylamine-based system is presented in Figure 5I. It bears a similarity to the ambulacral plates of the sea urchin *Lepidesthes*.[4] Thompson points out that the imposition of a steady shear force to a hexagonal pattern of cells deforms them into a characteristic cloud pattern with a curvilinear tessellated architecture.[4] Interestingly, by maintaining the shear, one expects a further transformation of this cloud pattern into another hexagonal one but now arranged orthogonally to the original.[4] An example of an aluminophosphate hexagonal pattern that portrays all three frozen-in stages of this shear-induced cellular-distortion phenomenon is depicted in Figure 5B. Thus, it seems that a shear deformation applied to a hexagonal pattern of aluminophosphate-coated vesicles could be responsible for the eiderdown and hexagonal-mesh patterns, Figure 5B,I. In this context, it is important to appreciate that shear forces are to be expected in our synthesis system. They originate from differential shrink effects created in an Al−OH + HO−P → Al−O−P vectorial condensation−polymerization of the aluminophosphate forming on a hexagonal array of vesicles. This proposal is consistent with Ringsdorf's work on binary phospholipid vesicles containing a polymerizable component.[10] Thompson,[4] Pearce,[5] and Ringsdorf[10] describe the various scenarios that result from the differential shrinkage of cellular systems. The main effects relate to alterations in cell curvature and shape. It therefore seems reasonable to expect that differential shrinkage in aluminophosphate-coated vesicles can induce shear and gradient distortions in the resulting cellular structures.

Shrink Patterns

In Figure 5J, we present an example of a micrometer-dimension aluminophosphate rhombohedral pattern obtained in the octylamine-based system. This pattern shows a striking resemblance to the star−dodecahedral arrangement of stellate cells in the pith of the rush *Juncus effusus*. Thompson[4] and Pearce[5] have both suggested that the latter illustrates an example of a shrink pattern in nature. They can arise when close-packed cells, instead of filling all accessible space, tend to collapse in regions around their point of adhesion. Changes in osmotic pressure can cause loss of fluid from the cells. A process of this type can explain the formation of the star−dodecahedral aluminophosphate patterns produced in our vesicle-based synthesis system.

Mesh Patterns

Examples of some spectacular aluminophosphate mesh patterns that are formed in our decylamine- and undecylamine-based synthesis systems are displayed in Figure 5A,E. They show interesting similarities to the filigree patterns found in certain siliceous radiolarian

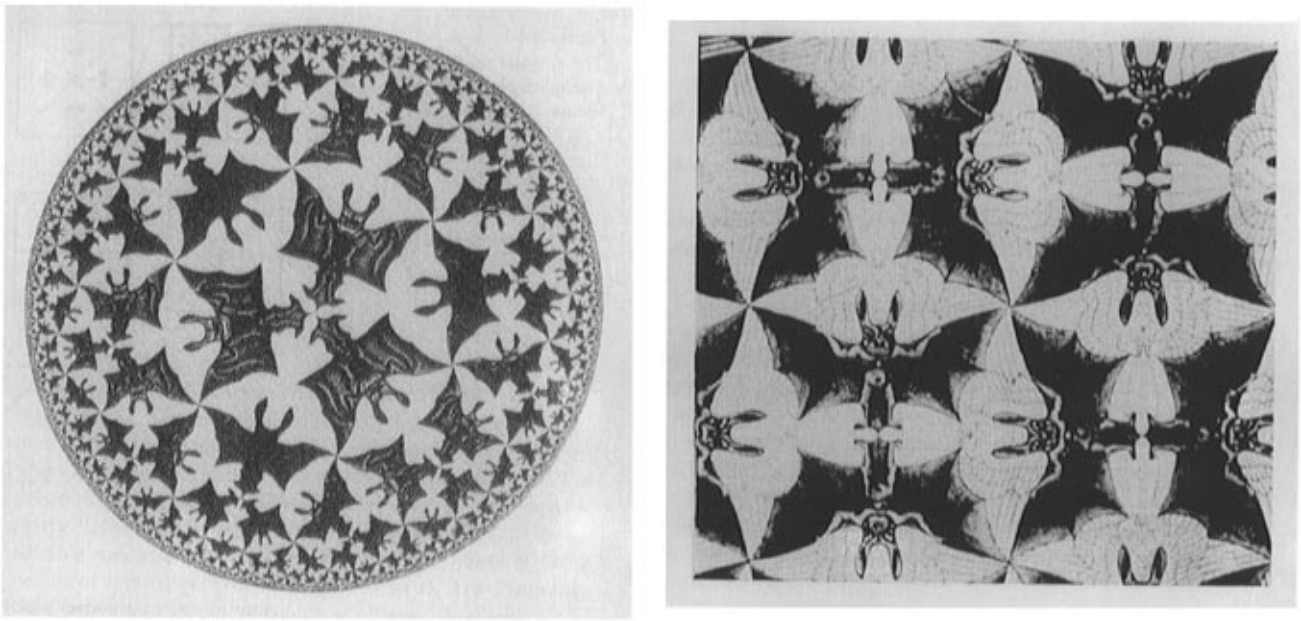

FIGURE 7. (A, left) Escher's "Circle Limit IV". (B, right) Escher's "Angels and Bats". Reprinted with permission from refs 15 and 16. Copyright 1996 M. C. Escher/Cordon Art-Baarn-Holland. All rights reserved.

microskeletons. These mesh patterns might arise from distortions of close-packed arrays of polydispersed vesicles or cells, subjected to boundary and/or shear effects. One cannot discount that the mesh patterns could alternatively originate from the deposition of aluminophosphate on phase-separated domains, existing in the surface bilayers of surfactant−cosurfactant binary vesicle templates.[3]

Patterns and Forms in Nature Are an Inspiration for Design and Structure in Science and Art

As our research into *morphosynthesis of biomimetic forms* and our understanding of the extent of its relationship to *morphogenesis of biomineral structures* evolve, it is a rather simple matter to recognize the expression of symmetry and patterns in certain classic art forms, in skeletal forms in nature, and in our artificial microskeletal forms. What is less easy to identify is the way in which these delicately sculpted natural mineral forms connect with art and art-making in ways that are a little more complex than just identifying these kinds of correspondences. In what follows we will muse about connections between our chemistry-derived "sculpture", its "reprographics" (computer images), Esher's drawings, and natural biomineralized structures.

Indeed, art is about images and image-making. In this context it is interesting to recognize the relationship between our concentric gradient mesh structure in Figure 5A and our extended mesh structure in Figure 5E and their natural morphological equivalents, Figure 4A,E. These artificial and natural skeletal forms strikingly emphasize the effect that a circle limit exerts on a contiguous assemblage of vesicles with an inorganic coating. Interestingly, Escher's classic drawings "Circle Limit IV",[15] Figure 7A, and "Angels and Bats",[16] Figure 7B, raise one's artistic consciousness by graphically illustrating the effect of a singular point and translational symmetry, respectively.[15]

Escher's bounded "Circle Limit IV", the radiolaria microskeleton, and the synthetic facsimile with singular points seen in these graphic illustrations satisfyingly amalgamate visual imagery in art, nature, and science. All three present structural forms having repeating features of gradually diminishing size radiating from the midpoints of circles. Similarly, Escher's unbounded "Angels and Bats", the radiolaria microskeleton, and the synthetic facsimile without singular points lead to regularity expressed in extended repetition which characterizes translational symmetry. It is interesting that the visible patterning in Escher's work codes exquisitely for an underlying physicochemical growth pattern. The visible, in the case of both Escher and nature, is just a manifestation of a hugely dynamic underlying system of regulatory features.

One can deduce from Escher's writings that his prints and drawings were inspired by "a keen interest in the geometric laws contained in Nature around us". The graphic expression of his ideas depict striking visual metaphors for many basic concepts in science, such as color symmetry, topological change, self-similarity, and infinity. Through Escher's eyes many details of nature were transformed to arresting visual images. The particular theme of duality which is portrayed in "Circle Limit IV" and "Angels and Bats" can be considered to give artistic meaning to the complex organic media that we have coaxed into a pattern generation role for our inorganic materials.

(15) MacGillavry, C. H. *Symmetry Aspects of M. C. Escher's Periodic Drawings*; Bohn, Scheltema and Holkema: Utrecht, 1976.
(16) Escher, M. C. Circle Limit IV; The Netherlands, Collection Haags, Gemeente-museum, The Hague, The Netherlands.
(17) Takahashi, K. In *Radiolaria*: *Flux, Ecology, and Taxonomy in the Pacific and Atlantic*; Honjo, S., Ed.; Ocean Biocoenosis Series No. 3; Woods Hole Oceanographic Institution: Woods Hole, MA, 1991.
(18) *Ouvrage dédié à la Mémoire du Professeur Henry Germain* (*1903-1989*); Ricard, M., Ed.; Koeltz Scientific Books: Koenigstein, Germany 1990.
(19) *Silicon and Siliceous Structures in Biological Systems*; Simpson, T. L., Volcani, B. E., Eds.; Springer-Verlag: New York, 1981.

Escher gives artistic significance to the idea of how an object and its complement define each other. There are no outlines, and the contours of the angels and bats define one another. An extension of this notion reminds us of the spontaneous, thermodynamically driven segregation of amphiphile molecules of a contradictory nature into domains. The interface of these complementary domains defines the topography of the system. Its very existence inspires our "Medusa chemistry" approach to the shaping and patterning of inorganic materials, by creating a stoney replica, a lithomorph of the boundary.

Conclusion

In conclusion, it is apparent that our cellular-synthesis paradigm, using vesicle templating of aluminophosphates, has the ability to create inorganic−organic composite materials with impressive morphologies and spectacular surface patterns on scales that begin to approach nature's structures. Our self-organizing synthesis system can be considered to "evolve" in time because of the continuously diminishing concentration of nutrients. Self-assembly synthesis in this dynamic environment creates a diversity of surface patterns that arise from the deposition of the aluminophosphate, on and in the spaces between close-packed arrays of vesicles, subject to changing intra- and intermolecular force fields. Not all of the forms and patterns observed in our synthesis system can be explained solely in terms of surface tension and the closest packing of vesicles. The resemblance, however, to equivalent forms and patterns that occur in nature compel us to believe that our vesicle-patterning paradigm has some fundamental connection to the minimal energy and physicogeometric principles of D'Arcy Thompson so faithfully employed in nature.

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