Sedimentological Interpretation of the Tonto Group Stratigraphy (Grand Canyon Colorado River)

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In my article published recently by *Lithology and Mineral Resources* [Berthault, 2002], I demonstrated on the basis of experiments in sedimentation of heterogeneous sand mixtures in flow conditions that the three principles of superposition, continuity and original horizontality of strata affirmed by Steno, should to be supplemented and re-considered.

I will now show that the stratigraphic divisions of the geological column founded on these principles do not correspond to the reality of sedimentary genesis. I will use the Grand Canyon as a concrete example.

Because Steno assumed upon observation of stratified rocks that superposed strata of sedimentary rocks were successive layers of sediment, a stratigraphic scale was devised as a means of providing a relative chronology of the Earth's crust. It was not constructed strata by strata because of the impossibility of following the same strata around the earth. It was built at a higher level of stratified layer called a "stage". According to the classical definition: *A stage is a unit defined from a "reference cut" (stratotype) characterised by a group of paleontological, lithological or structural criteria of universal value* [*Précis de Géologie,* 1967]. The "stratotype" is chosen from a marine formation situated in a "locality-type". It corresponds to an "age", e.g. the black marls of Oxford define the "Oxfordian" stage, which in relative chronology corresponds to an "age".

In theory, the formations which have the same "stratotype" all around the earth have the same age. This results in stratigraphic correlations between them. The reality is not so simple because changes in lithological facies are discovered when a layer is followed. This is why, to establish their correlations, geologists refer to marine index fossils over large geographical areas by applying the principle of paleontological identity based upon the affirmation that *an ensemble of strata having the same paleontological identity has the same age* [*Précis de Géologie,* 1967].

Locality-types are situated principally in the Anglo-Parisian basin where the stratigraphic scale started to be constructed. It can be verified that the layers, correlated respectively with the stratotypes, are superposed in the same vertical, and thus a classification in time of the stratotypes can be made by application of the principle of superposition. For example, the Oxfordian precedes the Kimmeridgian.

Geologists have recognised the existence of marine transgressions and regressions in sedimentary basins. They are characterised by discordances between two superposed formations (change in orientation of stratification and an erosion surface). These discordances indicate to geologists the occurrence of a chronological hiatus, and lead them to define a division larger than a stage. This is a "series" comprised between an initial transgression and a final regression.

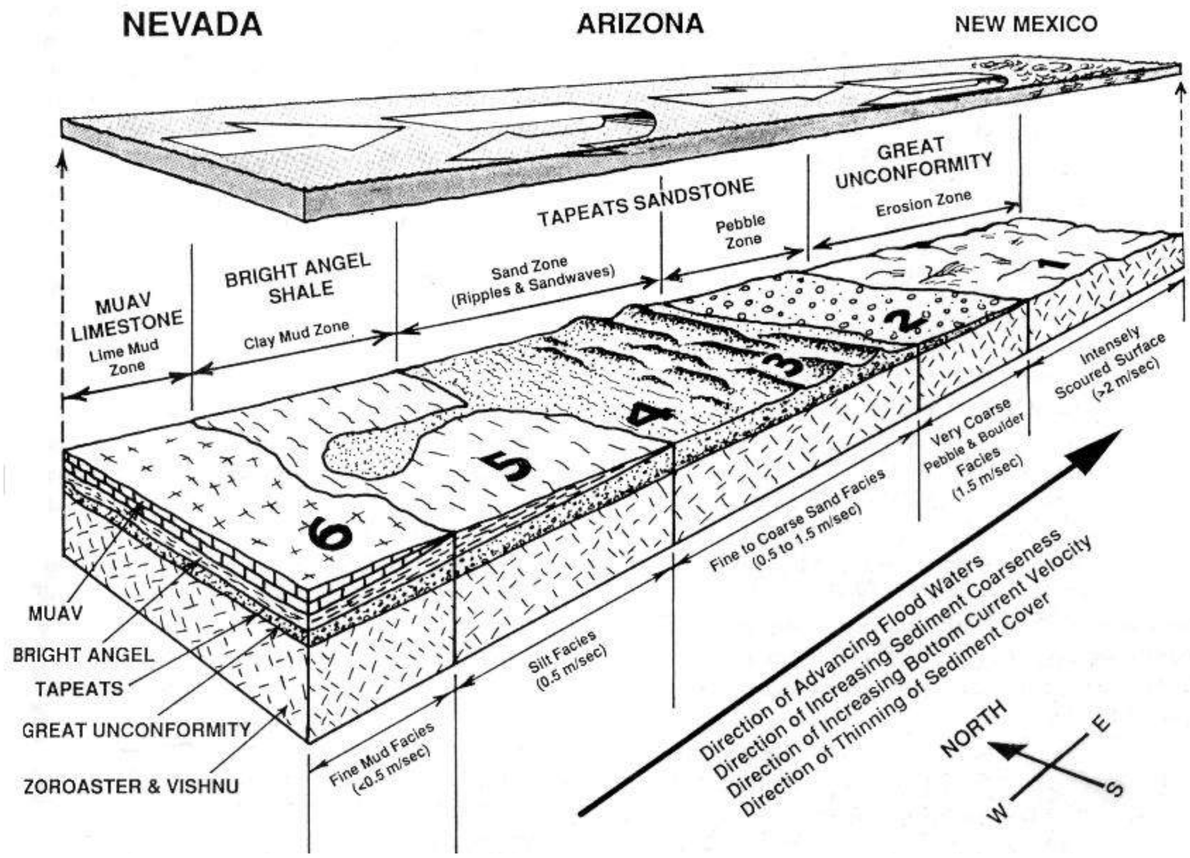
The series include several stages. For example, the two stages mentioned above constitute the Tithonian, a series of the Upper Jurassic. The series correspond in relative time to an "epoch". The grouping of two or more series constitutes a "system", and the corresponding interval of time to a "period". For example, according to the [International Stratigraphic…, 2002] the "Jurassic" system groups the "series" of the Lower/Early, Middle and Upper/Late. The grouping of several "systems" constitutes an "erathem", and the corresponding interval of time an "era". For example, the erathem corresponding to the "Mesozoic" groups the systems of the Triassic, Jurassic and Cretaceous.

This abridged summary of the stratigraphic scale is a necessary prologue to substantiate (or justify) the new approach of a sedimentological interpretation of the stratigraphic column. In my publication, I defined the sedimentological model corresponding to the three principles of Steno. The model is singular. It did not take into account the water current, the agent of marine sedimentation. It considered that fossils and sedimentary particles (detrital and chemical) fall vertically, depositing in a horizontal layer, which lithifies before the following layer deposits horizontally on top. This implies that each layer (and the index fossils contained in it) on the scale of the earth is the same age at each point, and that due to its horizontality, its speed of sedimentation, therefore its thickness, is uniform, so that the following layer reposes on a horizontal stratified layer.

The geologic column was based upon Steno's three principles to which the principle of paleontological identity was added by later geologists, the latter being simply a version of the principle of continuity applied to index fossils over a large geographical area. The fact is that rocks correlated with each stratotype change wherever they are on the Earth. In my publication I mentioned that contemporary sedimentological data and our experiments differed from this model, principally regarding the existence of a current during transgressions and regressions that determine sedimentary genesis. The sediment involved (detrital, chemical and its fossil content) develops vertically and laterally in the direction of the current. The component parts of the sediment whether detrital, chemical or fossil are not, therefore, the same age at any point in the strata. This fact, which calls both the principles of continuity and paleontological identity into question, should be used in interpreting of the stratigraphic series and sedimentary genesis.

SEDIMENTOLOGICAL FEATURES OF THE TONTO GROUP

To illustrate the difference, I would refer to the *'Tonto Group'* in the Grand Canyon which resulted from a large erosive transgression represented by the following block diagram"



To understand how the three formations superposed each other and juxtaposed as shown in the diagram, one must start with the powerful current from west to east which erodes the granites, schistes and gneiss of Zoroaster & Vishnu. An erosion from which produces clasts of all sizes, particles of quartz and clay, pebbles (20 to 64 mm in diameter) and boulders (up to 30 feet or nine meters in diameter). Lebedev [1959] indicated for each size of clast, the velocity of incipient motion relative to the depth of water. For pebbles it is 2 to 3 m/s and boulders more than 6 m/s. The velocity of the frontal mass of water is initially above 6 m/s sufficient for transporting the boulders as far as zone 2.

At each point, after the mass of water has passed, the depth of the water increases causing the current to reduce. The ensuing reduced current, nevertheless retains an erosive capacity sufficient to cause clasts smaller than boulders, such as pebbles, to be transported as far as zone 2.

The erosive current continues up to zone 1 diminishing in velocity and transporting clasts from the erosion (gravel, sand, silt and clay) also sediments coming from the ocean (particularly lime). The water in zone 1 is shallow. A regressive current starts, which carries westwards the largest particles in a bed load, and the smallest in a suspended load. The first deposits from zone 2 to 6, and the second in zones 5 and 6 only.

The proof that the current is regressive is that in zone 3, the deposit is dominated by coarse-grained sandstone having cross-beds with westward and southwestward dips (indicating water current flowing westward).

The base of the deposit on Zoroaster shows particles becoming finer from east to west. The thickness of the deposit shows a similar pattern with particles becoming finer from the bottom of the deposit to its surface. This can be explained as follows. The deposit of a particle occurs when the current velocity transporting it becomes less than the critical velocity which causes the particle to fall and deposit. This critical velocity is near to “incipient motion”, which usually refers to the threshold conditions between erosion and deposit of a single particle. The incipient motion increases with the size of the particle. Consequently, the diminution in the size of particles from east to west, and from the base to the surface of the deposit, results from a decrease of the current velocity during the time of the deposit. This diminution of velocity can result from the water withdrawing from zones 1 and 2 to the deeper water of zone 3 where the current is slowing.

Consider a particle A which deposits at time t_0 on the Zoroaster base in Zone 6. At the following time t_1, a finer particle B deposits on the same base to the west of A in the direction of the current. At the same time t_1, another particle C, finer than A, deposits on top of A. An ensemble of particles, amongst which B and C, deposit simultaneously at t_1. These constitute the sea-floor which is more inclined from west to east, than the Zoroaster slope.

The sedimentary genesis of the *Tonto Group* is explained by the movement of the sea-floor from east to west during the total time of the deposit and not by the stratigraphic concept of successive horizontal layers. It may be asked whether this simultaneity of deposit in Tapeats, might extend to Bright Angel and Muav. In other words could a particle of clay (Bright Angel) deposit in zone 5 at the same time as a particle of sand in zone 4? Without going into the calculations, an answer can be obtained by examining the data.

First, the velocity of the suspended load is about 50% more than the bed-load. If the case of two particles is taken, one of clay and the other sand, leaving zone 1 at the same time, the particle of clay will arrive at zone 5 much quicker than the other particle that falls and deposits in zone 4. Moreover, the incipient motion of clay and silt is much higher (0.91m/s) than fine sand which, similar to clay and silt, has the tendency to flocculate (0.46m/s). The ratio of their respective incipient motions is one to two. This indicates that although the transport velocity of clay and silt particles is 50% greater than that of sand, they can precipitate first. The fall velocity of clay and silt (0.15 to 0.60mm/s), because of flocculation is far from negligible, and much less than for fine sands (10 mm/s).

Overall, the velocity of transport of clay and silt particles from zones 1 to 5 is much greater than that of the fine sands depositing in zone 4, which is less far. The silt and clay, however, deposit quicker. One compensates the other. The simultaneous deposit of a particle of clay (Bright Angel) in zone 5 and sand (Tapeats) in zone 4 is therefore certain.

It should be added that clay is the first to fall on the subjacent Tapeats in zone 6 where the current is the weakest and where, therefore, its velocity drops first below the incipient motion of clay. It then falls in zone 5, for the same reason that the velocity of current diminishes to the point where it is below the incipient motion.

Bright Angel, therefore, progressively covers Tapeats from west to east in zones 5 and 6 and not successively as expressed by the principle of superposition. Also the sea-floor is not horizontal, as required by the principle of original horizontality. The same reasoning applies to Bright Angel and Muav in zone 6.

This analysis is in conformity with the results of our laboratory experiments in the University of Colorado [Julien *et al.*, 1993].

STRATIGRAPHIC INTERPRETATION

Let us now see how stratigraphy interprets the *Tonto Group*. According to the principle of continuity each layer is of the same age at every point. Sedimentation is held to be vertical and the velocity of sedimentation uniform and very low to justify the total time of deposit, i.e. 13 million years, corresponding to the epoch or series of the Middle Cambrian, correlated to the *Tonto Group*.

In the stratigraphic scale, the Cambrian is composed of three series, Lower/Early, Middle, Upeer/Late. According to the sedimentological model of the scale, these three series deposited successively over 50 million years. Whereas, the *Tonto Group* which corresponds to a transgression, includes three facies which deposit simultaneously, so they finally appear superposed and juxtaposed. The deposit is rapid. The stratigraphic scale at the level of the Cambrian “system”, therefore, does not take into account the reality of sedimentary genesis both in time and extent.

The superposed sequences on top of *Tonto Group* such as the *Supai Group* have been studied. Discordances exist between certain of the superposed sequences. This is particularly the case with the discordance between *Muav* and *Temple Butte* interpreted as representing erosion of the *Ordovician* and *Silurian* systems, namely 80 million years on the scale. Our flume experiments, however, show that an increase in current velocity causes partial erosion of the deposit, and a diminution of the velocity following the increase causes a deposit of sediment on the surface of the erosion, without discontinuity of sedimentation. It is the *scour and fill* effect. Similar erosion surfaces are observed in sedimentary cover of the Russian platform [Ignatiev, 1971]. Also, a variation in velocity can change the orientation of the strata.. Therefore, it is necessary to take into account that an apparent interruption of sedimentation can be the result of variation of hydraulic conditions of sedimentation

The sequences are correlated to the series and systems of the stratigraphic column. The above reasoning for the *Tonto Group* applies equally to all the series and systems and, consequently, to all parts of the stratigraphic scale. The scale has ignored the reality of the genesis of sedimentary rock both as to time and extent. In time because the transvressive/regressive sequences start and finish by powerful erosive currents, which rapidly transport and deposit enormous masses of sediment. The time, therefore, of sedimentary formation is much less than the geological time correlated with the scale. The actual time is evaluated by paleohydraulic analysis. In some cases actual time of sedimentation is only

0.0001 % [Romanovsky, 1988, p. 24] or 0.01–0.001 % [Meien, 1989, p.24] of the stratigraphic time for formation of the series. In extent because the sequences are composed, like those of the *Tonto Group*, of formations superposed and juxtaposed which form partly simultaneously and not successively as shown in the scale. Moreover, if two superposed sequences are considered showing discordance between them, it is not a hiatus except for the *Grand Unconformity* separating the *Tonto Group* from the subjacent base. Otherwise such discordance (angular or erosion) could characterises a variation of flow velocity during sedimentation.

As regards the *Grand Canyon*, stratigraphic position of the superposed formations should be re-interpreted by taking into account transgressive and regressive currents as the principal agent of their formation. In consequence, the scale must be considered with results of sedimentological observation and experimentation, i.e. an analysis of the paleohydraulic conditions which determined the deposition of sediment, and the creation of sedimentary rocks by diagenesis.

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FIGURES

Figure. A model for the formation of sedimentary deposits during Cambrian transgression in Nevada, Arizona, and New Mexico. The water mass advancing eastward over Arizona has been "lifted" off the surface of the earth to reveal, underneath, the erosion and simultaneous deposition of the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone.

Zone 1 is the highest elevation area of the continent, where waters of transgressive sea basin were causing intense scouring and erosion of underlying rocks.

Zone 2 is the adjacent shallow-water area, where coarse pebbles and lag boulders were accumulating at the base of the Tapeats Sandstone. All finer sand, silt, and mud were being winnowed from Zone 2, and moved westward into Zones 3 and 4 by intense bottom-surging current (velocity about 1.5 meters per second).

Zone 3 is composed of sand waves forming thinly cross-bedded sands, which compose the middle of the Tapeats. Here the water velocity was about 1.0 meter per second.

Zone 4 is plane beds of sand, with ripples representing the deepest and lowest-velocity waters depositing the uppermost Tapeats.

Zone 5 is located in still deeper and slower-moving waters. The silicate clay- and silt-size particles were accumulating as graded silt and clay beds of Bright Angel shales. Here, the water velocity was about 0.5 meter per second,

Zone 6 is farthest to the west, in the deepest and slowest-moving water, where there was a deficiency of silicate clay and silt-sized particles. Lime mud was accumulating, in Zone 6, as rhythmically laminated and bedded flat strata, where the water current velocity was less than 0.5 meter per second.

Diagram from [Grand Canyon, 1994].