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Analysis of Main Principles of Stratigraphy on the Basis of Experimental Data[1]

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Abstract—Stratigraphy, the basis of geological dating, was founded in the 17th century on the three well-known principles assumed by Nicolas Stenon: superposition, continuity, and original horizontality. Successive observations and experiments show that Stenon's stratigraphic model was not in line with experimental data, because it had "overlooked" the major variable factor of sedimentology: *the current and its chronological effects*.

Experiments were performed simulating the formation of sediment layers generated at variable current velocities from inequigranular particles. Results of the experiments showed that Stenon's stratigraphy can be applied only in the particular case of deposition at a nil current velocity. Modeling of sedimentation process and interrelation in sedimentology, stratigraphy and geological dating allows paleohydraulic conditions to be considered as the new approach to geological dating.

INTRODUCTION

Stenon was the founder of stratigraphy. It was in 1667 that he introduced in his work *Canis Calchariae* the postulate: *layers of sub-soil are "strata" of ancient successive "sediments."* From this partial interpretation, Stenon drew three initial principles of stratigraphy formulated in 1669 in his work *Prodromus* (Ellenberger, 1975).

(1) Principle of superposition

At the time when one of the highest stratum formed, the stratum underneath it had already acquired a solid consistence. At the time when any stratum formed, the superincumbent material was entirely fluid. Therefore, at the time when the lowest stratum formed, none of the superior strata existed.

(2) Principle of continuity

Strata owe their existence to sediments in a fluid. At the time when any stratum formed, either it was circumscribed on its sides by another solid body, or else it ran round the globe of the Earth.

(3) Principle of original horizontality

At the time when any stratum formed, its lower surface, as also the surfaces of its sides, corresponded with the surfaces of the subjacent body, and lateral bodies, but its upper surface was (then) parallel to the horizon, as far as it was possible.

The sedimentological model corresponding to these three principles is, therefore, the following. In a fluid covering the Earth, except for emerged land, a precipitate deposits strata after strata, covering all the submerged Earth. After the deposition of each stratum, the sedimentation is interrupted for the time it takes for the stratum to acquire a solid consistence. The stratum being contained between two parallel planes indicates that the sedimentation rate of the precipitate is uniform around the submerged Earth.

Stenon's assertion relies solely upon observation of stratified rocks and the superposition of strata, independently of data from the sedimentological process. This process is composed of three phases: erosion, transport, and deposition of sediments, the liquid current being the vector of transport. Stenon's stratigraphy only took account the third phase of sedimentology, i.e., the deposition, assuming implicitly a nil velocity of current.

PROBLEMS OF STENON'S STRATIGRAPHY

This model based upon a postulate, which takes into account only one particular case of sedimentation, namely the absence of current, implying succession of time on a global scale, according to the vertical sequence of strata, is not in accordance with experimental and field investigations.

The first part of the definition of the principle of superposition is as follows: *At the time when one of the highest stratum formed, the stratum underneath it had already acquired a solid consistence*. A stratum between 50 cm and 1 m is considered thick. Consequently, submarine drillings should encounter solid strata in the stratified oceanic sediments after a few meters.

The results of seafloor drilling showed that the first semiconsolidated sediments appeared at a depth of about 400–800 m. However, certain chert beds (siliceous beds) were found in sediments at a depth of 135 m near the

[1] This article was submitted by the author in English.

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oceanic transform fault zones (Logvinenko, 1980). Therefore, Stenon's definition concerning successive hardening, which spans over the total duration of deposition, is not supported by sedimentological observations mentioned above.

No sedimentary layer extends around the Earth. Seismic readings and submarine coring demonstrate that the strata in oceanic deposits are not always horizontal and the sedimentation rate in oceans is not uniform on a global scale of the Earth.

In the first part of the definition of the principle of continuity, Stenon affirms that *strata owe their existence to sediments in a fluid.*

Stenon says nothing about the influence of fluid on sediments. Thus, the relative stratigraphic chronology resulting from his principles did not take it into account this influence (the two later principles of paleontological identity and uniformitarianism changed nothing in this respect). Currents exist in present-day oceans that erode, transport, and deposit sediments, as was shown by Strakhov in 1957. Geologists have attributed changes in the orientation of stratification and erosion surfaces in sedimentary rocks to marine transgressions and regressions. This is the object of study in sequence stratigraphy today. Diagrams in sequence stratigraphy, however, give no indication of the current velocity of these transgressions and regressions, except for variations in the level of oceans. Detrital sedimentary rocks alone (resulting from mechanical desegregation) would have required a minimum current to transport the particles from where they were eroded to their sedimentation site.

Charles Lyell added a principle of uniformitarianism, giving as an example layers deposited in fresh water in Auvergne. Observing that the layers were less than 1 mm thick, he considered that each layer was laid down annually. At this rate, the 230-m-thick deposit would have taken hundreds of thousands of years to form. As will be shown below, these layers (laminae) do not always correspond to annual deposits and may be generated in a much less time interval than the modern geological time-scale indicates.

MAJOR STAGES OF THE LABORATORY RESEARCH

Two principal stages of the scientific program are reflected in the following lines of research: lamination (Fig. 1) and stratification (Figs. 2, 3).

(1) Lamination

The following abstract of my paper (Berthault, 1986) provided the basis of research on the deposition of inequigranular sediments in water (with and without a current):

Sedimentation experiments were conducted in still water with a continuous supply of inequigranular material. A deposit is obtained, giving the illusion of successive beds or laminae. These laminae are the result of a spontaneous periodic and continuous grading process, which takes place immediately, following the deposition of the inequigranular mixture. The thickness of laminae appears to be independent of the sedimentation rate but increases with extreme differences in particle size in the mixture. Where a horizontal current is involved, thin laminated layers developing laterally in the direction of the current are observed.

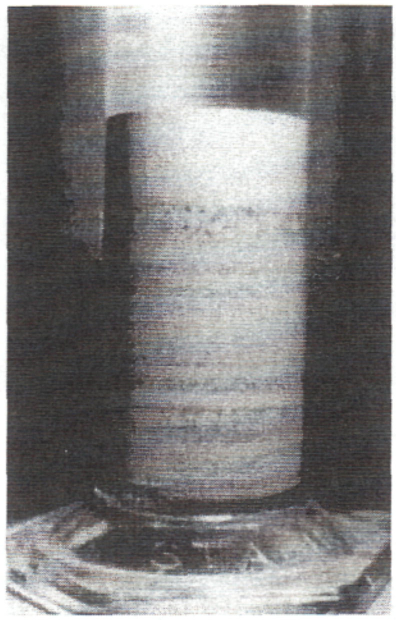

Fig. 1. Lamination resulting from sediment flowing into water.

The second series were performed at the Marseilles Institute of Fluid Mechanics.

The experiments demonstrate that continuous deposition of inequigranular sediments in still water gives rise to laminae, which disappear progressively as the height of the fall of particles into water (and apparently their size) increases. Laminae follow the slope of the upper part of the deposit. In running water, many closely related (even superposed) types of lamination appear in the deposit (Berthault, 1988).

(2) Stratification

Experiments in stratification were conducted in the Fort Collins hydraulics laboratory of Colorado State University with professor of hydraulics and sedimentology Pierre Julien.

It was necessary to operate with water in a recirculating flume traversed by a current laden with sediment. As Hjulstrom (1935) and his successors had defined the critical sedimentation rate for each particle size, the current velocity should be varied. By modulating the current velocity, a superposition of segregated particles could be obtained.

The flume experiment showed that in the presence of a variable current, stratified superposed beds pro-

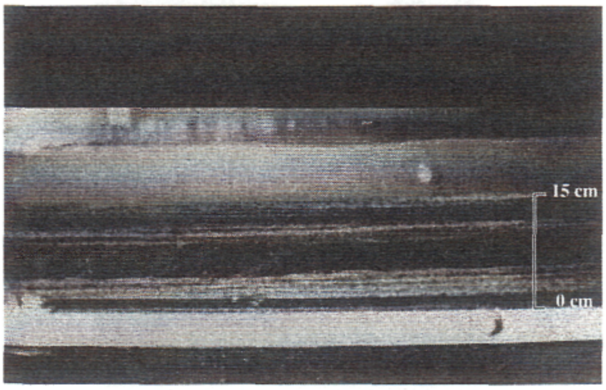

Fig. 2. Typical longitudinal view of deposition (flow from right to left).

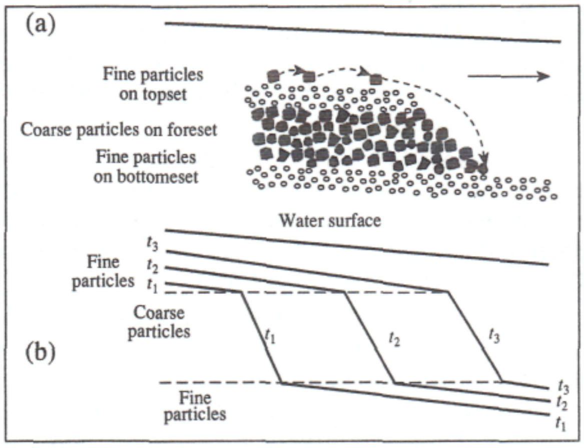

Fig. 3. Results of experiments. (a) Schematic formation of graded beds. (b) Time sequence of deposit formation for $t_1 < t_2 < t_3$.

grade simultaneously in the direction of the current. On the strata scale the obtained result, is consistent with the facies-scale Golovkinskii-Inostrantsev–Walther's law (Walther, 1894; Middleton, 1973; Romanovskii, 1988), according to which the extension of facies of a specific sequence is the same in both lateral and vertical directions.

The report of the experiment entitled *Experiments in Stratification of Heterogeneous Sand Mixtures* was published in (Julien *et al.*, 1993).

This experimental study examines the possible stratification of heterogeneous sand mixtures under continuous (nonperiodic and noninterrupted) sedimentation. Three primary aspects of stratification are considered: lamination, graded beds, and joints.

(a) Experiments on segregation of eleven heterogeneous mixtures of sand-sized quartz, limestone and coal demonstrate that through lateral motion, fine particles fall between interstices of the rolling coarse particles. Coarse particles gradually roll on top of fine particles and microscale sorting is obtained. Microscale segregation similar to lamination is observed on plane surfaces, as well as under continuous settling in columns filled with air or water.

(b) The formation of graded beds is examined in a laboratory flume under steady flow and a continuous supply of heterogeneous particles. Under steady uniform flow and plane bed with sediment motion, coarse particles of the mixture roll on a laminated bed of mostly fine particles. In nonuniform flow, the velocity decrease caused by tail-gate induces the formation of a stratum of coarse particles propagating in the downstream direction. On top of this cross-stratified bed, fine particles settle through the moving bed layer of rolling coarse particles and form an almost horizontally laminated topset stratum of finer particles. A thick stratum of coarse particles thus progresses downstream between two strata of laminated fine particles, continuously prograding upward and downstream.

(c) Laboratory experiments on the desiccation of natural sands also show preferential fracturing (or joints) of crusty deposits at the interface between strata of coarse and fine particles.

Rather than successive sedimentary layers, these experiments demonstrate that stratification under a continuous supply of heterogeneous sandy mixtures results from segregation for lamination, nonuniform flow for graded beds (Fig. 4), and desiccation for joints (Fig. 5). Superposed strata are not, therefore, necessarily identical to successive sedimentary layers.

Maxima permissible velocities or nonerosive for noncohesive grounds, in m/s (selon Lischtvan–Lebediev)

Average diameter of particles, in mm	Average flow depth, in m					
	0.40	1.0	2.0	3.0	5.0	>10
0.005	0.15	0.20	0.25	0.30	0.40	0.45
0.05	0.20	0.30	0.40	0.45	0.55	0.65
0.25	0.35	0.45	0.55	0.60	0.70	0.80
1.0	0.50	0.60	0.70	0.75	0.85	0.95
2.5	0.65	0.75	0.80	0.90	1.00	1.20
5	0.80	0.85	1.00	1.10	1.20	1.50
10	0.90	1.05	1.15	1.30	1.45	1.75
15	1.10	1.20	1.35	1.50	1.65	2.00
25	1.25	1.45	1.65	1.85	2.00	2.30
40	1.50	1.85	2.10	2.30	2.45	2.70
75	2.00	2.40	2.75	3.10	3.30	3.60
100	2.45	2.80	3.20	3.50	3.80	4.20
150	3.00	3.35	3.75	4.10	4.40	4.50
200	3.50	3.80	4.30	4.65	5.00	5.40
300	3.85	4.35	4.70	4.90	5.50	5.90
400		4.75	4.95	5.30	5.60	6.00
>500			5.35	5.50	6.00	6.20

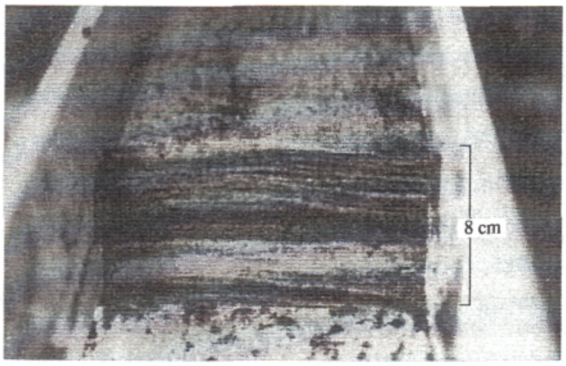

Fig. 4. Typical cross section of deposit.

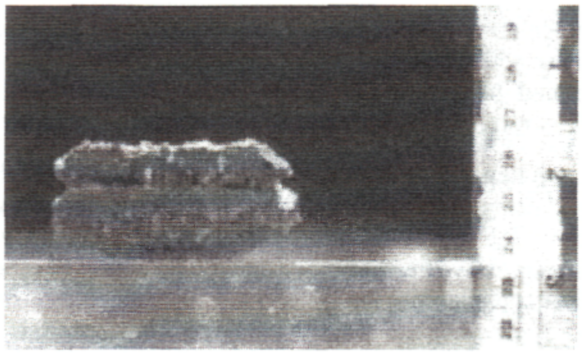

Fig. 5. Horizontal fracturing of the Bijon Creek sand.

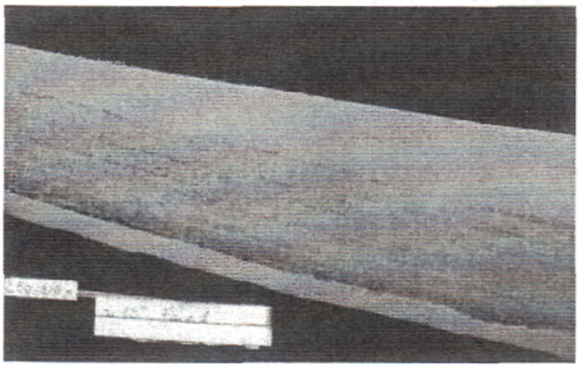

Fig. 6. Lamination parallel to a slope of 15°.

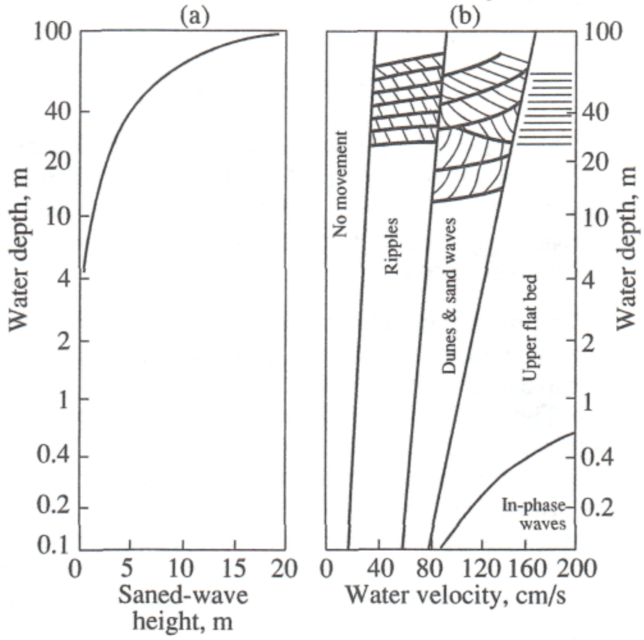

Fig. 7. Graphs of (a) water depth vs. sand-wave height and (b) water depth vs. water velocity, showing bedforms in fine sand expected under different water conditions. The thickness of cross beds observed in fine-grained sandstone is used to estimate sand-wave height. Then, sand-wave height is entered into the graph (a) to estimate the water depth where the sand wave formed. After a water depth is estimated on graph (a), the depth is transferred to graph (b), where the minimum and maximum velocities of water are indicated for the specific water depth.

Our flume experiments demonstrated that Stenon's assumption (strata are ancient successive sediments) and his principle of superposition can only apply in the absence of a current (nil transport velocity). Moreover, the experiments reported in my second paper to the Academy of Sciences, as well as experiments conducted by P. Julien and presented as video *Fundamental Experiments on Stratification* at several sedimentological congresses, clearly show that up to the limit of the angle of repose (30° to 40° for the sands), the lamination of sediments is parallel to the slope (Fig. 6). The principle of horizontality does not apply in this case. It should not, therefore, be concluded that the dip of strata necessarily implies tectonic movements subsequent to the horizontal deposition of strata.

(3) Paleohydraulic conditions

Analysis of the main principles of stratigraphy on the basis of experimental data is necessary to determine the hydraulic conditions that existed when the sediments, which have become rocks, were deposited.

In this respect, the relation between hydraulic conditions and configuration of deposits (submarine ripples and dunes and horizontal beds) of contemporary deposits have been the object, especially recently, of well-known observations and experimentation. Rubin and McCulloch (1980) reported data on the San Francisco Bay environment (Fig. 7), while Southard and Boguchwal (1990) presented results of flume experiments. Meanwhile, Hjulstrom and his successors (Hjulstrom, 1935; Lebedev, 1959; Neill, 1968; Levi, 1981; Maizels, 1983; Van Rijn, 1984; Maza, Flores, 1997) determined a minimum velocity of erosion and sedimentation for each particle size at a given depth (table). These relations can be applied particularly to detrital rocks, such as sandstone, the first stage of a transgressive marine sequence resulting from erosion, transport, and sedimentation driven by an initially erosive powerful current in shallow water. The *competence*, i.e., the paleovelocity of current below which particles of a given size are deposited, and the corresponding *capacity* of sedimentary transport of the current can be determined based on the above data. These two criteria determine the time required for sequence deposition.

When the transgression reached its maximum depth and correlatively the velocity of current tended toward zero, the finest particles transported initially by the transgressive current precipitated as a result of retardation and eventual flocculation. It is, therefore, possible to appreciate the time the particles took to fall and, based on the capacity, to evaluate the time taken for the sediment to precipitate. Such data would, of course, only be minimum, but it would nevertheless give access to knowledge of the genesis of sedimentation.

CONCLUSIONS

The dating principles determined in the 17th century by Stenon, an anatomy professor of Copenhagen University (Molyavko *et al.*, 1985), upon which the geological time-scale is founded should be re-examined and supplemented.

The most probable way of determining the genesis of sedimentary rocks is, first, to identify cycles of transgressive–regressive sequences by sequence stratigraphy. The results of our flume experiments are relevant in this connection. They show that in the presence of a current, strata in a sequence are not successive. Change of orientation in stratification, or erosion surfaces between facies of the same sequence, or between superposed sequences can result from a variation in the velocity of an uninterrupted current. Bed plane partings separating facies or sequences can result from desiccation following the withdrawal of water.

Having established the sequences of cycles, their paleohydraulic conditions must be determined. These would be minimum conditions, because it is possible that certain cycles, resulting from tectonic processes, attained an amplitude beyond anything comparable today.

Knowledge of paleohydraulic conditions should help to determine better the paleoecological zones (depth and site) of the species which, as with the sediments, were dragged along by the currents. It might also provide a better explanation of the layering of fossil zones in the sediments of sedimentary basins.

By calling into question the principles and methods, upon which geological dates are founded, and in proposing the new approach of paleohydraulogy, I hope to open a dialogue with specialists in the disciplines concerned, who are able to appreciate the implications, and propose a geological chronology in conformity with experimental observation.

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