Lithology and Mineral Resources, Vol. J9, No. 5, 2004. pp. 480-484. From Litologiya i Poleznye Iskopaemye, No. 5, 2004, pp. 552-557.

Sedimentological Interpretation of the Tonto Group Stratigraphy (Grand Canyon Colorado River)[1]

G. Berthault

28 boulevard Thiers, 78250 Meulan, France

Received October 27, 2003

Abstract—Sedimentological analysis and reconstruction of sedimentation conditions of the Tonto Group (Grand Canyon of Colorado River) reveals that deposits of different stratigraphic sub-divisions were formed simultaneously in different lithodynamic zones of the Cambrian paleobasin. Thus, the stratigraphic divisions of the geological column founded on the principles of Steno do not correspond to the reality of sedimentary genesis.

INTRODUCTION

In my previous article (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 N. Steno should be reconsidered and supplemented.

Because Steno assumed from 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) characterized by a group of paleontological, lithological or structural criteria of universal value* (Aubouin, 1967, p. 229). It corresponds to an "age," e.g., the black marls of Oxford define the "Oxfordian" stage, which in relative chronology corresponds to "Oxfordian" age. In theory, the formations which have the same "stratotype" all around the Earth have the same age. This results in strati-graphic 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 (Aubouin, 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 recognized the existence of marine transgressions and regressions in sedimentary basins. They are characterized by discordances between two superposed formations (change in orientation of stratification and an erosion surface). Inasmuch as "stages" and "series" are defined mostly by paleontological composition of the strata *(Geologicheskii slovar...*, 1960), stratigraphic units do not take into account lithological features and discordances of the sequences. Since stage (age) is the primary element for construction of the stratigraphic units of higher rank - series (epoch), system (period), erathem (era), these strati-graphic subdivisions also do not take into consideration Sedimentological processes.

This abridged summary of the stratigraphic scale is a necessary prologue to substantiate or justify a new approach of interpreting the stratigraphic column by sedimentology.

STRATIGRAPHY OF SEDIMENTARY STRATA OF GRAND CANYON

In order to illustrate the difference between sedimentological (particularly, our experiments) (Julien *etal.*, 1993) and stratigraphic interpretation, I would refer to the sedimentary sequence of the Grand Canyon (Colorado River) and especially the Tonto Group (Fig. 1) as described in *(Grand Canyon*, 1989).

The Precambrian basement of the sequence consists of a complex group of highly metamorphic and intensely folded rock (Vishnu Group), especially chlo-rite-mica schist, with minor amounts of amphibolite. gneiss, and calc-silicate rocks. Zoroaster pink feldspars granite occurs with intrusive contact with Vishnu rocks as vertical dikes and pegmatitic veins up to a few tens of meters thick. Both Vishnu and Zoroaster rocks are assigned to the Lower Proterozoic. In some tectonic

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

depressions, these rocks are overlain by tilted Upper Proterozoic volcanosedimentary Grand Canyon Supergroup. The Tonto Group assigned to the Cambrian System directly overlies Vishnu and Zoroaster rocks *(Grand Canyon,* 1989).

The Tonto Group can be divided into the following three formations (from the bottom to top): Tapeats Sandstone, Bright Angel Shale, and Muav Limestone.

The **Tapeats Sandstone** is the lowest horizontal formation of enormous lateral extent in the Grand Canyon. It is medium- to coarse-grained quartz-rich sandstone (thickness usually 40-100 m). The base of the formation is often dominated by pebbles and boulders. The central portion of the formation is dominated by coarse-grained sandstone having cross beds with westward and southwestward dips (indicating water current flowing westward). The top of the formation is dominated by plane beds of sand with ripples and by thinner fine-grained sand and silt beds, which form a gradational contact with the overlying Bright Angel Shale.

The greenish gray, silty-to-sandy **Bright Angel Shale** is 100 to 120 m thick. Prominent beds of sandy dolomite and silty limestone are very persistent within the shale throughout the Canyon. Green sandstones containing glauconite and dark brown ironstone are also common. The Bright Angel Shale represents deeper water and slower currents than does the Tapeats Sandstone. The top of the Bright Angel Shale intertongues with the Muav Limestone.

The yellowish brown, impure, silty and sandy **Muav Limestone** is from 100 to 300 m thick. Small irregular inclusions of clay within the Muav Limestone occur above the Bright Angel Shale. The Muav Limestone thickness and purity increases toward the west.

Because the Tapeats, Bright Angel, and Muav are not separated by unconformities but grade into each other, they have been collectively called the Tonto Group. The deposits are overlain by the sequence of sandstones, siltstones, shales, and carbonate rocks of Devonian, Carboniferous and Permian Systems.

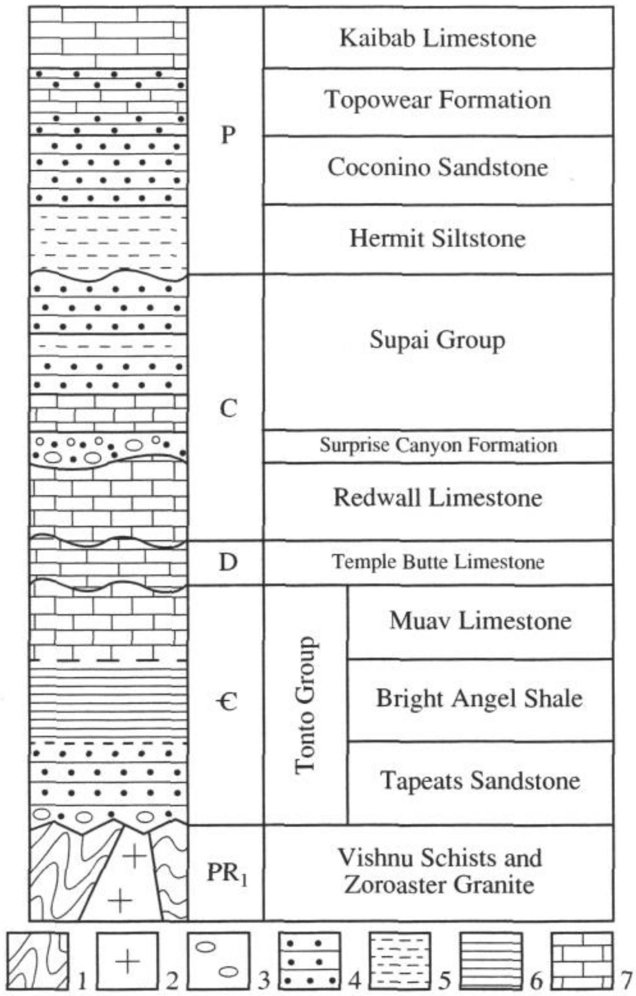

Fig. 1. Stratigraphic column of the Grand Canyon strata. (1) Schist; (2) granite; (3) pebble and boulder conglomerate; (4) sandstone; (5) siltstone; (6) shale; (7) limestone.

SEDIMENTOLOGICAL FEATURES OF THE TONTO GROUP

The Tonto Group resulted from a large erosive transgression. The erosion appears greatest in the western and central Grand Canyon, where the Tapeats Sandstone most often rests directly on schist and granite (Vishnu and Zoroaster). The depth of erosion is least on the eastern Grand Canyon where the Tapeats rests directly on tilted strata of the Grand Canyon Supergroup. A diagram of the Tonto Group formation is shown in Fig. 2.

In order to understand how these formations (Tapeats, Bright Angel, and Muav) superposed each other and juxtaposed as shown in the diagram, one must start with the powerful current that eroded the granites and schists of the Vishnu Group and Zoroaster granites. An erosion produced clasts of all sizes, particles of quartz and clay, pebbles and boulders. Lebedev (1959) indicated the velocity of incipient motion relative to the water depth for each size of clast. It was 2-3 m/s for pebbles and more than 6 m/s for boulders. The velocity of the frontal mass of water was initially >*6* m/s that was sufficient for transporting the boulders as far as zone 2 (Fig.2) and thus it was more than 1.5 m/s.

As the transgression advanced, the water depth increased, resulting in reduction of the current. The ensuing reduced current, nevertheless, retained an erosive capacity sufficient to transport clasts smaller than boulders, such as pebbles, as far as zone 2 where velocity of the current was about 1.5 m/s.

In shallow zone 1, the erosive current diminished in velocity and transported clasts of terrigenous (gravel, sand, silt, and clay) and carbonate material (particularly, lime). The ensuing regressive current carried westward the largest particles in a bed load and the smallest ones in a suspended load. The largest particles

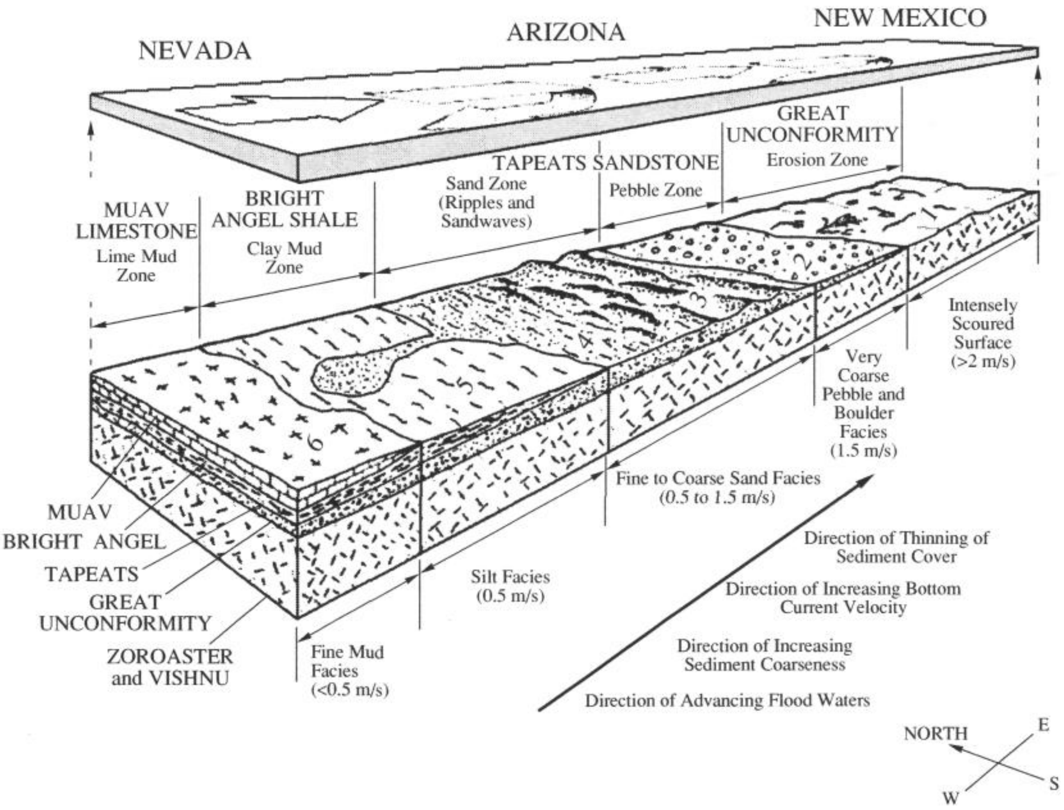

Fig. 2. A model for the formation of sedimentary deposits during the Cambrian transgression in Nevada, Arizona, and New Mexico. Zones: (1) upper pan of continental slope; (2) the adjacent shallow-water area; (3) submarine sand waves; (4) plane beds of sand with ripples; (5) silicate clay- and silt-sized particles with graded beds; (6) lime mud of deepest zone.

deposited from zone 2 to 6, while the smallest ones deposited only in zones 5 and 6.

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 m/s. Westward and southwestward dips of cross-beds indicate the predominant direction of the current.

Zone 4 represents 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-sized particles were accumulating as graded silt and clay beds of the Bright Angel Shale. Here, the water velocity was about 0.5 m/s.

Zone 6 is located farthest to the west in the deepest and slowest-moving water characterized by a deficiency of silicate clay and silt-sized particles. Lime mud was accumulating as rhythmically laminated and bedded flat strata where the water current velocity was less than 0.5 m/s.

At the level of the paleobasin bottom, particles become 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 particles deposited when the current velocity became less than the critical velocity, which caused the particles to settle. This critical velocity is close to "incipient motion", which usually refers to the threshold conditions between erosion and deposition of a single particle (Julien, 1995). The incipient motion increased with the particle size. Consequently, the diminution in the particles size from east to west and from the base to the surface of the deposit resulted from a decrease of the current velocity during the deposition. This velocity diminution could result from the water withdrawal from zones 1 and 2 to the deeper water of zone 3 where the current was slower.

Let us consider particle A that deposited at time to on the Zoroaster and Vishnu base in Zone 6. At the following time ti, a finer particle B deposited at the level of the paleobasin bottom to the west of A in the direction of the current. At the same time t,, another particle C, finer than A, deposited on top of A. An ensemble of particles, including B and C, deposited simultaneously at t_f (Fig. 3).

The sedimentary genesis of the **Tonto Group** is explained by simultaneous prograding of the strata both laterally and vertically and movement of the sedimentation area from east to west. This explanation does not correspond to 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 silt and clay particles of transported by the current was greater than that of sand the particles transported at a lower level.

Second, the velocity of particles decreased from the maximum permissible nonerosive velocity (Fortier and Scobey, 1926) to the incipient motion (Shields, 1936) modified by Yalin and Karahan (1979) corresponding to the threshold conditions between erosion and sedimentation. Consequently, considering two separate (silt and sand) particles traveling over the same distance, but with a certain delay of time of departure between them, the silt particle would deposit by flocculation in Bright Angel at the same time as the sand particle in Tapeats.

It should be added that clay was the first to fall on the subjacent Tapeats in zone 6 where the current velocity was the lowest and, therefore, dropped first below the incipient motion of clay. It then fell in zone 5 for the same reason that the velocity of current diminished to the point where it was below the incipient motion.

Therefore, the Bright Angel progressively overlies the Tapeats from west to east in zones 5 and 6. At the same time, the Tapeats Sandstone continued to deposit in zones of higher hydrodynamics (zones 2-4). Thus, the Tonto Group deposited not successively as expressed by the principle of superposition. 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 is assumed uniform and very low (8-17 mm/ka) to justify the total deposition time (30 Ma) corresponding to the epoch or series of the Lower to Middle Cambrian *(Paleozoic...,2003)*.

In the stratigraphic scale, the Cambrian is composed of three (Lower, Middle and Upper) series with a total duration of more than 50 Ma. The *Tonto Group*, which corresponds to a transgression, includes three simultaneously deposited facies. Therefore, they finally appear superposed and juxtaposed. Actual deposition was much more rapid than the calculated stratigraphic velocity of deposition. Hence, the stratigraphic scale at the level of the Cambrian System of Grand Canyon of Colorado does not take into account the reality of sedimentary genesis either in time or extent.

Discordances exist between certain sequences superposed on the top of the Tonto Group. Our flume experiments showed that an increase in current velocity provoked partial erosion of the deposit, while adiminution of the velocity following the increase promoted sediment deposition on the erosion surface without discontinuity of sedimentation. This is the *scour and fill* effect (Julien *et ai*, 1993). Similar erosion surfaces are observed in the sedimentary cover of the Russian Platform (Ignat'ev, 1971). Moreover, variation in velocity can change orientation of the strata. It is necessary, therefore, to take into account that an apparent interruption of sedimentation can be the result of variation of hydraulic conditions of sedimentation without chronological hiatus.

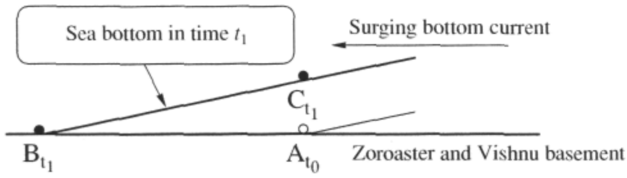

Fig. 3. Scheme of the deposition of heterogranular deposits in current conditions.

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 not taken into account the reality of the genesis of sedimentary rock concerning either time or extent.

In time, because the transgressive/regressive sequences start and finish by powerful erosive currents, which rapidly transport and deposit enormous masses of sediment. Therefore, the time 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) or 0.01-0.001% (Meyen, 1989) of the stratigraphic time for the formation of sediments. At the same time, a significant part of the time responsible for the formation of the sequence belongs to latent gaps of sedimentation (diastemes) (Romanovsky, 1988).

In extent, because the sequences are composed, like those of the *Tonto Group*, of superposed and juxtaposed formations, 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 could characterize a variation of flow velocity during sedimentation.

As regards the Grand Canyon, the stratigraphic position of the superposed formations should be interpreted by taking into account transgressive and regressive currents as the principal agent of their formation. Consequently, the scale must be considered in the light of observation and experimentation, i.e., analysis of the paleohydraulic conditions, which determined the deposition of sediments, and the creation of sedimentary rocks by diagenesis.

REFERENCES

Aubouin, J., *Precis de Geologie*, Paris: Dunod Univ., 1967, vol. 2.

Berthault, G., Analysis of Main Principles of Stratigraphy on the Basis of Experimental Data, *Litol. Polezn. Iskop.*, 2002, vol. 37, no. 5, pp. 509-515 *[Lithol. Miner. Resour.* (Engl. Transl.), 2002, vol. 37, no. 5, pp. *442-446]*.

Fortier, S. and Scobey, F.C., Permissible Canal Velocities, *Trans. ASCE,* 1926, no. 1588, pp. 940-984.

Geologicheskii slovar (Glossary of Geology), Moscow: Gos-geoltekhizdat, 1960, vol. 2.

Grand Canyon, Belknap, J.P., Ed., Evergreen, Colorado: Westwaterbooks, 1989.

Ignat'ev, V.I., Hiatuses and Disconformities in the Upper Permian and Upper Triassic Deposits of the Eastern Russian Platform, *Geologiya Povolzh 'ya i Prikam 'ya* (Geology of the Volga and Kama Regions), Kazan: Kazan. Univ., 1971, pp. 23-50.

Mien, P.Y., *Erosion and Sedimentation*, New York: Cambridge Univ. Press, 1995.

Julien, P.Y., Lan, Y., and Berthault, G., Experiments on Strat-ification of Heterogeneous Sand Mixtures, *Bull. Soc. Geol. France*, 1993, vol. 164, no. 5, pp. 649-660. Lebedev, V.V., *Gidrologiya i gidravlika v mostovom dorozh-nom stroitel'stve* (Hydrology and Hydraulics in Roadway Bridge Construction), Leningrad: Gidrometeoizdat, 1959. Meyen, S.V., *Vvedenie v teoriyu stratigrafii* (Introduction to the Theory of Stratigraphy), Moscow: Nauka, 1989. *Paleozoic Sedimentary Rocks of Grand Canyon,* Part 1. 2003. http://www.studyworksonline.com/cda/content/arti-cle/0,,EXP888_NAV2-77_SAR874,OO.shtml. Romanovsky, S.I., *Fizicheskaya sedimentologiya* (Physical Sedimentology), Leningrad: Nedra, 1988. Shields, A., *Anwendung der Aehnlichkeitsmechanic und der Turbulenz Forschung auf die Geschiebebewegung,* Berlin: Mitteil. Preussis. Versuch. Wasserbau Schiffbau, 1936. Yalin, M.S. and Karahan, E., Inception of Sediment Transport, *J. Hyd. Div. ASCE,* 1979, no. 11, pp. 1433-1443.