Fossils Record the Force of a Continental Collision

Terry Engelder

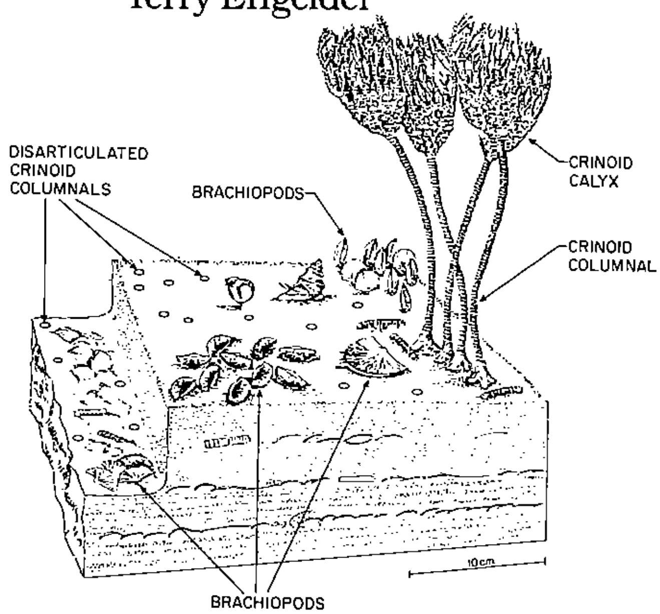

FIGURE 1: An example of a Paleozoic community in shallow ocean waters (after Cocks and McKerrow, 1978).

A Clue to Appalachian Strain

In western New York my father owns land surrounding one of the finest stream-cut rock outcrops in Allegany County. These outcrops are composed of fossil-rich shales and siltstones that were deposited in shallow marine waters about 350,000,000 years ago. As kids my brother and I often searched the rocks in the stream cut for the large shells of fossil brachiopods or for the stems and flower-like calyx of the crinoid, an echinoderm and relative of the starfish and sea urchin (Fig. 1). One summer day, after we had both become geologists, we were sitting on those same rocks gazing at some doughnut-like pieces of crinoid stem exposed on the surface of the rock, idly discussing how to use mathematics to describe them, since they were elliptical rather than round (Fig. 2). Suddenly I realized that I had the clue for which I had been searching during the past year.

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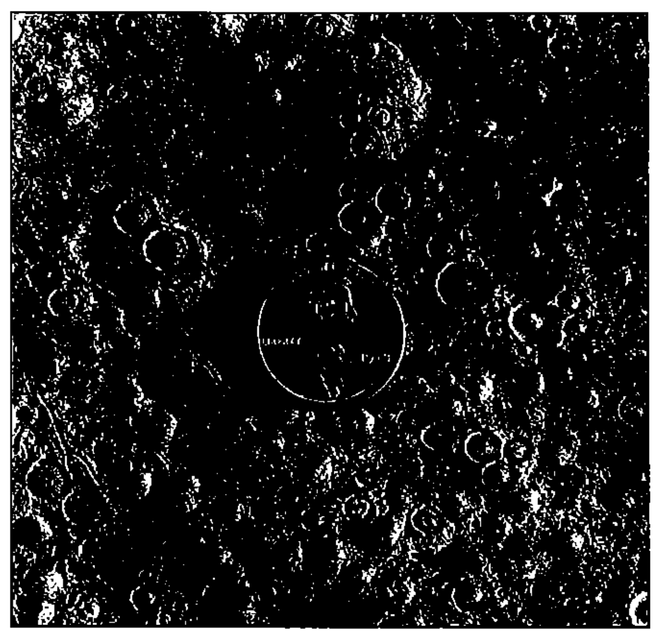

FIGURE 2: Deformed crinoid columnals within Devonian rocks of western New York.

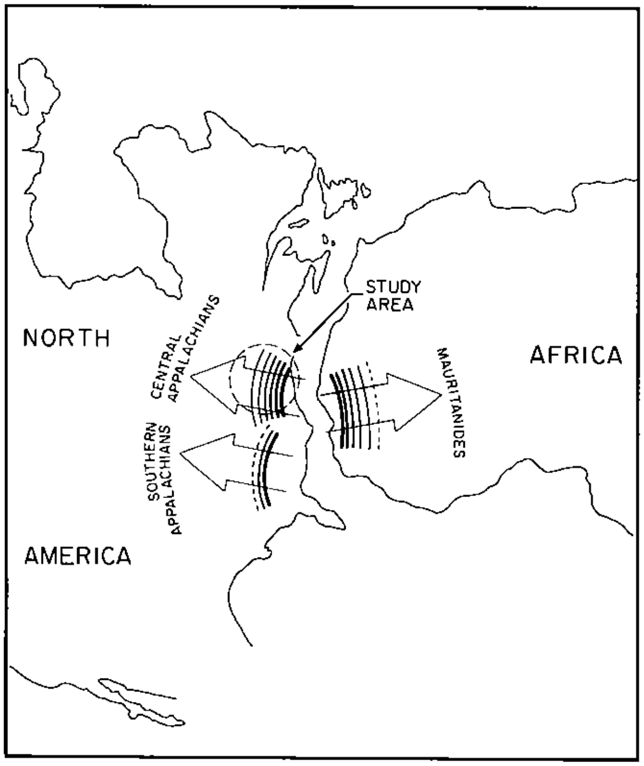

FIGURE 3: A map of the collision of America and Africa during the late Paleozoic.

The previous summer I had worked on a project sponsored by the Nuclear Regulatory Commission to measure earth stress in the northeastern United States. From data collected during these stress measurements I predicted that the Appalachian Mountains of western New York were compressed or strained a significant amount by a push originating in the vicinity of Baltimore, Md., and reaching 400 km to Buffalo, N.Y. Other geologists had calculated that the push originating in the vicinity of Baltimore occurred about 250,000,000 years ago, when, according to plate tectonic theory, western Africa bumped into North America between New York and Georgia (Fig. 3).

Continental Collision and Compression

During the collision the force of impact was driven far toward the heart of both continents. By looking at rocks tilting steeply one can see how the collision caused parts of central Pennsylvania to deform like a wrinkled rug. As the force diminished further from the point of impact the wrinkles or folds became smaller in northwestern Pennsylvania and in western New York they are not visible. A parallel phenomenon is evident in West Africa. The literature mentioned no evidence north of Philipsburg. Pa., of rock strain that could have resulted from this push, so I had not been sure what to look for in western New York to confirm my prediction. Evidently my brother and I were now looking at crinoid columnals that were once round but had been compressed into an elliptical shape much like an automobile tire that has lost some of its air. Each crinoid columnal in the rock outcrop had been compressed in the same direction and by the same amount, so that the pattern of ellipital shapes gave the rock an orderly appearance. This was the confirmation I had been looking for.

Continental Vs. Microscopic Deformation

Fossils that change shape during deformation are called strain markers, and fossils such as crinoid columnals are especially useful strain markers because their original shape is known. By comparing the deformed shape with the original shape, it is possible to calculate the amount of strain the rock experienced. We became curious about the process by which the crinoid columnals were deformed, for that would provide information on the magnitude and speed of the force of impact during the continental collision, since the force of impact on a continental scale is paralleled by the deformation of the crinoid columnals on the microscopic scale. We found that the manner in which the crinoid columnals change shape from circular to elliptical can be deduced from several features apparent in photomicrographs of the elliptical crinoid columnals (cover, and inside back cover).

The crinoid columnals are a single crystal of calcite, the constituent mineral of limestones. The individual columnals are similar to and serve the same purpose as the vertebra of the human back. The internal structures of the columnals include a five-lobed hollow interior called an axial canal, which carries nerves from the base of the crinoid to the blastoid top. The radial markings in the columnal are the crenularia, which aid in the connection of one columnal to the next. When viewed in thin section the initial round shape of crinoid columnals is evident in both the axial canal and the crenularia.

Pressure Solution

In the deformed columnals the exterior edge is more elliptical than the internal structures of the columnal. This means that part of the external edge has been removed by a process called pressure solution. A critical ingredient for pressure solution is that the rock contain water in its pores and cracks between grains. During pressure solution part of the rock is dissolved into the water within the cracks and pores. While in solution the components of the dissolved rock may diffuse away from the point where they entered solution. Evidently, pressure from the silt matrix surrounding the columnal enhances the solubility of the calcite in contact with the matrix. Enhanced solubility drives calcite into solution at an unusually high rate (Fig. 4).

Internal Dissolution

Part of the insides of some of these columnals have been removed by dissolving into the water that filled microscopic pores in the crinoid's axial canal (Fig. 5). This process of internal dissolution is different from the pressure solution on the external rim because the former is enhanced not by the normal pressure from the silt grains within the axial canal, but by an energy associated with internal deformation of the calcite crystal. Straight bands within the calcite crystal mark planes of atoms that have shifted to allow the calcite to deform

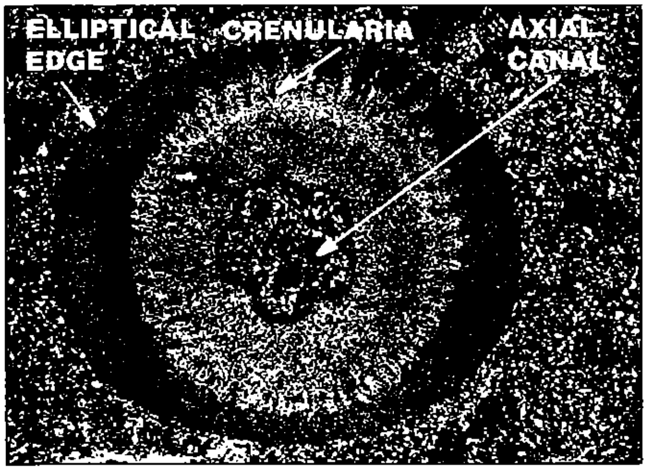

FIGURE 4: A thin section view of a crinoid columnal showing an elliptical edge generated by pressure solution.

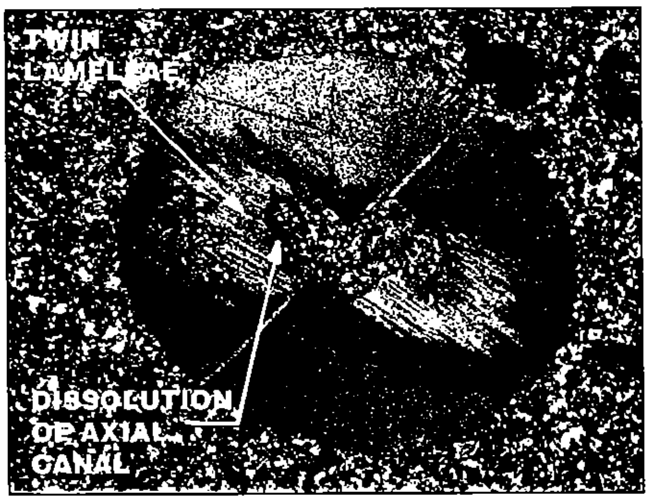

FIGURE 5: A thin section view of a crinoid columnal showing the dissolution of the axial canal.

internally. These deformation bands are known as calcite twin lamellae ("twins"). They disturb the atomic structure of the calcite so that the calcite crystal near the lamellae contains an abnormally high amount of strain energy. It is the strain energy associated with the twin lamellae that increases the rate of dissolution within the axial canal.

The Rock Deformation Process

The force of impact between two continents is manifested by the formation of mountain ranges. During such formation pressure solution is a common deformation process in rocks. One important aspect of pressure solution is that it coupled with flow of water, may cause rocks to decrease in volume, so that the rocks of many mountain ranges occupy a smaller volume today than they did before the mountains were formed.

One step in the pressure-solution process is the diffusion of rock components (i.e. calcite from the dissolved crinoid columnals) in a solution of pore water. The diffusion may occur either as mass flow of pore water as the result of a hydraulic pressure gradient, or the motion of ions responding to a concentration gradient caused by a variation in chemical potential between grain-grain contacts. The latter moves components or rocks a very short distance such as across a pore less than a millimeter in diameter, whereas mass flow of water can move components of rocks many kilometers. Through pressure solution by diffusion within pores, a rock will change shape without loss of volume, whereas though pressure solution by diffusion within circulating pore fluid a rock will change shape as well as lose volume. In the former case no volume loss occurs because all components reprecipitate within pores in the immediate vicinity of the place where they were dissolved, while the shape change is accomplished by the movement of components over small distances. In the latter, components are carried away from the immediate vicinity of the place of dissolution and so shape changes are accomplished by complete removal.

Pressure solution is also an important mechanism in the generation of folds in rocks. By losing volume rock can accommodate sharp bends that would otherwise be impossible without rupture. In effect, the large wrinkled rug that is the present folded Appalachians in central Pennsylvania owes its existence in part to pressure solution. The crinoids on our father's farm indicate that the rocks of western New York have lost about 10% of their volume by pressure solution and mass flow of pore water.

Stresses Confirmed in the Laboratory

From laboratory experiments that study the response of rock to stresses we know that pressure solution is a viscous process. This means that the harder a rock is pushed, the faster it changes shape by the pressure-solution process. Using the data from such laboratory experiments, we can deduce from the elliptical crinoids that the rocks of western New York were subject to a stress of about 100 bars (1500 pounds per square inch) and were deformed with a 10% loss of volume in a cumulative time of about 1,000,000 years. The orientation of the deformed crinoids also gives an indication of the direction from which the force of impact came. In the case of western New York this direction was south-southeast.

Our discovery of deformed crinoids in western New York led to further studies of pressure solution. Peter Geiser of the University of Connecticut and I conducted a regional analysis of strain within the central Appalachian Mountains where the details of the collision between Africa and North America are being documented. Walter Alvarez of the University of California, Berkeley, and I have studied the Apennine Mountains in central Italy where again pressure solution was the principal response of the local rocks to a push arising from plate tectonics. In the Lamont-Doherty rock mechanics lab Chris Scholz and I are studying the process of pressure solution with experiments that involve pushing water through joints in hot rocks that are subject to great pressures. This laboratory project is relevant to the recovery of geothermal energy and the disposal of nuclear waste.