How many plates?

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ABSTRACT

Herein I address the current number of plates, the number there should be, and whether there is a pattern in the plate mosaic. Related issues are the optimal sizes and shapes of plates and spacings of ridges, trenches, and transform faults. Similar questions arise in studies of foams, bubble rafts, buckyballs, mudcracks, columnar jointing, the tessellation of spheres, and the planforms of convection. In sphere-covering problems, and in dynamic problems, pentagons replace the familiar hexagons. The ''ground'' state of plate tectonics on a homogeneous planet may involve ~12 plates with five nearest and five next-nearest neighbors. The plate mosaic may be a self-organized network of plates and force chains, which are readily reorganized by stress changes. This paper starts with the premise that the mosaic may have simple and surficial explanations rather than convective or plutonic causes. The study of the tessellation of Earth can be called ''platonics'' to distinguish it from the idea that the lithosphere necessarily mirrors the planform of mantle convection.

Keywords: tectonics, plates, geodynamics, self-organization.

INTRODUCTION

Much of nature seems to be organized with little attention to the details of physics. Large interacting systems tend to self-organize. Thus, mudcracks, honeycombs, frozen ground, convection, basalt columns, foams, fracture patterns in ceramic glazes, and other natural features exhibit similar hexagonal patterns. In many cases there is a minimum or economy principle at work, e.g., minimum energy, area, stress, perimeter, or work. Dynamic systems, including plate tectonics, may involve dynamic minimization principles such as least dissipation. Natural processes spontaneously seek a minimum of some kind. These minima may be local; systems may jam before achieving a global minimum. Large, complex interacting systems can settle down into apparently simple patterns and behavior.

In the earth sciences polyhedra forms have been used to support contraction, expansion, and drift theories (Elie de Beaumont, 1829; Carey, 1976; Spilhaus, 1973). Thompson (1917) pointed out that identical forms can be generated by very different forces; it is impossible to deduce from observed patterns alone which forces are acting. The corollary is that pattern formation may be understood, or predicted, at some level without a complete understanding of the physical details. Dodecahedra, icosahedra, and icosidodecahedra have all been proposed for the underlying structure of global features (e.g., Spilhaus, 1973; Sears, 2001). This mathematization of geology is viewed with amusement by historians (Oreskes, 1999), and emphasis has shifted to modeling of mantle convection. These fluid dynamic simulations have not been successful in producing plate tectonics (e.g., Bercovici et al., 2000), and the most sophisticated treatments put in the observed plate configurations and motions as boundary conditions. The basic question then remains: in the ideal (platonic) plate tectonic world, what is the optimal shape and size of a tectonic plate and how many plates are there?

The shapes of buckminsterfullerenes, radiolaria, and viruses are spherical tessellation issues and are not yet fully understood. They are related to the tiling of a sphere and minimum perimeter problems. The optimal arrangement of tiles on a sphere has a correspondence with many distinct physical problems (e.g., carbon clusters, clathrates, boron hydrides, quasicrystals, distribution of atoms about a central atom, and bubbles in foam). It is often found that straight lines (great circles) and equant cells (squares, pentagons, or hexagons rather than rectangles) of identical size serve to minimize such quantities as perimeter, surface area, and energy. There is an energy cost for creating boundaries, and larger entities often grow at the expense of smaller ones. In phenomena controlled by surface tension, surface energy, stress, elasticity, and convection, there are often tripartite boundaries (called triple junctions or valence-3 vertices) and hexagonal patterns. The classic problem of convection goes back to experiments by Bénard (1900). The hexagonal pattern he observed was attributed to thermal convection for many decades, but is now known to be due to variable surface tension at the top of the fluid. Plan views of foams also exhibit this pattern. In all of these cases space must be filled and principles of economy are at work.

IN THE REAL WORLD

Table 1 gives the parameters of the plates. Plate tectonics on Earth, at present, consists of ~12 large semirigid plates of irregular shapes and sizes that move over the surface, separated by boundaries that meet at triple junctions. There are also many broad zones of deformation. The seven major plates account for 94% of the surface area of Earth. Gordon (2000) recognized 20 plates and an equal number of broad zones of deformation. To the usual plates, he added Borneo, Capricorn, Caroline, Indo-China, Nubia, North China, Okhotsk, Somalia, Yangtze, and Tarim. Asia and North America are collages of accreted terranes and the large Pacific plate grew by annexing neighboring plates (Hardebeck and Anderson, 1996).

Some of the larger plates have large fractions of their areas occupied by diffuse deformation zones and do not qualify in their entirety as rigid plates. At least 15% of Earth's surface violates the rules of rigid plates and localized boundaries. It is interesting that packing of similar-sized polygons or circles on a sphere leaves ~15% void space (except when n is 6 or 12; see Fig. 1). The minor plates, in aggregate, are smaller than the smallest major plate. In a close-packed or random assemblage of discs, the number of contacting neighbors decreases as the size disparity of the discs increases. At some point the system looses rigidity, typically at 15% void space. Six-coordinated structures

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TABLE 1. PARAMETERS OF PLATES

Plate		Area (10^6 km^2)	Growth rate (km^2/100 yr)	Notes	Plate type
Pacific	PAC	108	−52	*	O
Africa	AFR	79†	+30	*	C
Eurasia	EUR	69†	−6		C
Indo-Australia	INA	60†	−35	*	C
North America	NAM	60†	+9		C
Antarctic	ANT	59	+55		C
South America	SAM	41†	+13		C
Nazca	NAZ	15	−7	F	O
Arabia	ARA	4.9	−2	AF	C
Caribbean	CAR	3.8	0	**	O
Cocos	COC	2.9	−4	F	O
Philippine	PHI	~5		**	O
Somali	SOM			AF	C
Juan de Fuca	JdF			F	O
Gorda	GOR			F, D	O
Scotia	SCO			**	O
Southeast Asia	SEA			**	C
Indian	IND				C

Note: F, Farallon plate residues; AF, AFR fragments; *, possibly two or more plates; **, buffer plates?; O, mainly oceanic; D, possible diffuse boundary. †These plates are substantially reduced in area if the broad deformational zones are removed (Gordon, 2000). C, mainly continental.

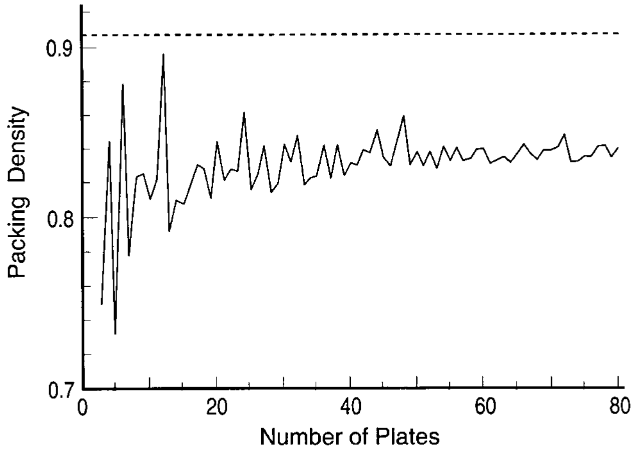

Figure 1. When tiles of given size and shape are packed on sphere, without overlap, packing density depends on number *n*. Optimal packing density is achieved for *n* = 12. This figure is for spherical caps, but other shapes give similar results. Voids between tiles have dimensions of ~10% of tile dimensions, so only small tiles or plates can be accommodated in interstices (after Clare and Kepert, 1991).

tend to be rigid. Fivefold coordination is rare in rigid crystals, but is common in fluids and glasses, on the surface of spheres, and at foam dislocations.

The Indo-Australian plate is divided into the Indian, Australian, and Capricorn plates and diffuse zones of extension and compression (Gordon, 2000). There are few earthquakes or volcanoes to mark these boundaries. The Pacific plate has several bands of earthquakes and volcanoes that could be cited as possible diffuse or incipient plate boundaries. One of these zones extends from Samoa and Polynesia to the East Pacific Rise and includes most of the intraplate earthquakes and active volcanoes in the Pacific (Favela and Anderson, 2000). There is little evidence for relative motion between the north and south Pacific plates, but current motions between Eurasia, Antarctica, and Africa are also very slow (Gordon, 1995). Therefore, there are between 8 and 20 plates; 12 is a frequently quoted number. Plate reconstructions in the past also recognize ~12 persistent plates.

OTHER STATISTICS

The coordination numbers of the present plates are: nearest neighbors 4.8 ± 1.2, and next-nearest neighbors 5.3 ± 0.6. These statistics are similar to those found in coarsening two-dimensional soap froths (Weaire and Hutzler, 1999). The number of nearest neighbors is six for a static equilibrium foam.

Ridges and trenches account about equally for 80% of the plate boundaries, the rest being transform faults. Most plates are not attached to a slab or bounded by a transform. Therefore, in the real world, plates are not equal in size or configuration.

A question arises whether the present situation is typical, or more representative of a transitional state. Active plate tectonics might require a number of small buffer plates as well as the larger plates. If the coordination numbers of the plates increased, the system may jam or lock up. In a world of rigid nonsubducting plates, the surface would lock up at ~15% porosity. Most plates are not attached to slabs and their freedom to move is constrained by the surrounding plates.

BUBBLES AND MINIMAL SURFACES

Foams are collections of surfaces that minimize area under volume restrictions. The 4 basic confined bubble structures have 12 pentagonal faces and are composed of a basic pentagonal dodecahedron with 2, 3, or 4 extra hexagonal faces (Weaire and Hutzler, 1999). These structures have only pentagonal and hexagonal faces, with no adjacent hexagons. Clathrates and zeolites also adopt these structures. Carbon cages involve the basic pentagonal dodecahedron unit supplemented by hexagonal faces with an isolated pentagon rule for the bigger molecules. These structures are minimal energy surfaces, and may serve as models for the tessellation of Earth. All vertices of these structures are triple junctions, meeting at 120°; all faces are pentagons or hexagons. Sheared bubbles in foams can adopt complex shapes, such as boomerangs, but they are still minimal surfaces (Weaire and Hutzler, 1999). In close-packed arrays of bubbles the dominant hexagonal coordination is interrupted by linear defects characterized by five and seven coordination. The midpoints between objects packed on sphere often define a pentagonal network. Even on a plane, random dense packings involve pentagonal networks, and this is more likely on a sphere, even for optimal dense packings (Tarnai and Gaspar, 1991, 2001).

From analogous geometric problems (foams, Marangoni convection, buckyballs, clathrate structures, tiling of spheres), I suspect that the ideal plate will be bounded by 5 or 6 edges and that plate boundaries will approximate great circles that terminate at triple junctions dominated by 120° angles (Fig. 2).

JAMMING

Two-dimensional foam is a classic minimum energy system and shows many similarities to plate tectonics. They are examples of soft matter; they readily deform and recrystallize (coarsen). Foams are equilibrium structures held together by surface tension. A variety of systems, including granular media and colloidal suspensions, exhibit nonequilibrium transitions from a fluid-like to a solid-like state characterized by jamming of the constituent particles (Trappe et al., 2001). The jammed solid can be refluidized by thermalization, temperature, vibration, or by an applied stress. These are termed fragile media (Cates et al., 1998).

Granular material and colloids tend to organize so as to be compatible with the load on them. They are held together by compression. They are rigid or elastic along compressional stress chains, but they collapse and reorganize in response to other stresses, until they jam again in a pattern compatible with the new stresses. The system is weak to incompatible loads. Changes in porosity, temperature, or stress are equivalent and can trigger reorganization and apparent changes in rigidity. The jamming of these materials prevents them from exploring

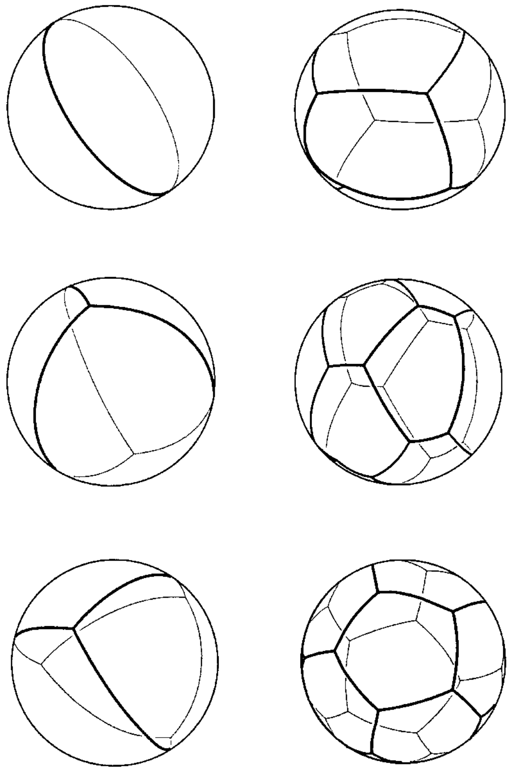

Figure 2. There are 10 possible configurations of great-circle arcs on sphere that meet 3 at a time with angles of 120°. Six of these are shown here. Only five have identical faces. These represent possible optimal shapes of plates and plate boundaries. These figures have 2, 3, 4, 6, 10, and 12 faces or plates (after Taylor and Gladbach, 1976).

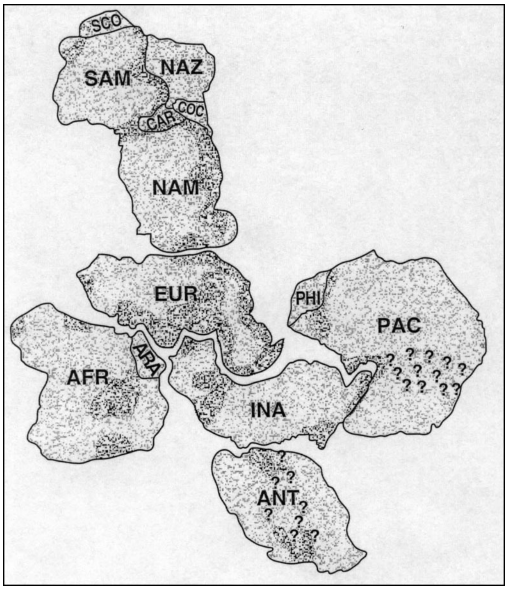

Figure 3. Disjointed Lambert equal-area projection centered on each plate. Note band of medium-sized plates encircling large African (AFR) and Pacific (PAC) plates. Possible deformation zones are shown by dark patterns and question marks. Some of the plates can be described as composite plates (Royer and Gordon, 1997).

phase space, so their ability to self-organize is restricted, but dramatic when it occurs.

In the plate tectonic context, compression keeps plates together. When the stress changes, and before new compatible stress circuits are established, plates may undergo extension and collapse. New compatible plate boundaries must form. Widespread volcanism is to be expected in these unjamming and reorganization events. These events are accompanied by changes in stress and in the locations and nature of plate boundaries and plates, rather than by abrupt changes in plate motions. Volcanic chains, which may be thought of as chains of tensile stress, will reorient, even if plate motions do not. Jamming theory may be relevant to plate sizes, shapes, and interactions. The present plate mosaic is presumably consistent with the stress field that formed it, but a different mosaic forms if the stresses change, e.g., as with the docking of the Ontong Java Plateau or India or the final transform motion between South America and Africa.

The Platonic philosophy distinguishes between the real world and the ideal world; the world that is, and the world that it will become. The principle that controls the shapes and numbers of plates I call ''platonics.'' The principle is not necessarily thermal convection in the interior of the planet (plutonics), but may be one of self-organization.

IS THERE A PATTERN?

The two largest plates are antipodal and are surrounded by a band of intermediate-sized plates and geoid lows (Anderson, 1989). An equal-area projection centered on Africa emphasizes the pentagonal shape of the African plate and the symmetry of the surrounding polygons (Spilhaus, 1973). Figure 3 shows an unwrapped globe where each plate is an equal-area projection.

Most plates have five nearest neighbors and five next-nearest neighbors, the coordination of a pentagonal dodecahedron. The plates, however, are far from regular pentagons in shape and size. Bubbles in foams and bubble rafts also show little dispersion from the mean values of five to six nearest neighbors in a plane, in spite of variations in size and shape. Foams also have the familiar 120° triple junctions, which evolve and annihilate (Weaire and Hutzler, 1999). The optimal packing of circular caps on a sphere involves five or fewer kissing neighbors (Tarnai and Gaspar, 1991; Fejes-Tóth, 1964; Fowler and Tarnai, 1999). Packings of pentagons on a sphere involve five nearest neighbors (Tarnai and Gaspar, 2001).

IN THE IDEAL WORLD

The ideal world may have n identical faces (plates, tiles) bounded by great circle arcs that meet three at a time at 120°.

This simple conjecture dramatically limits the number of possibilities for tessellation of a sphere and possibly for the ground state of plate tectonics. In soap bubbles and plate tectonics, junctions of four or more faces are unstable and are excluded. There are 10 such possible networks of great circles on a sphere (Taylor and Gladbach, 1976). Some of these are shown in Figure 2. If plate boundaries approximate great circles meeting 3 at a time at 120°, then there can be a maximum of 12 plates.

The study of convective planforms and pattern selection is a rich field (Bercovici et al., 2000). Regular polyhedral patterns are common even in complex convection geometries. Pattern selection in the plate tectonics system may have little to do with an imposed pattern from mantle convection. Of the 10 ways of drawing arcs of great circles on a sphere so that all intersections are at 120°, 8 are equilibrium configurations for soap bubbles. Five of the shapes are regular in that they have identical faces.

The optimal arrangement of spheres is a classical topological problem. The best packing in two dimensions is the familiar hexagonal lattice. The fraction of the plane occupied by circles is 0.9069. Packing circles on a sphere depends on the number of circles. The area covered ranges from 0.73 to 0.89 for $n \leq 12$ and oscillates about 0.82 at least to $n = 80$ (Fig. 1). Packing of more than 6 regular tiles on a sphere is inefficient except for 12 equal spherical pentagons, which can tile a sphere with no gaps. The efficiency of packing, the sizes of the voids, and their aggregate area depend little on the size distribution, within limits (Fejes-Tóth, 1964). The voids between regular tiles on a sphere, when close packed, are typically 10% of the radius of the discs. Typically, equal-sized circular or polygonal nonoverlapping caps can cover only ~70%–85% of the surface of a sphere. About 15% void space occurs even for optimal packing of large numbers of circular or pentagonal caps. However, one can efficiently arrange 12 caps onto a sphere, with only 0%–10% void space. This is much more efficient than, e.g., 10, 13, 14, or 24 caps. Furthermore, the difference between the sizes of caps that pack most efficiently (least void space), and cover the whole surface most economically (least overlap), is relatively small for 12 caps (the difference is zero for regular spherical pentagons).

Because plates are held together by networks of compressional forces, it is important that they pack efficiently. However, they must be mobile, and cannot be a permanently jammed system. Materials with this rigid-fluid dichotomy are called fragile (Cates et al., 1998). Close-packed networks of objects are jammed or rigid. However, even open networks can jam by the creation of load-bearing stress chains (Cates et al., 1998), which freeze the assemblage so that it cannot minimize the open space. These networks can be mobilized by changing the stress.

The least dense closest packing for similar size and shape caps on a sphere is ~70% coverage. The area of thin hot lithosphere along ridges is as much as ~14% of the surface area of Earth (Elsasser, 1971), which gives a total of ~30% when added to the broad deformed zones. In principle, this could still jam considering the tradeoffs between porosity, stress, and temperature (Trappe et al., 2001). Jamming represents a self-organized network of stress chains.

DYNAMICS

The forces acting on the surface of a planet that tend to subdivide it might involve thermal contraction, slab pull, ridge push, tearing (changes in dips of bounding slabs), stretching (changes in strike of boundaries), bucking, flexure, convection, jamming, and force chains. In far-from-equilibrium systems the minimizing principle, if any, is not always evident. The first step in developing a theory is recognition of any patterns and identification of the rules. To date, most of the emphasis on developing a theory for plate tectonics has involved thermal convection, driven from within and below. If plates drive and organize themselves, and organize mantle convection, or if plates are rigid and can jam, then a different strategy is needed. The mechanical integrity of a plate probably results purely from the applied load (gravity).

The definition of a plate and a plate boundary is subjective. Things are constantly changing. It is improbable that there is a steady-state or equilibrium configuration of plates because both ridges and trenches migrate and only a few of the 16 kinds of triple junctions are stable. Nevertheless, there does seem to be a pattern in the plate mosaic and there are similarities with so-called minimal surfaces. From strictly static and geometric considerations the ideal (Platonic) world may consist of 12 tiles with 5 nearest and next-nearest coordinations. The real dynamic world appears to contain a hint of this ideal structure (Spilhaus, 1973). A regular pentagonal dodecahedron with rigid faces would be a jammed structure.

DISCUSSION

On a homogeneous sphere one expects that surface tessellations due to physical processes will define a small number of identical domains. This will be true whatever the organizing mechanism, unless symmetry breaking and bimodal domains are essential for the operation of plate tectonics. There are only a few ways to tessellate a sphere with regular spherical polygons that fill space and are bounded by geodesics and triple junctions. Whether the surface is subdivided into faces by deep mantle convection forces or by superficial (Platonic) forces, we expect the surface of a homogeneous sphere to exhibit a semiregular pattern, although this pattern will not be stable if the triple junctions are not.

The problems of tessellations of spheres and global tectonic patterns are venerable. No current theory addresses the issues raised in this paper. The planform of a freely convecting spherical shell may have little to do with the sizes, shapes, and number of plates. The plates may self-organize and serve as the template that organizes mantle flow.

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