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SEDIMENTARY STRUCTURES AS AN IMPORTANT FACTOR IN THE CLASSIFICATION OF SANDSTONES

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ABSTRACT. Deep water sediments deposited by turbidity currents and shallow water sediments deposited by traction currents are each characterized by a set of sedimentary structures, graded bedding being the most significant in the former and current bedding in the latter. The sedimentary structures of the two depositional types provide a basis for the division of sandstones into two suites: (1) the graywacke suite, deposited by turbidity currents, and (2) the arkose-quartzose sandstone suite deposited by traction currents. The graywacke suite includes labile graywacke, sublabile graywacke and subgraywacke; the arkose-quartzose sandstone suite includes arkose, felspathic sandstone, quartzose sandstone, labile sandstone, and sublabile sandstone. The latter two types differ from arkose and felspathic sandstone in being derived from a non-granitic terrain. Although the two suites have overlapping textural features, the typical representative of each suite is significantly different from the other. The typical graywacke suite sandstone is muddy and poorly sorted whereas the typical sandstone of the arkose-quartzose sandstone is clean and moderately well sorted.

INTRODUCTION

The many attributes of sandstone make it possible to devise a number of different classifications. Those in general use today are based entirely on mineralogical and textural characteristics. As a result there has been a good deal of disagreement about the genetic significance of certain sandstone types. The author is of the opinion that the difficulty can be largely overcome by using as a basis for classification those features which are of genetic significance, that is, features indicating the physical environment and agent of deposition. Within classes defined on the basis of these features it is possible to make a subdivision according to mineralogy or texture.

Sedimentary structures make it possible to diagnose two main agents of deposition among water-laid sandy sediments; they are traction currents and turbidity currents. Traction currents are easily observable and have consequently been known for a long time, but it is only in the past few years that the importance of turbidity currents has been appreciated, principally as a result of the work of Kuenen. Traction currents are the chief agents of deposition in neritic and non-marine environments, whereas turbidity currents are the most important agents of deposition in deep water.

FEATURES OF SHALLOW AND DEEP WATER SEDIMENTS

Since the observation of Bailey (1930) that "graded bedding and current bedding are the distinguishing marks of two different sandstone facies," many other sedimentary structures have been found to be associated more or less exclusively with current or with graded bedding. Some of these features are listed by Pettijohn (1943); those associated with graded bedding are drawn principally from his observations of Archean sediments of the Canadian Shield. The graded bedding association has also been studied by Kuenen and various associated workers, in sediments ranging in age from Cambrian to Upper Tertiary, and a list tabulating the features observed in these various sediments is given in Kuenen and Carozzi (1953). The conclusion Kuenen reached by both field observations and experimental studies is that this association occurs in deep water and is the result of sediment deposition by turbidity currents. Table 1 lists the more important features of both shallow and deep water sediments.

The environments of deposition of these two classes of sediments can be compared with those defined by Rich (1950, 1951). His classification is based largely on macroscopic sedimentary features. The sediments with features listed in table 1 under the heading, shallow water, are ones which would be deposited in his unda-environment. The sediments classified here as deep water deposits would be laid down in Rich's clino- and fondo-environments. Unfortunately Rich underestimated the importance of turbidity currents in these latter environments; in fact, he says that coarse sediments are rare. That this is not the case, particularly in the clino-environment, has been pointed out by Kuenen (1953).

TABLE 1
Sedimentary Structures in Sediments

Shallow Water	Deep Water
One lithology often dominates.	Interbedded coarse and fine sediments, fine sediments tend to be pelagic.
Bedding tends to be lenticular and the features of the bed change over the outcrop.	Bedding regular and the beds maintain their characters over the outcrop.
Wave ripples, channel scour and coarse, often mutually opposed current bedding.	Current ripples, small scale current bedding (unidirectional). Scour absent or insignificant at the base of beds, load casting often present.
Slumps common only in current bedded units.	Slump structures, pull aparts* and slide deposits occur.
Shallow water benthos occurs in both fine and coarse beds.	Shallow water benthos absent from finer beds, reworked fossils sometimes considerably older may occur in coarser beds.
Graded bedding rare.	Graded bedding common. Finer graded beds often laminated and may show convolute bedding. Lower contacts of beds sharp, upper contacts generally so, but may grade up into pelagic beds.
Thickness of beds generally not related to grain size.	Coarser beds tend to be thicker than finer ones.

* Kuenen (1953), p. 1054.

THE GRAYWACKE PROBLEM

Apart from realizing that two distinct sandstone facies existed, Bailey (1930) considered that their sedimentary structures were important in classification. He said: "Many of the early paleozoic sandstones of Scotland and Wales are linked by three well marked characteristics. They are typically (1) muddy sandstones (2) without current bedding (3) with graded bedding. They obviously deserve a distinctive name. . . . If the original Harz greywackes show these same three characters as listed above, it would certainly be wise to retain the title greywacke and introduce into its definition a mention of the bedding characters of the type. It may be said at once that while graded sandstones as a class are muddier than current bedded sandstones there is a well marked overlap in this respect." In a recent study by Helmbold (1952) of the Tanner graywacke (a Devonian graywacke formation of the Harz region) it is stated that graded bedding is common in the formation but does not occur in every bed. This feature is typical of all graded sandstone sequences. The Tanner graywacke is a badly sorted sandstone, as are other graywackes of the Harz region (Fischer, 1933). Thus it seems that some at least of the Harz graywackes have the features of the Scottish and Welsh graywackes described by Bailey. It is not known whether they have the other features common in sediments deposited in deep water.

It is evident that Pettijohn (1943, p. 944) is thinking of the same rock type as Bailey when he says: "Graywacke connotes a type of sandstone marked by large detrital quartz and felspar 'phenocrysts' set in a prominent to dominant clay matrix . . . and certain macroscopic structures (graded bedding, intraformational conglomerate of shale or shale chips, slip bedding etc.)." Pettijohn (1949) adds: "Cross bedding is very rare and at best is very local and on a small scale, i.e. it is restricted to layers a few inches thick."

The term graywacke has become more and more frequently used over the past twenty years, but it has not always been applied to turbidity current deposits. This is the result of the use of a number of different definitions, some of which emphasize mineral composition, others texture, and so on. For example, Krynine (1937) described the Siwalik sandstones as graywackes. They are a sequence of terrestrial sediments on the southern margin of the Himalayas. In this case the sandstones have both the texture and the mineralogy of typical graywackes, but their sedimentary structures distinguish them as shallow water traction current deposits. This is evident from what Anderson (1927, p. 679) says of them: "Throughout the system cross bedding is a notable and characteristic feature of the sandstones and to a lesser extent it may be observed in the siltstones as well."

It has been customary to think of all sandstones as belonging to a series which commences with badly sorted angular detritus containing a good deal of unstable material. As this material is transported further from the source the sorting is improved, the roundness of the grains increases, and the percentage of unstable material decreases. The final product of such a process is a pure quartz sandstone. During the process the texture of the sandstone passes through the various stages established by Folk (1951).—immature, submature, mature and supermature. The quartz index (percentage of quartz + chert divided by the percentage of all the other allogenic materials) simultaneously increases. Dapples, Krumbein, and Sloss (1953), who introduced the quartz index, found that its value ranged between 3 and 19 in the sandstones they examined. In some of the sediments studied here it reaches its possible minimum value of zero. The series described above applies only to sandstones which are deposited by traction currents, and the Siwalik sandstones are conceived as being at a point near the beginning of the series.

Graded sandstones have the characters of a texturally immature sandstone and in many cases have a low quartz index, but this does not imply that they are an early stage in the traction current sandstones series. The textures of graded sandstones are dependent only on the fact that they are deposited from a turbidity current. Theoretically the detritus could have reached any stage of textural and chemical maturity before redeposition. The roundness of grains and the amount of unstable material present will give an indication of the previous history of transportation by traction currents. When finally deposited in deep water by turbidity currents the sediment can suffer no further transport and consequent textural modification; it is thus the end product of a process divergent from normal sandstone evolution. As a result of the overlap in textural and mineralogical features of shallow and deep water sediments, classifications depending on texture and mineralogy will group certain sandstones from each environment and hence of different origin under the same name. Such a classification is clearly an unnatural one.

If the term graywacke is to be retained for certain muddy sandstones, it is clear that it should not be used for both the Siwalik-type sandstones and graded sandstones, because of their differences in mode and environment of deposition, and consequent differences in sedimentary structures. Thus if restricted to one of them, the kind deposited by turbidity currents seems the best choice.

The problem of definition of subgraywacke also arises here. Pettijohn (1949) stated that "subgraywacke by definition contains 15 to 85 percent quartz, 0 to 10 percent felspar, 15 to 75 percent silty and clayey matrix. They usually have appreciable (5 percent) rock fragments." In other words, this definition indicates that subgraywacke is a felspar-poor variant of graywacke as defined by Pettijohn and has a similar texture. In his discussion, however, he says that subgraywacke characterizes molasse deposits. This is in accordance with his later opinion (Pettijohn, 1950) that the difference between graywacke and subgraywacke is not the percentage of felspar but the introduction of a mineral cement. Such rocks could fall almost anywhere on Pettijohn's triangular diagram; they would certainly not be confined to the subgraywacke field. Cayeux (1929, p. 166) described molasse (in the petrological sense) as follows: "Roche généralement très feldspathique, plus ou moins micacée, chloriteuse, glauconiteuse, lorsque'elle est d'origine marine, et renferment ou non des débris de roches cristallophylliennes, fréquent ou rares. . . . Gangue calcaire, ne faisant á l'argile qu'une place très négligeable et seulement notable dans une proportion très limitéchantillons." These rocks would not fall in the subgraywacke field on Pettijohn's triangular diagram; they would fall among the arkoses or graywackes depending on the degree of sorting. The sedimentary structures of the molasse sandstones indicate that they are shallow water traction-current deposits, and are hence quite unrelated to graywackes. Thus both the composition and the sedimentary structures of these sandstones suggest that the name subgraywacke should not be applied to them. The most logical usage of the term subgraywacke is to retain the original definition and to specify that the sedimentary structures and environment of deposition is the same as for graywacke.

PROPOSED CLASSIFICATION OF SANDSTONES

Sandstones of the graywacke suite.—Accepting the above argument, all graywacke-suite sandstones are deep water sediments. They occur in beds containing the structures listed under the heading "deep water" in table 1. The most important single structure is graded bedding; although it is common, it does not occur in every bed. The sorting of these sandstones is generally very poor. The percentage of matrix (as distinct from mineral cement) gives some indication of the sorting. It has been plotted against the frequency

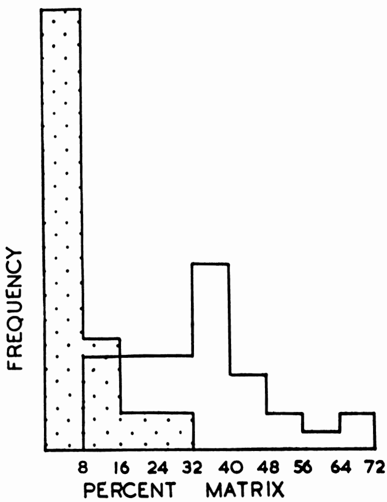

Fig. 1. Frequency of matrix percentages in sandstones studied. Stippled: Arkose-quartzose sandstone suite; unstippled: Graywacke suite.

with which it occurs in the sandstones studied (fig. 1). The range of variation is from 10 to 70 percent but there is a pronounced maximum in the interval 32 to 40 percent. The percentage of matrix is not an ideal choice for the textural study of sandstones since it gives little indication of the entire grain-size distribution. A plot of the sorting coefficient against the median diameter would be better. The ease of determination of the percentage of matrix makes it, however, the most convenient measure to use. The reason for textural variation within the graywacke suite may be related to the degree of dilution of the turbidity current depositing the sediment. This however is conjectural, and the ultimate solution of the problem will depend on the results of more experimental studies of the type described by Kuenen and Migliorini (1950).

The mineralogical variation is similarly very large. The suite shows every variation from quartz-free to quartz-rich rocks. Both the mineralogy and the texture of the sandstones studied are shown in figure 2. The mineralogical variation is a reflection of the nature of the source rocks and the transport history of the detritus previous to its deposition as a deep water sediment. The sedimentary structures and the textures are solely the result of the process of deposition. This means that Folk's terms for textural maturity are inapplicable to the graywacke suite. Certain mineralogical compositions are more likely to occur in some tectonic environments rather than others. In eugeosynclinal regions the importance of volcanic contributions will be great, the exact mineralogy of the sediments depending on the nature of the vulcanism. The material would be derived from unconsolidated volcanic products in most cases. The graywackes of the Aure trough in New Guinea are an example of sediments in which basic volcanic material has been the principal source of detritus. As would be expected, the quartz content is small, and in some cases less than 0.1 percent is present (Edwards, 1950). The Franciscan sandstones have been derived from plutonic rocks (Taliaferro, 1943), and their association with radiolarian cherts suggests that they too are graywackes.

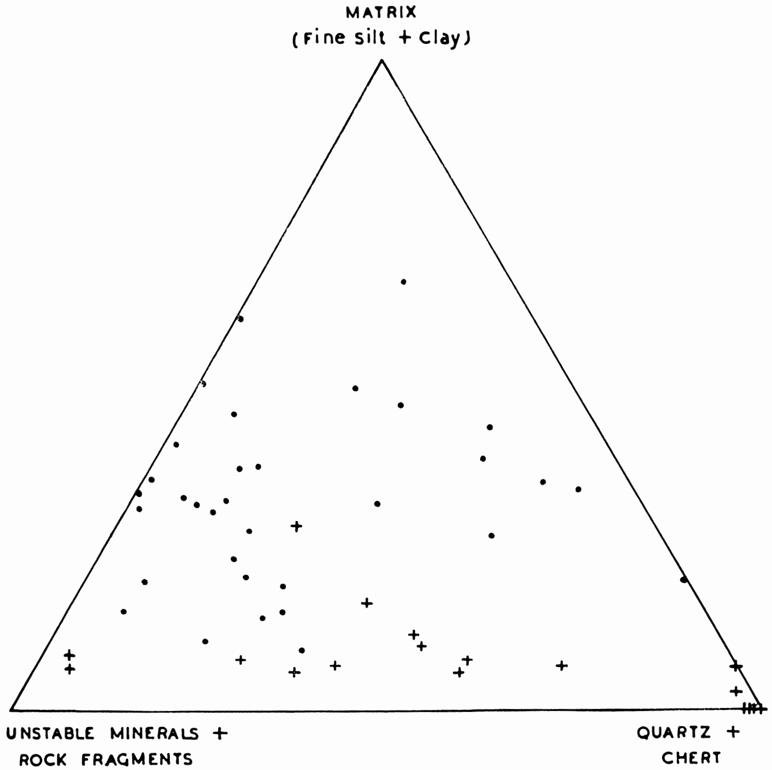

Fig. 2. Texture and mineralogy of 51 sandstones; 15 have been measured by the author, the remainder are recorded in the literature. Sandstone of the graywacke suite indicated by dot; sandstone of the arkose-quartzose sandstone suite indicated by plus sign.

They are the deep water equivalents of arkoses. Some authors have suggested oscillation of the sea floor to explain the interbedded sandstone, conglomerate, and radiolarian chert; others have disclaimed the deep water origin of the latter. The best explanation seems to be that the sediments are in fact deep water deposits and the arenaceous and rudaceous material has been brought in by turbidity currents and by sliding. The sediments containing smaller percentages of unstable material are characteristic of miogeosynclines where vulcanism is absent and the detritus is derived from the weathering of older crystalline rocks or their sedimentary cover. Tectonism is usually less, and hence the percentage of unstable material will be substantially smaller than in a eugeosynclinal region with its large supply of unconsolidated volcanic products. Thus under these conditions subgraywackes are more probable than graywackes.

Pettijohn's graywacke-subgraywacke boundary is based on the felspar content. The definition of subgraywacke which is used here is only a minor modification of Pettijohn (1949). It is that a subgraywacke should contain less than 10 percent non-quartzose material in the rock excluding the matrix. Figure 3 shows the scheme of classification of the graywacke suite. The boundary between the fields of graywacke and subgraywacke is a line radiating from the apex (matrix) to a point on the base of the triangle representing

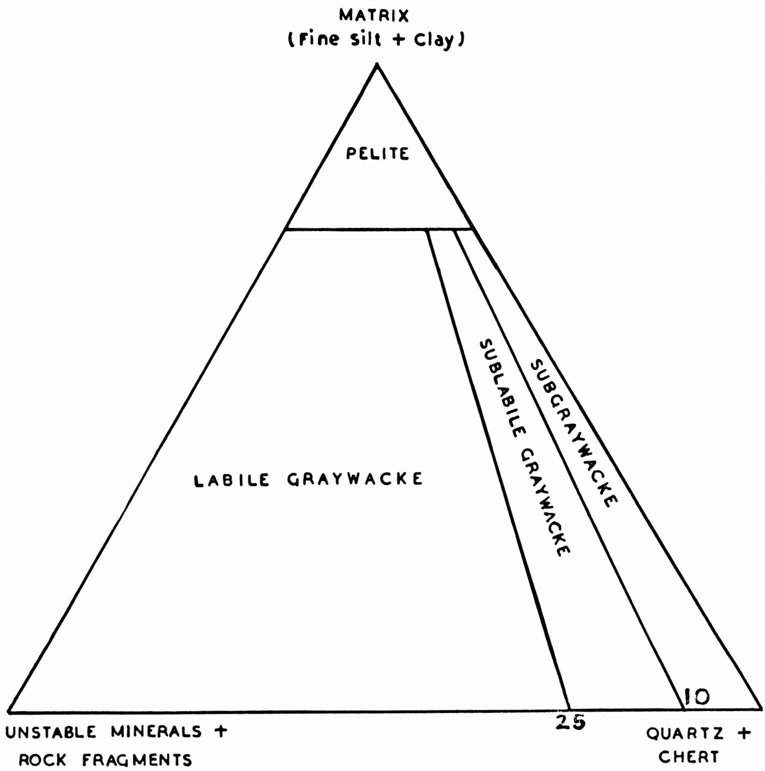

Fig. 3. Classification of the graywacke suite.

90 percent quartz plus chert. This means that the proportion of the quartzose material in the non-matrix fraction of the rock is the factor used in classification and not its absolute percentage of the entire rock.

The graywacke field has been subdivided into two parts at 25 percent unstable material in the non-matrix fraction. The graywackes with more than 25 percent unstable material are designated labile graywackes and those with less are termed sublabile graywackes. This threefold division of the graywacke suite brings to mind the division of graywackes into quartzwackes, quartzmengwackes, mengwackes and quartz-free wackes by Fischer (1933). The boundaries of Fischer's members of the group are at 10, 33, and 90 percent unstable material respectively. His definition of the group is purely a textural one, a wacke being defined as a sandstone in which the grains are divided more or less evenly among a number of size grades. In the present paper, 10 and 25 percent unstable material in the non-matrix fraction are chosen as the boundaries between the members in order to obtain a parallelism with the classification of the sandstones of the arkose-quartzose sandstone suite.

Sandstones of the arkose-quartzose sandstone suite.—Not only the shallow water sandstones of arkosic affinity but others with widely diverse compositions have the shallow water features listed in table 1. Their sorting is indicated in figure 1; it will be seen that there is a considerable textural overlap with graywacke-suite sediments. The percentage of matrix varies from 30 percent to zero with a maximum in the region of 5 percent. Since the graywackes range from 10 to 70 percent matrix with a pronounced maximum about 35 percent, the 20 percent boundary used by Pettijohn is a good first approximation to the present classification.

If the definitions of graywacke and subgraywacke are restricted as suggested, then the only sandstone types left in the shallow water sandstone series are quartzose sandstone, felspathic sandstone and arkose, using the nomenclature of Krumbein and Sloss (1951). As arkose and felspathic sandstone are specialized types derived from granitic terrains and the names cannot be applied to sediments derived from all other possible source rocks, two analogous terms are required for sediments derived from non-granitic terrains. The use of the term molasse suggests itself, but since a good deal of confusion has arisen in its use as a facies term, a petrological usage would be ill advised. Thus it seems necessary to introduce two new terms to cover the field vacated by the restriction of graywacke and subgraywacke.

The definition of these two new types can be based on texture or mineralogical composition. Although the two are interdependent to a certain extent, their degree of freedom means that definition of one will not fix the other. For ease of determination, and more important for parallelism with the definition of graywacke and subgraywacke on one hand and arkose and felspathic sandstone on the other, mineralogical composition has been used.

The two terms proposed are labile and sublabile sandstone. A *labile sandstone* is a sandstone in which there is more than 25 percent non-quartzose material, calculated on a matrix- and mineral-cement-free basis. It also exhibits the shallow water features listed in table 1. A *sublabile sandstone* contains 10 to 25 percent non-quartzose material calculated on a matrix- and mineral-cement-free basis. The relation to other shallow water sandstones is at once apparent. Labile and sublabile sandstones may be regarded as impure arkoses and felspathic sandstones or else the latter two can be regarded as specialized types of labile and sublabile sandstones. The textural variation within one of the defined types can be indicated by prefixing the name with one of the textural terms introduced by Folk (1951). The classification of the arkose-felspathic sandstone suite is illustrated in figure 4.

The relation between the members of the two sandstone suites is that labile graywacke is the deep water equivalent of labile sandstone and arkose, sublabile graywacke is the deep water equivalent of sublabile sandstone and felspathic sandstone, and subgraywacke is the deep water equivalent of quartzose sandstone.

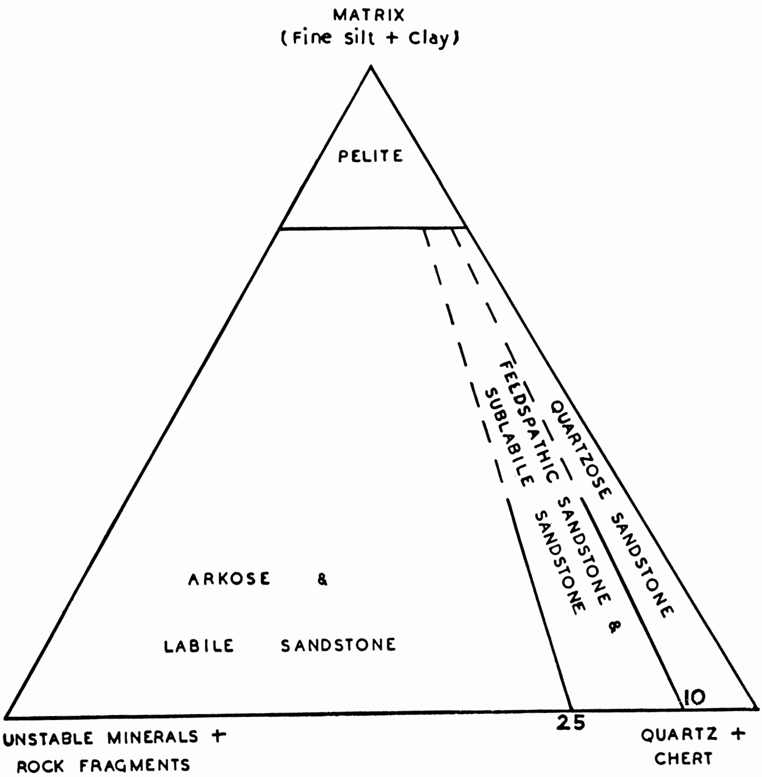

Fig. 4. Classification of the arkose-quartzose sandstone suite.

The mineralogical composition of shallow water sandstones is extremely variable, the percentage of quartzose material varying from 0 to 100 percent. The sandstones with the greatest percentage of unstable material would be expected to occur in regions where tectonic activity was strong at the time of sedimentation. The epiorogenic sediments (Glaessner and Teichert, 1947, p. 575) of the Alpine molasse are typical of these conditions. According to Kuenen and Carozzi (1953) the Alpine flysch and molasse have almost identical bulk petrographies, but the environment and agent of deposition are

TABLE 2
Classification of Sandstones

Quartzose material in non-matrix fraction	Shallow water sandstones		Deep water sandstones
	Granitic source	Non-granitic source	Granitic or non-granitic source
75%	Arkose	Labile sandstone	Labile graywacke
75-90%	Felspathic sandstone	Sublabile sandstone	Sublabile graywacke
90-100%	Quartzose sandstone	Quartzose sandstone	Subgraywacke

the factors which are responsible for their vastly different appearances. Sediments with large amounts of unstable material may also occur on unconformities or at the margins of basins of sedimentation; the unstable material in such cases is an expression not of tectonism but of proximity to the source.

CONCLUSIONS

By means of the sedimentary structures listed in table 1. it is possible to divide sandstones into types deposited in deep and shallow water. Further subdivision can be made within each class according to the percentage of unstable material in the nonmatrix fraction. This classification is summarized in table 2.

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