Art. XX.—*Note on the Shape of Pebbles;* by Herbert E. Gregory.

Attempts to establish criteria for distinguishing beach pebbles from those formed by rivers, glaciers, or wind, or resulting from weathering in place, have led to unsatisfactory results. The summary classification of Mansfield:* marine pebbles, "fairly uniform in size, well rounded"; fluviatile pebbles, "all sizes, generally subangular"; glacial pebbles, "faceted, rounded edges, snubbed ends, polished and striated"; is better adapted for use in the classroom than in the field. With respect to shape and distribution of pebbles, the same may be said of the criteria established by Trowbridge.† The distinctions drawn by Suess and Hoernes,‡ that marine and lacustrine pebbles are round and oval or roller-shaped, but not wedge-shaped; that fluviatile pebbles are flat and wedge-shaped; are not applicable to shores and streams which have come under my observation.

The assumption that flat pebbles are characteristic of river deposits is usually accompanied by the explanation emphasized by Liburnau,§ that horizontal rotation rather than rolling is the normal method of attrition for river pebbles. Field observations show that this process of shaping is of local significance. Vertical and horizontal rotation, saltation, rolling and sliding, are effective at the same time, or at different times, in all moving water. Snubbed slabs, blunt wedges and disks may be collected from lake and ocean shores, and where conditions are favorable—as along shale cliffs—the beach gravel may consist in large part of these. Strong waves overturn and vigorously roll pebbles, while weak waves may shove pebbles of suitable shape and size or may not disturb them at all. On a shore fretted by waves of slight power the only modification in shape may be that due to the wearing accomplished by streams of sand which pass to and fro. Along a coastal belt whose shore line is rapidly migrating landward, and especially if the coast is low and the waves are weak, pebbles may be preserved by burial or drowning without much change in orig-

* The characteristics of various types of conglomerates, Jour. Geol., xv, pp. 550–555, 1907.

† A classification of common sediments and some criteria for identification of the various classes, Jour. Geol., xxii, pp. 420–436, 1914.

‡ Suess: Der Boden der Stadt Wien, 1882; quoted by Grabau, Stratigraphy, p. 595.

Hoernes: Gerölle und Geschiebe, Verhandl K.-K. geol. Reichsanstalt, No. 12, 1911.

§ Die geologischen Verhältnisse von Grund und Boden, 1888.

inal form. Likewise a retreating shore line may strand gravels which have not been completely reshaped. Material furnished to waves is quarried from coasts composed of all sorts of material, both consolidated and unconsolidated. Glacial and river-borne pebbles and bowlders, as well as joint-bounded and irregular fragments of rock, find their way to the beach, and the shape which they assume at various stages of their life history on the shore is believed to be predominantly controlled by their original form. Round and oval fragments tend to retain those shapes; blocks with rectangular and square cross sections develop elliptical or circular cross sections; flat fragments tend to remain flat or to become discoid. If the material supplied to waves consisted of silver dollars and marbles, it is difficult to imagine how any pebbles other than flat and round could result from the most vigorous and long-lived wave abrasion. It may be noted also that for stratigraphic purposes lacustrine and delta gravels are to be included with marine sediments, although their constituent pebbles are obviously of sub-aërial origin.

That pebbles may be well rounded by streams is proven by direct observation and by experimentation. As pointed out by Bonney,* the results of Daubrèe's well known studies are not of general application, since the only phase of river work comparable with travel of irregular blocks in revolving cylinders is the attrition of pebbles in potholes. Omitting the time factor, the conditions surrounding Daubrèe's experiments may be approached and a high degree of sphericity of pebbles be attained in cases where irregular blocks, unmixed with much finer stuff, are carried *en masse*. Under such circumstances the pebbles experience a continuous direct bombardment among themselves. As bearing on this point, it was noted that gravel bars on the Navajo Reservation shift their position from year to year and even during sudden floods. A deposit composed of about 80 per cent of coarse gravel on Bonito Creek, Arizona, moved bodily down stream between 1910 and 1913, for a distance of about 300 feet, without apparent change in texture or composition. It was also observed at several localities that the pebbles on bars and terraces exposed between floods have a distinctly higher degree of rotundity where the mass is composed almost wholly of pebbles one-half inch to three inches in diameter, than where composed of sand, adobe, and pebbles. In studying these deposits it was noted that highly angular pebbles, and even blocks one foot in diameter, have been carried for distances exceeding 30 miles. In the lower Chinli valley a block of monzonite 5 inches in diameter, after a journey of 40 miles, has a form almost identical with that of talus

* Geol. Mag., v, pp. 54-61, 1888.

blocks on Carrizo Mountain, from which it was derived. It would appear that such pebbles and bowlders had made their journey without the companionship of fragments of similar size. The slowness with which pebbles are rounded where they constitute a minor portion of the transported materials is a matter of everyday observation in the Colorado Plateau Province. In humid regions characterized by continuous stream flow, and where the sediment is largely supplied by surface run-off, the finer materials are strained out by running water. In regions where dry and wet seasons alternate and where wind is effective, the proportionate amount of finer stuff is greatly increased. Dunes strewn along valley bottoms, and formed of material carried from inter-stream areas, are abundant in arid regions. Following sudden showers, resulting in concentrated run-off, this material is swept into streams in enormous quantities. In 1914 Black Falls, 10 feet high, on the Little Colorado River, became obliterated, between two periods of stream flow, by a deposit of 36,000 cubic yards of wind-blown sand. So much sand is supplied along the middle portions of the Little Colorado that pebbles and bowlders, though large in number, have little chance to be abraded on rock bottoms or by grinding against each other. Such blocks may exist without change throughout an entire physiographic cycle, for during the time of the stream's greatest erosive power they may remain embedded in finer materials. Alternate wet and dry seasons would appear to favor subangularity of pebbles regardless of distance.

In regions characterized by intermittent stream flow it may be observed that the abrasive power of sand streaming past and over bowlders on a river bed is an important factor in determining form. For stretches of hundreds of feet in certain streams on the Navajo Reservation the upstream sides of bowlders are polished and worn and rounded, even faceted and etched, while the downstream sides are essentially unmodified. In places working up-valley across huge bowlders involves climbing precipitous faces and descending slopes, like travel over miniature cuestas. To obtain a quantitative estimate of erosion by this process, holes one inch deep were drilled in opposite faces of sandstone bowlders at eight localities. On visiting two of these localities a year later (in 1910) it was observed that in the case of three bowlders abrasion had reduced the depth of the upstream holes ·03, ·06 and ·06 inches respectively. Five localities, including the two mentioned, were re-visited in 1914, at which time the deepest hole was 0·4 inch and at one locality no trace of the drilling remained. A hammer scar, made by clipping sandstone rock, exhibited fairly well-rounded edges after the passage of a single heavy flood. On the downstream side of the same bowlder, a blue pencil mark had not been erased. Of the holes made in 1909 on the downstream side of the bowlders, none had been perceptibly modified. On quartzite and limestone bowlders the abrasion during four years amounted to less than ·01 of an inch. That this process is continuous is shown by the presence of percussion marks on upstream faces of bowlders and their absence on the opposite side. In torrential streams of Connecticut the upstream faces of many bowlders are perceptibly worn, while lichens cover their downstream sides. On those portions of the Connecticut shore where current action prevails over wave work, comparable illustrations may be found.

In streams of semi-desert regions the rate of transportation appears to have high value in shaping pebbles, regardless of distance traveled, and to a lesser degree, of hardness and specific gravity. Pebbles in "washes" are prevailingly angular, but are less uniformly so in their torrential portions. At the base of steep slopes, approaching the perpendicular, such as exist on Navajo Mountain and the edges of Black Mesa, pebbles appear to be somewhat better rounded than along the Puerco, the Moencopi and the Kayenta valleys after traveling many times as far.

Moreover, many pebbles in fluviatile gravel bars are decomposed, and may be crushed in the hand, although retaining their form. It appears that the conditions surrounding such pebbles particularly favor chemical action, and that ancient river gravels may not in all cases be distinguishable from residual deposits resulting directly from weathering.

Wind-made pebbles when maturely developed and fresh are characteristic, but until faceting is far advanced and also after decomposition has modified their shape, may not be unlike certain classes of river and glacial pebbles.

At first sight it appears that pebbles resulting from glaciation could readily be distinguished, and the geologic literature is characterized by the assumption that the presence of "soled," striated, faceted, or polished pebbles demonstrates glaciation. That this criterion should be used with great caution is evident from the fact that "typical" glacial pebbles and bowlders are rare. Fluvio-glacial drift together with surficial and terminal moraines is many times more abundant than ground moraine, and is prevailingly lacking in striated and polished pebbles. The exceeding rarity of such pebbles about the existing glaciers in Switzerland, Peru and California is a matter worthy of comment. In the terminal moraines of Long Island striated and polished pebbles must be sought for with care; and in the "stony till" of Connecticut, even in well-exposed sections, an hour's search may be rewarded by the discovery of one "characteristic" glacial pebble. From a study of a number of deposits including drumlins and recessional remains, it appears that pebbles and bowlders which may be unqualifiedly assigned to ice work do not exceed one in a thousand for the Connecticut glacial deposits.

Pebbles with "characteristic glacial forms and markings" produced by processes other than glacial have been described from various parts of the world, and the presence of "impressed" pebbles in conglomerates implies pressure and differential motion more than sufficient for the production of striæ. Even from dikes, "glacial" pebbles suitable for classroom demonstration have been collected.

Of the many factors whose evaluation is essential in establishing distinctions between various modes of origin of conglomerate, that of shape of pebbles has perhaps the least significance. No constant difference between the constituents of marine, lacustrine and river gravel is likely to be established. Polished, striated, and soled pebbles are not of diagnostic rank, and their absence does not imply the absence of glaciation. In well-exposed and widely extended outcrops, or where proof of origin rests on other grounds, pebble form may have supplementary value; under other circumstances this criterion should be applied with extreme caution.

Yale University, New Haven, Conn.