Hydraulic Equivalence of Grains of Quartz and Heavier Minerals, and Implications for the Study of Placers

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By HARRY A. TOURTELOT

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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CONTENTS

ILLUSTRATIONS

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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By Harry A. Tourtelot

ABSTRACT

Hydraulic equivalence is the concept that describes the relation between grains of a mineral of a given size and specific gravity and the smaller grains of heavier minerals that are deposited simultaneously. Hydraulic-equivalent grains have the same settling velocity under the same conditions. Settling velocity is an essential element in the theory of the dynamic processes of sediment transport but does not by itself, of course, directly explain the origin of a placer deposit. It is, however, a useful guide to the expectable sizes of minerals of different specific gravity that will tend to be associated as a result of a given hydraulic process. The hydraulic-equivalent sizes for spheres of magnetite, silver, and gold are given for quartz spheres ranging from 0.001 to 8.0 mm. The hydraulic-equivalent sizes of gold spheres, for example, range from about 0.0003 to about 0.8 mm. Settling velocities of flakes of gold are given for water, bromoform, and diiodomethane at 15° C, as are the settling velocities of spheres of gold in the same liquids and quartz in water. A flake of gold with a diameter : thickness ratio of 30 settles at a velocity of only 12.5 percent of the velocity of a gold sphere of the same diameter.

INTRODUCTION

Hydraulic equivalence is the concept that describes the relation between grains of a mineral of a given size and specific gravity and the smaller grains of heavier minerals that are deposited simultaneously under given hydraulic conditions. Tyrrell (1912, p. 597) used the concept in referring to equivalent volumes and weights of quartz and gold that a given stream velocity can move. The effect of specific gravity of other heavy minerals on their distribution in sediments was recognized by Mackie (1923, p. 139–140), and Rubey (1933a) dealt specifically with the effect of specific gravity on the size distribution of heavy minerals in samples. Although Rubey worked with the concept of hydraulic equivalence, Rittenhouse (1943, p. 1741) formalized the term, particularly in the form "hydraulic-equivalent sizes." The concept is useful in guiding sampling and analysis of placers of several heavy metals and minerals, although the transport and deposition of particles of different specific gravities are a result of far more complex processes than simple settling in quiet water, which is the one factor in such processes that is considered here.

This paper presents data on the diameters of grains of different specific gravities that have the same settling velocities under the same conditions. The effect of different shapes of grains also is considered, mostly with respect to flakes. The effect of settling velocity in water, bromoform, and diiodomethane on concentration of samples for analysis is discussed. Through awareness of the hydraulic principles involved in this relatively simple type of particle behavior in fluids, new data on placer deposits should be acquired, and from these data more complex processes of sedimentation can be studied.

PLACER MINERALS

Minerals and metals commonly produced from placers are listed by McKelvey (1950, p. 488) and are shown below along with their specific gravities:

- Chromite, 4.1–4.9
- Columbite-tantalite, 5.3–7.3
- Magnetite, 5.18
- Precious metals:
  - Gold, 15.0–19.3 (19.33 when chemically pure)
  - Platinum metals
    - Platinum, 14.0–19.0 (21.0–22.0 when chemically pure)
    - Palladium, 12.2
    - Iridium, 22.4
    - Osmium, 22.5
    - Rhodium, 12.5
    - Ruthenium, 12.2
  - Silver, 10.1–11.1

Thorium concentrates:
- Monazite, 4.9–5.33

Tin
- Cassiterite, 6.8–7.1

Titanium concentrates:
- Ilmenite, 4.5–5.0
- Rutile, 4.18–4.25

Tungsten concentrates:
- Scheelite, 5.9–6.1
- Wolframite (and huebnerite), 7.0–7.5

The specific gravity of most of these materials depends on their composition.

The discussions that follow are based on the relation between quartz, magnetite, metallic silver, and metallic gold. Magnetite is an obvious mineral to include in a set of hydraulic-equivalent relations because it is the most common indicator of concentrations of heavy minerals in sedimentary rocks and sediments. In addition, its specific gravity of 5.18 falls within the range of specific gravity for several common placer minerals. The specific gravity of gold ranges from about 15 to about 19, depending on purity. The figure 18.0 has been used arbitrarily, and equivalence data for grains of metals of larger specific gravity can be extrapolated. Metallic silver does not commonly occur as grains in placers, but its specific gravity of 10–11 provides a convenient point on curves (to be discussed later) from which the effect on grain size of different specific gravities of gold, and the grain size of metals or minerals of smaller specific gravity, can be interpolated.

WEIGHT EQUIVALENCE

Mineral grains of different specific gravities can be equivalent in terms of weight. Factors for determining the equivalent diameters for spherical grains of equal weight of four minerals are as follows:

	Specific gravity	*Diameter (mm)*
Quartz	2.65	1.000
Magnetite	5.18	.800
Metallic silver	10.00	.642
Metallic gold	18.00	.528

The diameters of weight-equivalent spheres of gold, magnetite, or silver for any size sphere of quartz can be determined by multiplying the diameter of a quartz grain by the appropriate factor above. For example, a sphere of gold 4.22 mm in diameter is equal in weight to a sphere of quartz 8.0 mm in diameter ($0.528x=4.22$; $x=8.0$).

HYDRAULIC EQUIVALENCE

The difference in size of spheres of equal weight for minerals of different specific gravities is consistent with the general knowledge that gold placers, for instance, occur often in conglomerates and coarse-grained sediments and rocks that are indicative of strong currents. The differences in size of spheres of equivalent weight are, however, a function only of differences in specific gravity. Such differences in size are not related by any hydraulic principle by which some of the behavior of the grains under given hydraulic conditions can be examined.

The term "hydraulic conditions" refers to the complexly related variables of the velocity of current and its distribution in a stream profile and cross section, the proportions of turbulent and laminar flow, the volume of water, the morphology of the channel in which the water flows, and the characteristics of sediment load. The transport of sediments by water is a very complex subject on which there does not yet seem to be general agreement as to the principal factors responsible for observed effects. (See Bagnold, 1966.) Sorting by size, for instance, can be effected by uniform water flow and uniform sediment load under some conditions (Jopling, 1964, p. 3405–3408). Despite the complexity of sediment-transport theory, Jopling (1966) was able to reconstruct some parameters of paleoflow regimes from sediment characteristics.

An essential feature of all concepts of sediment transport is the settling velocity of the grains in water as determined by Stokes' law or modifications of it. The velocity sufficient to move a grain along a smooth stream bed is directly related to the settling velocity of that grain (Rubey, 1933b, p. 330; Hjulström, 1935, p. 303; Krumbein, 1942, p. 628). It is also possible to use the settling velocity alone to examine the behavior of grains of different specific gravity by assuming that the conditions that permitted the deposition of quartz grains of a given size would also have permitted the deposition of grains having higher specific gravity but the same settling velocity (Rubey, 1933a, p. 5). In addition, settling velocity "is the primary variable that determines the interaction between the bed material and the fluid [in sediment transport]" (Simons and Richardson, 1966, p. J19). The settling velocity thus is a useful relationship between grains of different specific gravity that has hydraulic significance for all aspects of sedimentation.

HYDRAULIC EQUIVALENCE OF SPHERES

Stokes' law (see "Equations," p. F11) relates the velocity of settling to the diameter (or radius) of a spherical grain, the specific gravity of the grain, the specific gravity of the fluid, the viscosity of the fluid, and the acceleration due to gravity. The development of Stokes' law and the assumptions inherent in it were discussed fully by the Tennessee Valley Authority (1941, p.

29–37). Rubey (1933b, p. 326), among others, pointed out that Stokes' law is applicable only insofar as viscosity of the fluid is the controlling factor in its resistance to the settling of a grain, and that the maximum diameter of spherical grains for which this is so is 0.14 mm at 16°C. Other factors involved are the interactions of the properties of particle and fluid such as the viscosity and density, the size of the particle, and the mean velocity of the movement of the particle in the fluid. This interaction is usually expressed by relation between the coefficient of resistance (C_D) and Reynolds number (**R**) (Rouse, 1937). Settling velocities for grains more than 0.2 mm in diameter cannot be estimated even approximately by Stokes' law (Rubey, 1933b, p. 326). For grains larger than 0.2 mm in diameter, the settling velocity is proportional to the square root of the diameter rather than the square (Rubey, 1933a, p. 17; 1933b, p. 327). The two equations for settling velocity—one for spheres less than 0.14 mm in diameter and the other for spheres greater than 0.2 mm in diameter—were combined in a single equation (Rubey, 1933b, p. 331–333). Other methods of determining the settling velocity of quartz spheres of a wide range of diameters have also been developed (Tennessee Valley Authority, 1941, p. 41; Schulz and others, 1954, p. 31–34; Inter-Agency Committee on Water Resources, 1957). Although these methods are precise, their use would result in relations not greatly different from those obtained by using one equation for grains smaller than 0.25 mm in diameter and another for larger grains and then empirically adjusting the transition between them.

The hydraulically equivalent diameters for quartz, magnetite, silver, and gold shown in figure 1 were calculated according to the method of Rubey (1933a, p. 6, 17). The Stokes' law equation for the settling velocity of quartz, if a grain diameter of 1.0 mm is assumed, is made equal to the equation for the settling velocity of magnetite and the expression solved for the diameter of a grain of magnetite. This results in a factor that can be applied to the diameters of grains of quartz, within the size range for which Stokes' law is applicable, to give hydraulically equivalent diameters of magnetite. The same procedure was followed using the modified velocity equation (Rubey, 1933a, p. 17) for grain sizes of quartz larger than those that can be treated by Stokes' law. The process was repeated for silver and gold, and the results are plotted in figure 1 with the ordinate being millimeters on a logarithmic scale and the abscissa being specific gravity on a logarithmic scale. The lines connecting the points for grain sizes equivalent to a given grain size of quartz form a slightly convex curve, but points for specific

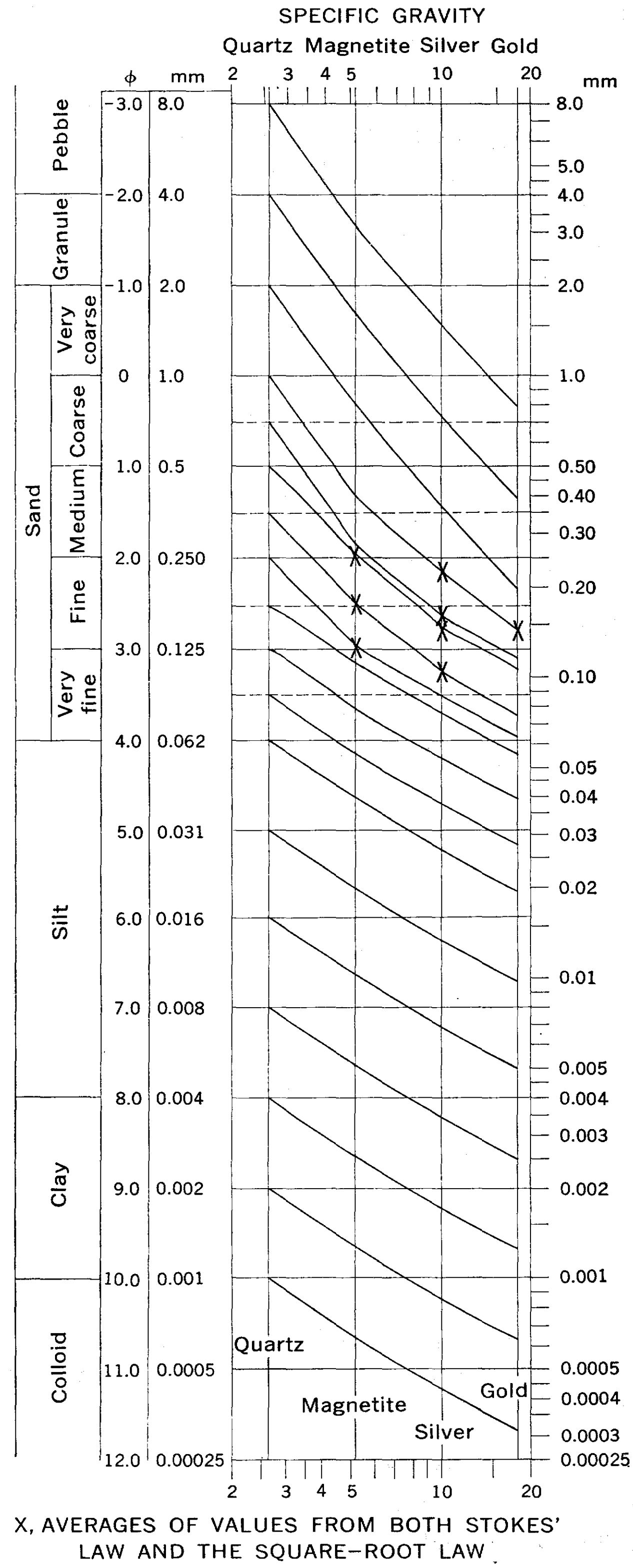

Figure 1.—Hydraulic-equivalent grain sizes of quartz, magnetite, silver, and gold. X, averages of values from both Stokes' law and the square-root law.

gravities other than those plotted can be interpolated easily. Grain sizes for platinum metals with specific gravity greater than 18 can be extrapolated with sufficient accuracy for most purposes.

The area of crowded and nonparallel curves in figure 1, between the grain sizes of 0.062–0.250 mm, marks the empirical adjustment between the two equations for settling velocity. Rubey's combined equation (1933b, p. 332) results in a hyperbola-shaped curve for quartz that has its apex at about the 0.250-mm size. This has been taken as the point of beginning of empirical adjustment even though Stokes' law is applicable strictly only to grains smaller than about 0.14 mm (Rubey, 1933b, p. 326). Adjustment is necessary because for some sizes of quartz grains larger than 0.250 mm the equivalent size of magnetite, silver, or gold is below 0.250 mm, and the behavior of the smaller grains should approach that predicted by Stokes' law. The settling velocity of such a grain of magnetite, silver, or gold calculated by the square-root modification of Stokes' law will be too low. In this intermediate size range—0.062–0.250 mm—the settling velocity calculated from Stokes' law in its original form will be too high. Therefore, the average of these two settling velocities was used for each of the three heavy materials for the first grain size smaller than 0.250 mm that is equivalent to a quartz grain larger than 0.250 mm. These points are indicated in figure 1, as for silver and gold equivalent to quartz 1.0 mm in diameter, and for magnetite and silver equivalent to quartz 0.5 mm in diameter. For the next heavier minerals for each of these average points, the equivalent settling velocity was calculated according to Stokes' law.

The net effect of these empirical adjustments is to change gradually the slope of the curve for the square-root modification of Stokes' law for coarse grains to the slope of the curve for the unmodified Stokes' law for fine grains.

Diameters of grains of magnetite, silver, and gold of less than 0.001 mm (1 micron) are plotted in figure 1. At these small diameters, it can be expected that the grains will begin to behave as coarse colloids rather than discrete particles. No data have been found, however, that allow evaluation of the extent or intensity of colloid behavior.

HYDRAULIC EQUIVALENCE OF OTHER SHAPES

The shape of grains has an effect upon settling velocity. To a considerable extent, the effect with respect to Stokes' law is proportional to the degree that the grain departs from the form of a sphere. Krumbein (1942) discussed some of the reasons for the effect. Much work has been done to measure the effect (Heywood, 1933; Wadell, 1936; Krumbein, 1942; Schulz and others, 1954; and references in these papers). To illustrate the effect of shape on the hydraulic equivalence of quartz and other minerals in placers, the following discussion will emphasize flakes. Flakes do not necessarily have the maximum effect on settling velocity, but they are of considerable interest because gold commonly occurs as flakes. Euhedral zircon crystals would settle differently than zircon spheres, of course, and the effect of crystal form or any other grain shape on settling velocity and hydraulically equivalent grain sizes can be calculated by the same method used for flakes.

The shape constant, k, developed by Heywood (1933) is the ratio between the volume of the particle and the cube of its projected diameter. The projected diameter is the diameter of a circle of area equal to that projected by the particle when it is in its most stable position. (See "Equations," p. F11.) A circular flake can be considered to be a right cylinder with a large ratio between its diameter and its thickness; thus, a simple calculation can be made of its volume, of the cube of the diameter, and of the shape constant, k. This shape constant is plotted against the ratio of diameter to thickness of circular flakes in figure 2. A flake with a diameter 10 times its thickness has $k=0.08$. Common small coins have diameter: thickness ratios ranging from about 10 (a nickel) to about 16 (a quarter), and some measured gold flakes fall within this range (L. B. Riley, U.S. Geol. Survey, oral commun., 1966). Hite (1933, p. 687–689) reported that the thinner flakes of gold from the Snake River placers have a diameter: thickness ratio of 10 but that a ratio of 5 was applicable to much of the material smaller than 0.1 mm in diameter. Pardee (1934, p. 26) reported grains of platinum ranging from 0.05 to 0.8 mm in diameter and from 0.0005 to 0.05 mm in thickness (which would therefore have ratios of 10 or more), but he only mentioned that gold occurs in "thin flakes" that are slightly larger than the platinum grains. Gold flakes from the Pinyon Conglomerate and associated rocks in western Wyoming have diameter: thickness ratios of 30 or more (J. C. Antweiler, U.S. Geol. Survey, oral commun., 1967). After determining a range of shape constant k reasonable for flakes, Heywood's graphic solution can be used to determine the velocity of a flake of a given diameter compared with that of a sphere of the same velocity. The use of Heywood's diagram for graphic solution is well explained in the Tennessee Valley Authority report (1941, p. 42–45), and the details of the solution are not repeated here. The method was used to obtain the data plotted as the heavy line labeled "velocity correction" in figure 2. The flake with $k=0.08$ will settle at a velocity of only 0.23 of the velocity of a sphere of the same diameter. Because the sphere is taken as the

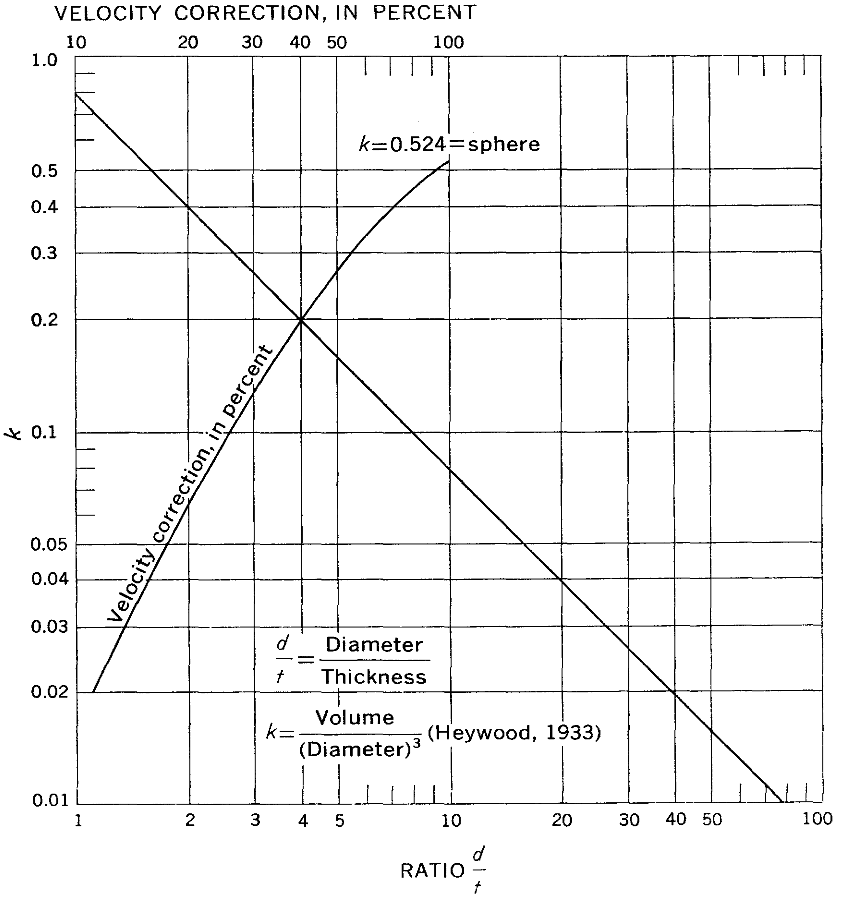

FIGURE 2.—Relation of shape constant, k, to diameter: thickness ratio of circular flakes, and correction to be applied to the settling velocity of spheres to determine the velocity of flakes.

standard of reference, the velocity-correction curve terminates at 100. The lower part of the velocity-correction curve is not well-controlled, and the velocity-correction factor is uncertain for flakes with diameter: thickness ratios of more than about 40 (that is, $k<0.02$).

The settling velocities of quartz and gold spheres and of equivalent gold flakes for a range of diameter: thickness ratios and shape constants k are shown in figure 3. A sphere of quartz 0.1 mm in diameter settles at the same velocity, 8 mm per sec, as a sphere of gold 0.031 mm in diameter or a circular flake of gold having a diameter: thickness ratio of 10 and a diameter of 0.062 mm. Gold and quartz grains of these dimensions and characteristics are in hydraulic equilibrium, and they tend to be deposited together although certain dynamic processes in streamflow can lead to their separation. The ratios between diameter and thickness for the flakes cover the expectable range of values for natural gold flakes.

The values for the Heywood shape constant k, equivalent to the diameter: thickness ratios of flakes also are shown. Thus, the settling velocity and diameter of an equivalent quartz sphere can be determined for an oblate spheroid, an octahedron, or any other geometric form of a grain of gold that has a shape constant within the range shown. To do this for another mineral, such as zircon, requires the use of Heywood's graphic solution (Heywood, 1933; Tennessee Valley Authority, 1941) to determine the appropriate correction factors.

Wadell's work on the effect of particle shape on settling velocity is difficult to evaluate with respect to grains of different specific gravities (Wadell, 1936). As summarized by Krumbein and Pettijohn (1938, p. 107), Wadell's conclusion was that the settling velocity of a disk is 64 percent of the settling velocity of a sphere of the same diameter. Krumbein and Pettijohn stated that this relation is equivalent to that of a disk 1.25 times the diameter of a sphere that settles at the same velocity. These relations do not agree with those found by Heywood (1933). No reason for the discrepancy is apparent, but Wadell approached the problem theoretically, and Heywood's conclusions were based on experiments.

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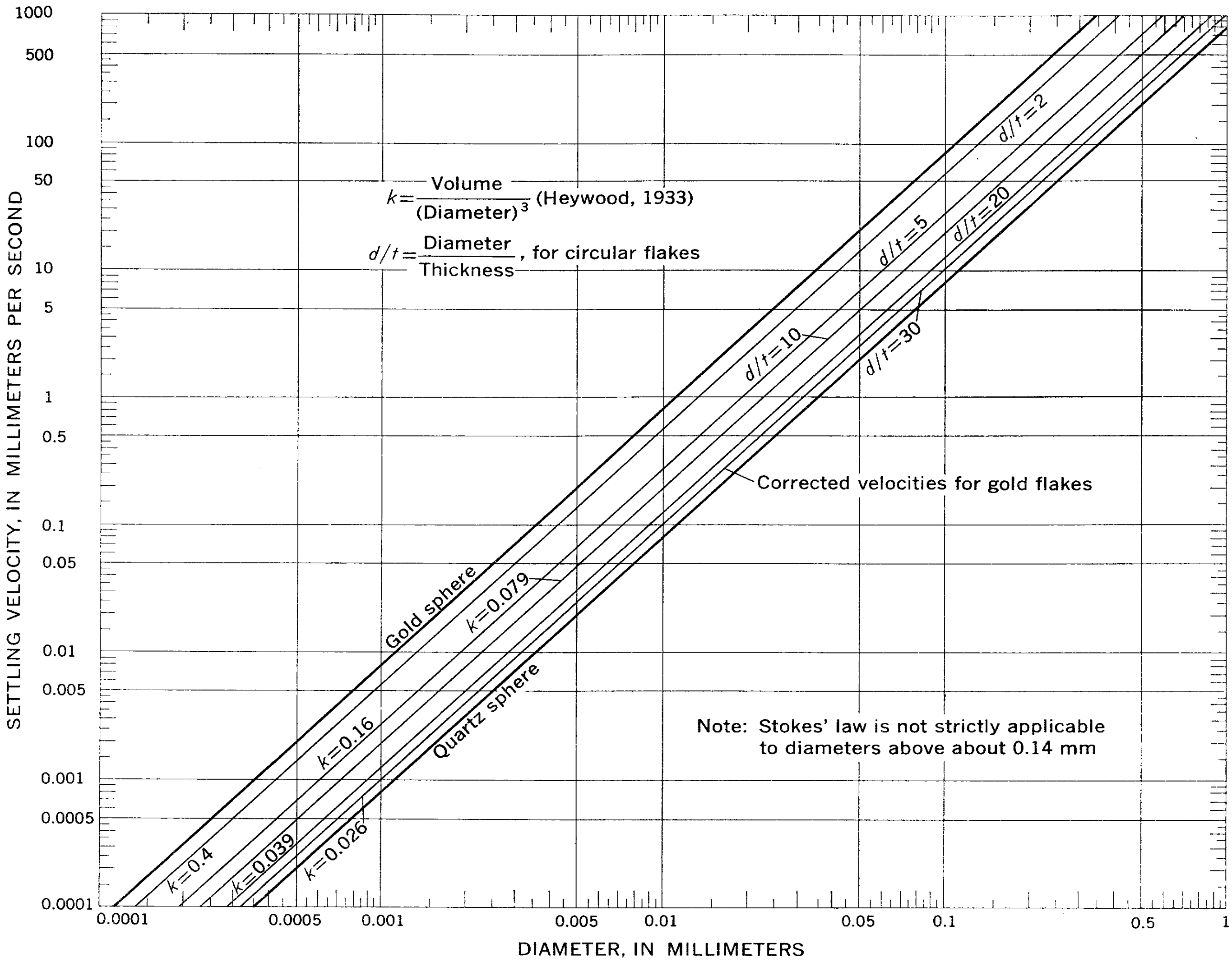

FIGURE 3.—Settling velocities in water for quartz and gold spheres and gold flakes at 15°C.

Schulz, Wilde, and Albertson (1954) considered the effect of shape on settling velocity, after both theoretical analysis of the problem and extensive experimental work. They were concerned mainly, however, with the problems of size analyses using sedimentation methods and with grain shapes that did not depart much from a sphere. Heywood's shape constant, *k*, was not used by Schulz, Wilde, and Albertson because of the practical difficulties of determining the volume of the grains to be used in experiments. Instead, they adopted a shape factor defined by Corey (1949) as the ratio between the short axis of a grain and the square root of the product of the long and intermediate axes of the grain. Corey's shape factor is always less than one, and its effect on settling velocity was not investigated by them below a value of 0.3. Schulz, Wilde, and Albertson's work was summarized by the Inter-Agency Committee on Water Resources (1957, p. 22), and data on the effect of various Corey shape factors are presented in its report. A Corey shape factor of 0.3, for instance, reduces the settling velocity of a quartz sphere 0.2 mm in diameter from 25.8 mm per sec to 18.6 mm per sec at 24°C, a reduction of about 28 percent. Other shape factors between 0.3 and 1 reduce the settling velocity of the same sphere by smaller amounts. The effect for a given shape factor increases with increase in grain size, and no data are presented for grains smaller than 0.2 mm in diameter. The effect of shape on settling velocity, however, cannot decrease continually with the smaller grain sizes. Such extreme forms as flakes were not investigated either by Corey or by Schulz, Wilde, and Albertson.

Corey's shape factor, the ratio between the short axis of a grain and the square root of the product of the long and intermediate axes of the grain, reduces to the ratio between the short axis and the diameter for a circular flake. A Corey shape factor of 0.3, the smallest investigated by Schulz, Wilde, and Albertson (1954), thus corresponds to a diameter: thickness ratio of about 3, which is very small for a flake. A flake with a diameter: thickness ratio of 10 has a Corey shape factor of 0.1. Further investigation by the methods of Schulz, Wilde, and Albertson (1954) is needed to determine the behavior of flakes with Corey shape factors less than 0.1.

APPLICATIONS

The concept of hydraulic equivalence and the associated data on settling velocities have important applications to sampling a deposit, preparing the samples for analysis, and considering the distribution of minerals in a deposit and, thus, the origin of a placer.

SAMPLING

If it is known or assumed that gold, ilmenite, or magnetite within a certain size range is disseminated in a source rock, then grains of these minerals will tend to be found in water-formed placers derived from that source rock associated with each other in certain sizes, and they will tend to be associated with quartz grains of a certain size. Magnetite about 0.5 mm in diameter that occurs in the source rock will be associated with quartz about 1.25 mm in diameter or will be found where hydraulic conditions are such that quartz of that size would be deposited. Gold occurring in the source rock in particles about 0.002 mm in diameter should be found generally in derived sedimentary rocks associated with the very fine silt fraction. Such relations can be used in sampling a given deposit or in searching for places to sample.

With respect to searching for places to sample, the few data on the size of gold in California placers are of interest. The size of gold from the Red Point channel was reported by Hoffman (Lindgren, 1911, p. 67) as follows:

Screen (meshes per inch)	*Percent retained*
10 (2.54 mm)	16
20 (1.27 mm)	48
40 (0.63 mm)	36
>40	<1

The apparent absence of gold finer than 0.63 mm means either that gold finer than this did not occur in the source rock or that methods of recovery were not effective for grains smaller than this. The latter interpretation seems the more reasonable, and it implies that much fine gold actually entered the sedimentational system represented by the placer. Such fine gold probably would have been deposited within the system at places that would not have attracted the attention of the early miners, so ground worthy of investigation might still exist. Undoubtedly, much of the gold finer than 0.63 mm was deposited in the lower reaches of streams draining the region and has now been recovered by dredging. In view of the intensity of the search for gold in California, the finding of such deposits does not seem very likely there, but the reasoning can be applied to potential placer situations elsewhere. Gold, and perhaps other heavy minerals, may be more concentrated in fine-grained rocks than the general concepts on placers might suggest, but it may be too fine grained to be recovered by present mining and treatment methods.

ANALYSIS

Sample inhomogeneity is a significant source of analytical error, no matter what constituents may be involved, and discrete grains of gold, platinum, or other heavy minerals offer the maximum possibilities for such inhomogeneity. Either data or assumptions about the size of the grains permit an approach to the problem. The number of particles of gold of a given size and at a given concentration in a 5-pound sample was shown by Miesch (1967). In general, serious problems in obtaining an adequate field sample arise only if the gold grains are larger than 0.015 mm in diameter at a concentration of 1 part per billion or if grains are at least 0.68 mm in diameter at concentrations greater than 16 ppm (parts per million).

The effects of the probable size of gold particles on the sample taken for analysis was discussed by Pardee (1934, p. 34). He pointed out that the uneven distribution of the gold grains at concentrations equivalent to about 2 ppm may make unreliable the assay of even an assay-ton sample (about 30 grams). This effect is shown in figure 4. The plotting is based on the data of Miesch (1967).

The diagram shows curves representing 1-, 10-, and 100-gram samples containing 1 ppm gold and a curve representing a 1-gram sample containing 0.1 ppm gold plotted against the grain size and the number of grains in samples of the indicated sizes. For example, a 10-gram sample assaying 1 ppm gold may contain one particle of gold with a diameter of 0.10 mm, and a 30-gram sample assaying 1 ppm gold is required to insure a 50–50 chance that the sample will contain one particle of gold with a diameter of 0.15 mm. A field sample weighing 5 pounds and assaying 1 ppm gold will contain about 70 particles of gold 0.15 mm in diameter. A sphere of gold that amounts to 1 ppm in a 1-gram sample will have a diameter of about 0.046 mm. If the gold particles are about 1 micron (0.001 mm) in diameter, a 1-gram sample will contain more than 100,000 particles of gold. At a concentration of 0.1 ppm, the gold must have a diameter of about 0.020 mm for there to be one particle of gold in a 1-gram sample.

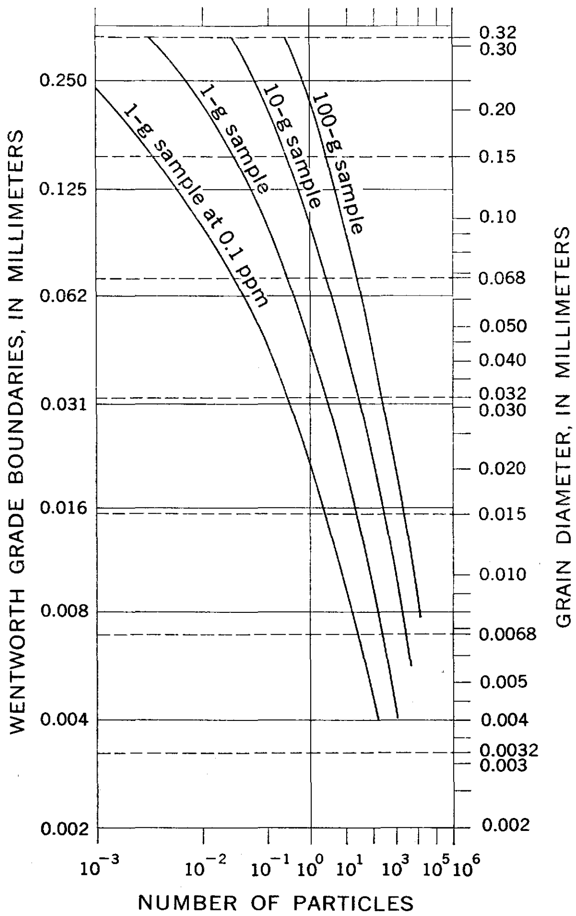

FIGURE 4.—Number of particles of gold at 1 ppm in samples having different weights, and for a 1-gram sample at 0.1 ppm. Dashed lines represent diameters used by Miesch (1967), which are the basis for the diagram.

The expectable particle size of gold and some assumption about the concentration obviously have a strong bearing on the size of the subsample taken for analysis. The subsample is the result of several preparation processes, the effectiveness of which must be assumed. For instance, it must be assumed that when the 5-pound sample is split, the few grains that may be in the sample will be evenly distributed among the splits, whatever the size of the splits. It must also be assumed that the subsequent grinding procedures reduce the size of the gold proportionally with the other constituents so that the gold is homogeneously distributed through the ground sample and a 1-gram split taken for analysis is representative of the material that was ground. Although such problems exist to some extent in analyzing for any constituent (Hillebrand and others, 1953, p. 52–53), they are accentuated when the constituent is a discrete grain and is also malleable (Bugbee, 1940, p. 47–49, 70–71). Owing to the possibilities for departures from representativeness beginning when the sample is taken at the outcrop and ending when a split is taken for analysis, it is difficult to place much confidence in the analysis of a split of 1 or 2 grams from a natural sample. This conclusion is independent of the precision and sensitivity of the analysis itself.

SAMPLE PROCESSING

One solution to the problems of analysis of samples containing grains of gold or other heavy minerals, as discussed in the preceding section, is to process the field sample so that the gold or other element sought is concentrated. More grains are thus made available, the proportion of the grains to accompanying material is increased, and the content of the sample will fall within a more convenient range for the method of analysis. If the concentration is done in a quantitative way, the resulting analysis of the concentrate can be calculated to give meaningful data for the original sample.

The easiest way to concentrate gold is to sieve or otherwise size-separate the sample to remove as much quartz and other minerals as possible. Size fractionation is effective in concentrating gold in a particular fraction because gold will always be smaller in grain size than the bulk of the grains with which it is associated, owing to its higher specific gravity. E. D. Clifton (U.S. Geol. Survey, oral commun., 1966) has made effective use of a concentration procedure in which size fractionation is an important part.

The much greater specific gravity of gold also immediately suggests that gold can be concentrated from a certain size fraction by separation in bromoform with a specific gravity of 2.89 or in diiodomethane (methylene iodide) with a specific gravity of 3.3. Use of diiodomethane eliminates a few minerals such as biotite, the amphiboles and pyroxenes, tourmaline, and apatite (Krumbein and Pettijohn, 1938, p. 349) that sink in bromoform. The choice of the heavy liquid to be used could depend on the expected abundance of such minerals or the cost of the liquid.

The techniques of heavy-mineral separation in heavy liquids are well known and were discussed by Krumbein and Pettijohn (1938, p. 319–356). It is useful here to provide data on settling velocities of gold, in particular, in heavy liquids so that the velocities can be taken into account in the design of procedures to avoid the loss of fine-grained gold. These data, translated into minutes to settle 100 mm, a common height for the heavy-liquid column in a separatory funnel, are given in figures 5 and 6 for gold in water, bromoform, and diiodomethane. Also shown are the settling velocities for flakes with different diameter: thickness ratios as were shown for gold settling in water (fig. 3). The velocities are nearly the same as those for single particles falling freely, and

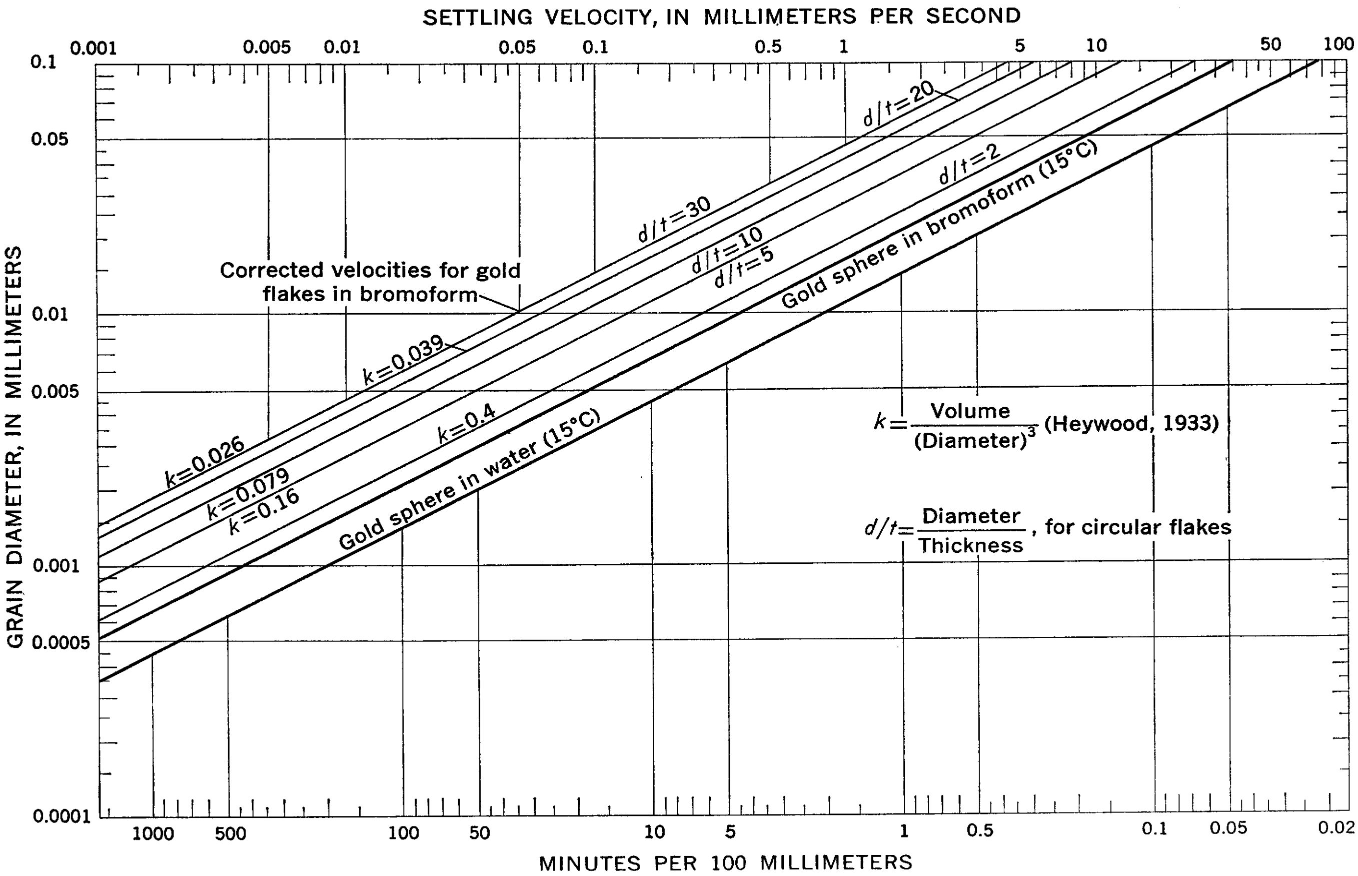

FIGURE 5.—Settling velocities of gold spheres in water and bromoform and corrected velocities for gold flakes of various characteristics in bromoform.

they would be somewhat slower if the proportion of grains to heavy liquid were high.

Hulsey (1961) showed the effect of sample size on settling velocities. Heavy-mineral separations are best carried out on fractions that have as narrow a size range as possible. A single grade size represents the most desirable range. Serious problems can result if very fine grains and coarse grains are mixed. Currents set up by the more rapidly settling coarse grains may be sufficient to keep fine grains in suspension for some time after theoretical settling velocities alone would indicate that the fine grains had settled. In addition, light minerals in the medium-silt and finer sizes have a tendency to clot in heavy liquids and may thus greatly hinder the settling of heavier grains.

Some fine flakes of gold may, in a sense, plate themselves to the sides of a glass separating funnel and, even more likely, to the sides of plastic funnels. Either vibration or periodic light taps on the funnel may minimize this possibility. Allowing the column of heavy liquid to be drawn down with the heavy fraction rather than with the light fraction would tend to wash such plated grains down also. Fine flakes of gold trapped in filter paper fibers are another possible source of loss of gold in sample processing.

The settling-velocity data (fig. 5) show that 10 minutes at 15° C is sufficient for spherical grains of gold coarser than about 0.006 mm (6 microns) to settle 100 mm in bromoform, after any currents created in the heavy liquid by inserting the grains have been dispelled, provided that there is no undue interference between grains and that terminal settling velocity is attained almost instantaneously. If any of these conditions are not met, settling times will be longer. It is important to notice, however, that if the grains are flakes with diameter: thickness ratios of 30 and a diameter of 6 microns, settling will take almost 90 minutes. Flakes with the same diameter: thickness ratio but with a diameter approaching 0.1 mm (100 microns), however, will settle 100 mm in less than half a minute.

Settling velocities for micron-size gold in water also are very slow. Settling 100 mm takes almost 1 hour for a sphere of gold 2 microns in diameter and almost 400 minutes for a flake 2 microns in diameter and with a diameter: thickness ratio of 30. Regardless of the liquid used, settling times can be reduced considerable by using a centrifuge.

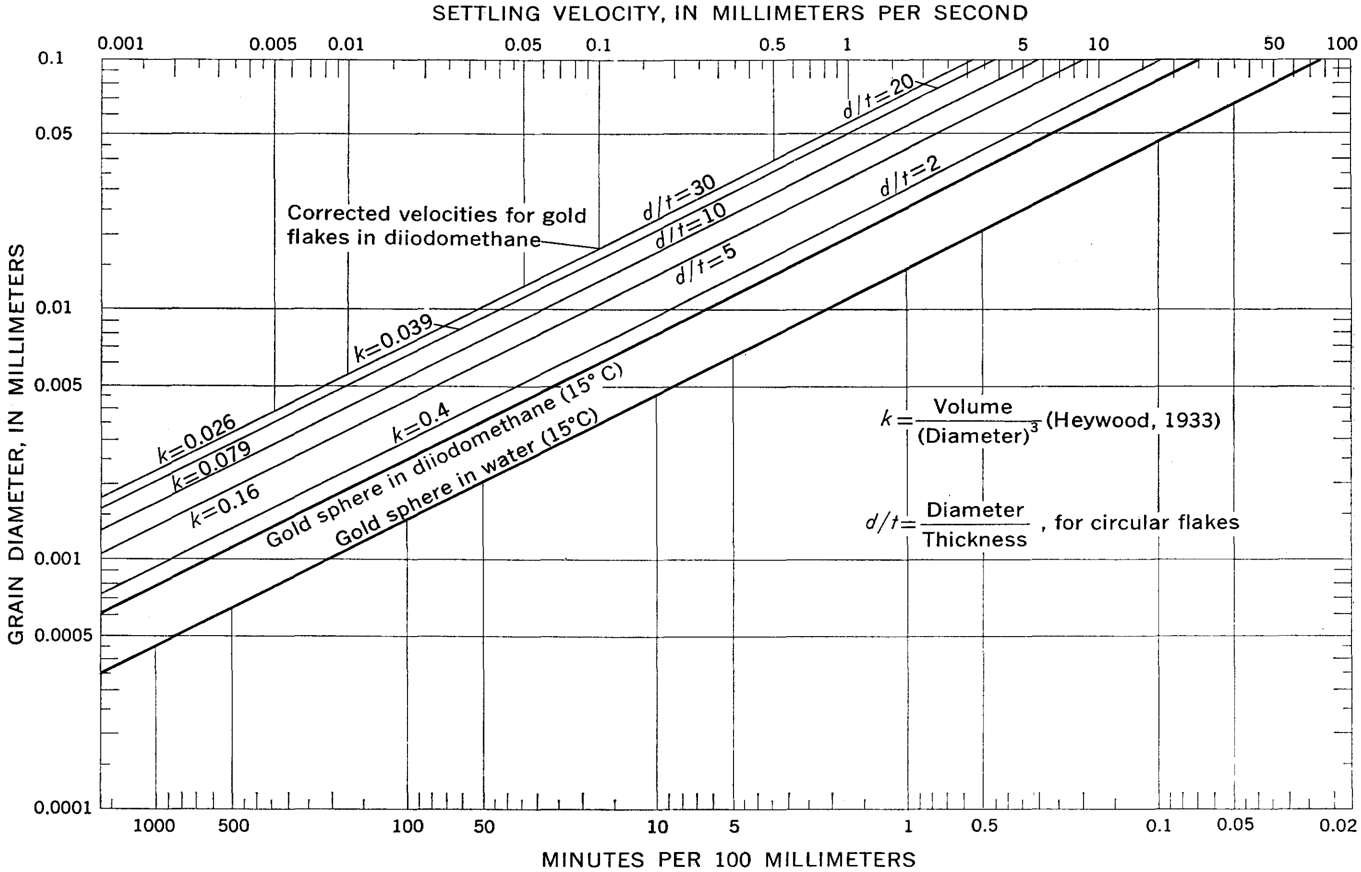

FIGURE 6.—Settling velocities of gold spheres in water and diiodomethane and corrected velocities for gold flakes of various characteristics in diiodomethane.

The settling velocities for gold in diiodomethane (fig. 6) are about 70 percent of those in bromoform. Thus in 10 minutes a sphere of gold about 8 microns in diameter or a flake about 23 microns in diameter will settle 100 mm. A flake of gold 8 microns in diameter will take almost 90 minutes to settle 100 mm.

A settling time of 10–30 minutes probably is adequate even for the heavy-liquid separation of flakes of gold of diameters ranging from 50 to 100 microns (0.05–0.1 mm).

Very fine gold, from 50 to 100 microns in diameter, probably is the finest material for which commercial physical separation has been attempted. There are very few data on the size of such gold. Gold in the Snake River is notorious owing to the difficulties caused in its recovery by its fine size, and yet much of this gold is larger than 100 microns in diameter (Hite, 1933). The difficulty of recovering gold finer than 100 microns probably is a factor in the lack of data on fine-size gold. Lorain and Metzger (1938, p. 85), however, reported that many particles of gold from the lower Salmon River in Idaho will pass through a 100-mesh screen (0.110 mm), and that some will pass through a 200-mesh sieve (0.074 mm). Janin (1918, p. 19) reported that about 21 percent of the gold recovered from dredge cleanups in the Oroville field, California, was finer than 150 mesh (0.1 mm). Considerable gold in suspension is usually lost during dredge work, and much of this gold is fine enough to settle behind the dredge more slowly than the mud (Janin, 1918, p. 146). Bouery (1913, p. 1060) found that about 1–6 percent of the gold in sluice boxes of a hydraulic operation near Weaverville, Calif., was finer than 200 mesh (0.074 mm). He also noted that the largest amounts of such fine gold were found in the lowest sluice box, but that the total recovery in this box was less than one ounce.

It seems possible that gold even finer than 50 microns or so can be found concentrated in hydraulically favorable situations. Research in recovery methods might make it possible for such deposits to be utilized commercially. Even if exploitation is not possible, however, such occurrences of very fine grained gold need to be studied to shed light on the processes by which gold and other heavy minerals are distributed in sedimentary rocks.

After a heavy mineral fraction that contains all the gold in a given size fraction has been obtained, the gold can be further concentrated by removing magnetic minerals. A hand magnet will remove magnetite, and a magnetic separator will remove a wide range of minerals with different magnetic susceptibilities. The effectiveness of magnetic separation obviously depends on the heavy minerals present. Any magnetic separation, however, has to be carried out very carefully to avoid loss in processing. Fine flakes of gold, for instance, may adhere to grains of magnetite, particularly if the bromoform or diiodomethane has not been completely washed from the heavy-mineral fraction. The vibrating tray and hopper of most magnetic separators may cause some loss of gold if they are operated at power settings that are too high or at either vertical or lateral inclinations that are too large.

CONCLUSIONS

Hydraulic equivalence with respect to settling velocities in quiet water does not, of course, explain the origin of placers in general. Placers, whether beach or stream, are the result of a complex of dynamic processes acting upon a wide variety of distributions of placer minerals in source rocks. Different sets of dynamic processes may operate on the same deposits at different times, or through a long period of time, so that the end result cannot be related easily to the source materials. Nevertheless, settling velocity, and therefore the concept of hydraulic equivalence, is an essential element in the theory of the dynamic processes that can result in placers.

Consideration of hydraulic equivalence of mineral grains of different specific gravities thus should be a major factor in the study of placer deposits. The concept is very useful in preparing concentrates for analysis. Data are needed on the size distribution of valuable placer minerals and the other minerals associated with them in samples. These data would make it possible to assess the applicability of hydraulic equivalence to conditions of deposition. Both conformity with and departures from hydraulic equivalence in specific deposits should make it possible to identify more fully the dynamic processes that formed the deposits. In this way, the search for placers of all kinds could be greatly improved.

EQUATIONS

Equations used in calculations in this paper are brought together from scattered sources to avoid interruption of the text and to make them available for considering the data presented in diagrams and for use on heavy minerals or metals other than those dealt with in this paper.

Stokes' law for particles less than 0.1 mm in diameter (Rubey, 1933a, p. 6) is:

$$v=\frac{g}{18}\times\frac{(\rho_1-\rho_2)d^2}{\mu}$$

where

v = terminal settling velocity, in centimeters per second,
g = acceleration due to gravity (981 cm per sec^2),
ρ_1 = specific gravity of mineral grain,
ρ_2 = specific gravity of fluid,
μ = viscosity of fluid, in poises, and
d = diameter of mineral grain, in centimeters.

Equivalent diameters of quartz (q) and magnetite (m) are calculated by equating the right-hand term of the above equation for quartz and magnetite, respectively, and eliminating constants:

$$(2.65-1.00)d_q^2=(5.18-1.00)d_m^2$$

$$d_m=\sqrt{\frac{2.65-1.00}{5.18-1.00}}\times d_q=0.628d_q.$$

Settling velocity for particles more than about 0.25 mm in diameter (Rubey, 1933a, p. 17) is:

$$v=\sqrt{\frac{2}{3}\times g\frac{\rho_1-\rho_2 d_q}{\rho_2}}.$$

Calculation of equivalent diameters of quartz and magnetite using method above gives:

$$(2.65-1.00)d_q=(5.18-1.00)d_m$$

$$d_m=\left(\frac{2.65-1.00}{5.18-1.00}\right)d_q=0.395d_q.$$

Equivalent diameters for other pairs of minerals are calculated similarly. The constants for minerals and metals used in this report are as follows:

	Stokes' law	*Coarse particles*
Quartz-magnetite	0.628	0.395
Quartz-silver	.428	.183
Quartz-gold	.312	.0971
Magnetite-silver	.681	.464
Silver-gold	.727	.529

Heywood's shape constant, k (Heywood, 1933; Tennessee Valley Authority, 1941, p. 28, 42–45) is:

$$k=\frac{\text{volume}}{d^3}$$

where

d=diameter of circle equal to area of grain in its most stable position.

Corey's shape factor is:

$$SF=\frac{c}{\sqrt{ab}}$$

where

a=long axis of grain,
b=intermediate axis of grain, and
c=short axis of grain.

Settling velocities within the applicable range of Stokes' law can be calculated conveniently by substitution of values. The rather low temperature of 15°C is used in these calculations because the viscosity of bromoform is available only for this temperature. Grain dimensions and velocities are in centimeters.

Quartz in water at 15°C:

$$v=\frac{g}{18}\frac{(\rho_1-\rho_2)d^2}{\mu}$$

ρ_1 for quartz=2.65
ρ_2 for water=1.00

$$v=\frac{981\times 1.65\times d^2}{18\mu}$$

$$v=\frac{89.93d^2}{\mu}$$

For water at 15°C, μ=0.0114:

$$v=\frac{89.93d^2}{0.0114}=7{,}889d^2$$

Gold in water at 15°C:

$$v=\frac{981}{18}\times\frac{(18.0-1.0)d^2}{\mu}$$

$$v=\frac{926.5d^2}{0.0114}=81{,}272d^2$$

Gold in bromoform at 15°C:

$$v=\frac{981}{18}\times\frac{(18.0-2.89)d^2}{\mu}$$

$$v=\frac{823.5d^2}{0.0215}=38{,}302d^2$$

NOTE.—The viscosity of bromoform at 20°C is close to 0.020 poise.

Gold in diiodomethane at 15°C:

$$v=\frac{981}{18}\times\frac{(18.0-3.3)\ d^2}{\mu}$$

$$v=\frac{801.2\ d^2}{0.3}=26{,}707\ d^2$$

NOTE.—The viscosity of diiodomethane at 15°C is estimated by extrapolation of data from Griffing, Cargyle, Corvese, and Eby (1954, p. 1055) for temperatures of 30°C and higher.

Factors for conversion of settling velocities of quartz spheres in water and gold spheres in various liquids at 15°C to each other are given in the following table. The table can be entered only from the left. For instance, the settling velocity of quartz in water is 0.097 times the settling velocity of gold in water. Likewise, the settling velocity of gold in bromoform is 1.43 times the settling velocity of gold in diiodomethane, and that of gold in diiodomethane is 0.697 times the settling velocity of gold in bromoform.

	Quartz in water	Gold in water	Gold in bromoform	Gold in diiodomethane
Quartz in water	1.0	0.097	0.206	0.295
Gold in water	10.3	1.0	2.12	3.03
Gold in bromoform	4.86	.471	1.0	1.43
Gold in diiodomethane	3.39	.329	.697	1.0

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