ROCK STARS

Laurence L. Sloss and the Sequence Stratigraphy Revolution

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Stratigraphy is one of the oldest branches of geology, dating back 200 years to William Smith and Georges Cuvier at the beginning of the nineteenth century. It was then that the value of fossils for subdividing and correlating strata was first demonstrated. The new method served well for 150 years, but by the mid-twentieth century, detailed studies showed that fossil occurrences were dependent not only on time, but also on environment. As changes to environment occurred, the fossil animals migrated and so could vary in age laterally, contradicting the long-held assumption of strict time dependence of species.

By the 1930s, Laurence L. Sloss noted that stratigraphy was beset with "stupefying arguments" about abstract time versus actual rocks and how to classify such things. The concept of time-stratigraphic divisions addressed some of the concerns, and bio-, litho-, and chrono-stratigraphy were separately defined. For folks who delighted in describing and classifying, there was plenty of work, but for others, frustration prevailed. Sloss entered our profession during this period and, to quote him, "My enthusiasm for paleontologic taxonomy expired even as I was completing a dissertation on Devonian corals" (1984, p. 3). He was soon to discover several important unconformities in the Montana region, which did not conform to any classical, fossil-based stratigraphic divisions, yet they seemed to divide the rock record into meaningful, natural packages. Thus, the germ of sequence stratigraphy was born.

WHO WAS LAURENCE L. "LARRY" SLOSS?

Sloss was raised in the San Francisco Bay Area. His grandfather was a forty-niner who passed up gold in favor of seal skins for a fortune. "He amassed a considerable fortune by killing nearly all the seals on the Pribilof Islands—an enterprise unimpeded by a Sierra Club and not even requiring an environmental impact statement" (1980 William H. Twenhofel Medal acceptance speech, *in* Anonymous [1999, p. 79]). Grandpa returned to California and used his fortunes to create a successful fruit-raising business. Young Sloss followed his friends to Stanford University, where he discovered geology. His summer field course was taught in western Nevada by distinguished petrologist, Aaron C. Waters

Figure 1. Stanford Field Course, 1933; Sloss: front left; Waters: standing (courtesy Stanford University).

(Fig. 1). Sloss told me that Waters was a bit of a martinet, who made good on his threat to leave them to the coyotes if they did not show up at the designated spot at exactly 4 p.m. He remembered "arriving late one day at the pick-up point with empty canteens to see a cloud of dust marking the passage of the camp transport truck… We made it back to camp after dark." He also remembered that Waters snored terribly, and one night the boys carefully moved his cot right next to the spring pool where they were camped. Sure enough one great snore was suddenly drowned out in the wee hours as Waters rolled over.

In spite of what Sloss described as a desultory undergraduate career, he was admitted to the University of Chicago graduate program (having been rejected by Harvard) where he completed a paleontological dissertation directed by Professor Carey Croneis. While Sloss was honeymooning, Croneis found him a job in Montana. During the academic year, he was to teach stratigraphy at the School of Mines in Butte, and during summers he would work for the Montana Bureau of Mines. He felt very lucky because in 1937 jobs were mighty scarce.

BIRTH OF THE SEQUENCE CONCEPT

It was during his seven years in Montana that Sloss first recognized those regional unconformities, which would become the basis for sequence stratigraphy (Fig. 2). Several petroleum companies were actively exploring in the region, and they became interested in his work. Sloss became especially well acquainted with Gulf Oil Company geologist Max Littlefield, who introduced him to geophysical techniques for studying stratigraphy in the subsurface.

In 1947, Sloss accepted a faculty position at Northwestern University, where he joined Edward C. Dapples and former University of Chicago associate, William C. Krumbein. Thus was formed an unusually fruitful team of sedimentary geologists, which was to have a major impact upon the field during the next four decades (Fig. 3). Dapples and Sloss knew regional stratigraphy well and found that they had observed separately several of the same unconformities in different parts of the central craton. Krumbein was a pioneer in quantification of sedimentary data and was trying to develop a way to provide some quantitative rigor to the analysis of sedimentary facies. He needed some basis for

Figure 2. Sloss leading a pack train in Montana, 1944 (courtesy Northwestern University).

Figure 3. The Northwestern triumvirate in 1950: left to right: Sloss with trademark pipe and bow tie, Krumbein, and Dapples (courtesy Northwestern University).

subdividing the stratigraphic record into *operational units* for facies mapping, so the trio seized upon those unconformity-bounded packages of strata as such units and named them stratigraphic *sequences.* To emphasize the distinction of their sequences from the conventional European fossil-based stratigraphic subdivisions, they cleverly chose the names of Native American tribes indigenous to the areas where a given sequence was best represented. Thus the Sauk Sequence was named for Sauk County, Wisconsin. At first, four sequences were so named, which approximately spanned all of the Paleozoic systems. Later, as they became more acquainted with the younger record toward the margins of the craton, two more sequences were named (Fig. 4).

In 1948, the Geological Society of America sponsored a symposium on sedimentary facies, the results of which were published in six papers as GSA Memoir 39, *Sedimentary Facies in Geologic History.* It was in this timely volume that the Northwestern scheme for facies analysis was introduced. Sloss told me that their paper violated Krumbein's Rule that a published paper should present only one new idea; they had introduced not only the new quantitative facies analysis, the main topic, but also the new concept of stratigraphic sequences.

Sequence stratigraphy, like many new ideas, was not met with immediate acclaim. Most of the profession's members did not quite know what to think of it. One distinguished member of the symposium audience, Philip B. King, complimented their statistical approach to facies, but then declared, "Why should these authors then proceed to detract from their excellent technique by superimposing on it the wholly unwarranted 'operational units,' which are newly named and which have no relation to time-stratigraphic units? The reasons given for adopting such units are specious, the new names confuse rather than illuminate" (Longwell, 1949, p. 169). This was a common reaction.

Sloss and his two associates had also adopted the sedimentary rock classification of Paul D. Krynine, and much of that author's ideas about sedimentary tectonics. Rather than being flattered, however, Krynine remarked in a 1951 paper, "They (Sloss, Krumbein, and Dapples) quote, but do not utilize my ideas of the diastrophic and geosynclinal cycle of sedimentation" (p. 745), adding, "The very moderate success of their effort suggests that the proper genetic bridge between sedimentation and tectonics has not quite been established" (p. 746). Apparently Krynine harbored little respect for stratigraphy, because two of his former students quoted him as saying that stratigraphy represents the "Complete triumph of terminology over facts and common sense" (Folk and Ferm, 1966, p. 853).

When I questioned Sloss in 1996 about influences upon the original conception of sequence stratigraphy, he acknowledged that the paleogeologic or subcrop maps of A.I. Levorsen and others and the novel ideas about cratonic stratigraphy of E.O. Ulrich during the 1930s certainly had been influential, as had the later stratigraphic thinking of Harry E. Wheeler. Sloss and Wheeler had overlapped at Stanford and had been associated as co-consultants to oil companies during the 1950s, exploring the western states, with many opportunities to exchange ideas. Sloss emphasized, however, that "the growing scope of stratigraphic investigations and, most importantly, the emergence of subsurface data, made it (sequence stratigraphy) inevitable."

SEISMIC SEQUENCE STRATIGRAPHY

In the late 1960s, Sloss and Dapples had several exceptional students, notably Peter Vail, Robert Mitchum, and John Sangree, who completed dissertations involving Pennsylvanian strata. They became aware that glacial eustatic changes of sea level could have been responsible for the numerous widespread unconformities in the famous cyclothems. Following receipt of their degrees, these men joined an Exxon research group, which was to develop modern seismic stratigraphy. They adopted and greatly refined their mentors' sequence stratigraphy to the interpretation of subsurface seismic data. They recognized similar successions of sequences and unconformities on different, widely separated continental margins, which implied some global cause, perhaps glacial eustatic fluctuations.

Their approach recognized shorter-duration successions than Sloss' original sequences. Whereas each of his six craton-wide sequences represented hundreds of millions of years, the seismic

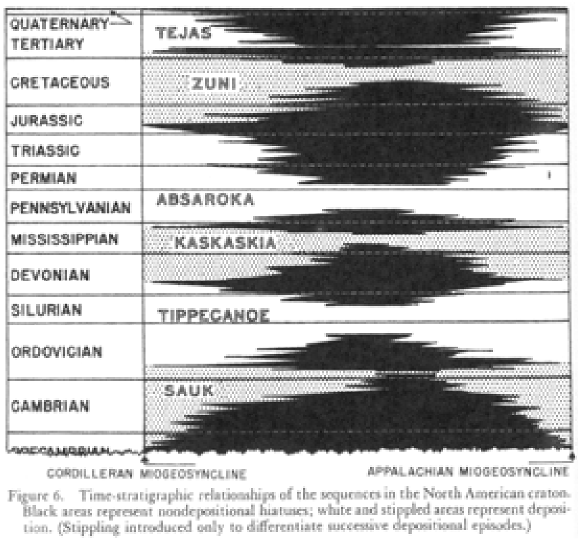

Figure 4. The sequences in 1963 (Sloss, 1963, fig. 6, p. 110).

sequences typically represent only thousands to a few million years. History has shown that the concepts developed for seismic stratigraphy have widespread application to outcrop geology as well as to the subsurface, and so it is this refined sequence stratigraphy that has so revolutionized modern stratigraphy.

In 1984, Sloss had this to say about his intellectual children: “This group was pre-adapted to recognize unconformity-bounded units on reflection seismic records and they are deeply impressed by the apparent global synchrony of stratigraphic patterns clearly related to the freeboard of continental margins. … They find that they sleep well when they place their faith in eustatic sea levels and dream pleasant dreams when glacial controls on eustatics can be invoked” (p. 9–10).

To his grave, Sloss remained assured that tectonics, presumably plate tectonics, somehow controlled the sequences (1988). Recent seismic tomography shows large-scale heterogeneity in the mantle beneath North America, which is being interpreted as due to relict subducted slabs. Regardless of their cause, is it not possible that isostatic adjustments of the overlying crust as plate motions carry the continent over such heterogeneities could explain the warping of cratonic arches and basins?

HONORS

Sloss received many honors, including the Penrose Medal of the Geological Society of America (GSA) and the Twenhofel Medal of the Society for Sedimentary Geology (SEPM). In 1999, the GSA Sedimentary Division created the Sloss Medal in his honor. He was president of GSA, SEPM, and the American Geoscience Institute, and he served on many professional committees and commissions. Sloss was a geological statesman, philanthropist, and an influential teacher who always encouraged the young.

I conclude with Sloss’ own droll remarks from his 1980 Twenhofel Medal acceptance speech: “I wish I could leave you with… some trenchant maxim that would make me seem a worthy role model for rising young geologists; instead, all that runs through my mind is that a lack of virtue does not necessarily lead to a lack of rewards, that procrastination saves time (the problem may go away) and, that there **is,** indeed, a free lunch, and I just had one” (*in* Anonymous, 1999, p. 80).

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