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AN OCCURRENCE AND DISTRIBUTION SURVEY OF EXPANSIVE MATERIALS IN THE UNITED STATES BY PHYSIOGRAPHIC AREAS

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16. Abstract
The report concludes a study of physiographic areas within'the continental United States which contain sources of potentially expansive materials. Following the definition of the physiographic provinces, generalized maps were developed which give a subjective indication of the occurrence and distribution of potentially expansive materials. Narrative descriptions which include lithology, geologic age, stratigraphic association, and mineralogy of the potentially expansive geologic units are included to complement the maps. The information within the report is designed to provide additional working knowledge of expansive materials to forewarn soils and pavement design engineers of impending problems. The most troublesome expansive materials consist of argillaceous sediments, shales, or less frequently occurring residual soils of the Mesozoic age or younger which have undergone minor modification by either deep burial or tectonism. The origin of montmorillonite is, in many cases, due to the diagenetic alteration of volcanic glass particles in the original sediments. Although montmorillonite may occur in several geologic environments, its presence in marine sediments is most common and contributes to widespread occurrence of expansive materials, notably in the Great Plains and Gulf and Atlantic Coastal Plains Physiographic Provinces.

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PREFACE

The study of the methodology for prediction and minimization of detrimental volume change.of expansive soils in highway subgrades is a 4-yr' investigation funded by the Department of Transportation, Federal Highway Administration, under Intra-Government Purchase Order No. b-l-0195, Work Unit No. FCP 34D1-132.

The work was initiated during June 1974 by the Soils and Pavements Laboratory (S&PL) of the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. Dr. Donald R. Snethen, Research Group, Soil Mechanics Division (SMD), was the principal investigator during the period of this report. The work reported 'herein was performed by Dr. David M. Patrick, Engineering Geology Research Facility, Engineering Geology and Rock Mechanics Division (EGRMD), S&PL. Dr. Patrick was assisted by Mr. Harry K. Woods, Terrestrial Sciences Branch, EGRMD, in analyzing the collected information. The report was prepared by Dr. Patrick and reviewed by Dr. Snethen. The investigation was accomplished under the general supervision of Mr. Clifford L. McAnear, Chief, SMD, and Mr. James P. Sale, Chief, S&PL.

Director of WES during the conduct of this portion of the study and preparation of the report was COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

AN OCCURRENCE AND DISTRIBUTION SURVEY OF EXPANSIVE MATERIALS IN THE UNITED STATES BY PHYSIOGRAPHIC AREAS

INTRODUCTION

1. The purpose of this study was to delineate physiographic areas within the continental United States which contain expansive materials and to describe the origin, mineralogy, geological relationships, and extent of these materials. The term expansive material as used herein defines a natural rock or soil which, due to its intrinsic and/or extrinsic nature, will exhibit some degree of volume change with variations in moisture conditions. Volume changes associated with mineral alteration and rebound are excluded.

2. This report concludes a study of the geological aspects of expansive soils presented in a previous report for the Federal Highway Administration (FHWA).[1] The initial report included an introduction into the geology and mineralogy of expansive soils and also presented distribution maps and listings of geologic formations which were believed to possess varying degrees of expansive properties. This report is concerned with a more detailed discussion of these geologic formations, their distribution, and a refinement of their relative expansiveness.

GEOLOGY OF EXPANSIVE ROCKS AND SOILS

3. Expansive rocks and soils are natural earth materials which, because of certain intrinsic and extrinsic characteristics, are subject to volume change with changes in their ambient environment. The change in volume consists of expansion caused by the intake of water, and shrinkage when moisture is removed by drying. In this report the term "expansive" is used to describe these materials; however, it should be borne in mind that shrinkage is a related phenomenon and may also be detrimental to structures.

4. Expansive materials comprise two distinct classes; sedimentary rocks and soils. Expansive sedimentary rocks include shales,* claystones, some siltstones, and other materials which are fine-grained, exhibit some degree of lithification, and possess the extrinsic and intrinsic properties which cause volume change.[2] Expansive soils may either be transported or residual. Transported expansive soils are, geologically, fine-grained, unlithified, argillaceous sediments having expansive properties. Residual expansive soils are soils having expansive properties and have originated by the in situ weathering of a parent material which may or may not have any expansive properties itself.

5. The intrinsic properties which affect the expansiveness of soils and rocks include type and amount of clay minerals, fabric, grain size distribution, cementation, and effects caused by deep burial, diagenesis, folding, and metamorphism. The clay mineralogy, grain size, and cementation are intrinsic properties which are important in affecting the volume change of both soils and rocks; whereas burial, folding, and metamorphism primarily affect the expansiveness of rocks.

6. The extrinsic properties are climate, particularly amount and distribution of rainfall; topography; depth; soil moisture; fluctuation of groundwater level; and the effects of man including compacted

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* The term "shale" is sometimes used as a general term for all clastic, fine-grained rocks including claystone, clayshale, siltstone, etc.

density, type of structure, and the drainage features related to the structure.

7. Those properties which are most important in affecting volume changes are the clay mineralogy and the aqueous environment. Clay mineralogical composition is critical because of the extremely expansive nature of certain clays, particularly montmorillonites. Since the expansion (or shrinkage) of these minerals results from the sorption (or removal) of water, the effects of the aqueous environment must also be evaluated to determine the degree of expansion which the materials may exhibit.

8. The intrinsic and extrinsic' properties of expansive materials briefly discussed above have been treated in more detail by Snethen et'al.[1] and the reader should consult this source for information on interrelations between the extrinsic and intrinsic factors. The following section deals with the mineralogical and petrological aspects of the problem which relate to the geology and distribution of expansive materials.

Mineralogy

9. The key to the distribution of expansive materials is the distribution of the clay mineral, montmorillonite.* This three-layer clay mineral possesses a structural configuration and chemical makeup which permit the sorption of larger quantities of water in interlayer and peripheral positions on the clay crystallite. The other clay minerals, kaolinite, illite, vermiculite, and chlorite, also exhibit some degree of expansiveness but the amount is much less than that of montmorillonite.[3]

10. Generally, the occurrence of montmorillonite is limited to

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* The term "montmorillonite," as used here, is defined as a dioctahedral clay mineral of the Smectite Group exhibiting limited substitution of magnesium for aluminum in the octahedral layer. In some classification schemes, montmorillonite is used as a group name for both dioctahedral and trioctahedral three-layer clay minerals.

rocks or transported soils which are of Mesozoic age or younger[4]. This is explained by the fact that montmorillonite is diagenetically unstable and tends to alter with time and deep burial to other less expansive clay minerals such as illite and chlorite or mixed-layer types. Thus, the Paleozoic and older rocks which have been buried or covered for many millions of years usually contain minor amounts of this mineral. Exceptions do occur such as the Ordovician K-bentonites of the Appalachian region and various Pennsylvanian and Permian lithologic units in the mid-continent and elsewhere. In any event, the presence of montmorillonite in rocks or transported sediments older than the Mesozoic is usually limited and the clay mineral itself generally occurs in an interlayer relationship with other clay minerals such as illite. Table 1 presents an estimate of the distribution of expansive clays, including mixed-layer types, with geologic time.[5]

11. The occurrence of montmorillonite in residual soils is controlled by the nature of the parent material and by climate. Ordinarily, climatic and drainage conditions which allow for the retention of silica and bases favor the formation of montmorillonite and other three-layer clay minerals.[6] Also, montmorillonite is the primary clay mineral constituent of residual soils formed upon parent material containing appreciable montmorillonite. The expansive effects of montmorillonite in residual soils are dependent upon the amount of montmorillonite present, the thickness of the soil, and the elevation of the roadway grade with respect to the soil profile.

12. Generally, the effects of expansive residual soils will be minimal with respect to large structures and Interstate Highways on parent materials which do not contain montmorillonite. However, smaller structures founded on residual soils containing montmorillonite derived from nonmontmorillonite-bearing parent material may be affected by subgrade expansion. The most serious problems occur on rocks and transported soils composed of montmorillonite. These materials are discussed in the following section.

Table 1

Estimates of the Percentage of Expandable Clay Present in Precambrain Through Pliocene Age Rocks (from Weaver[5])

Age	Percent
Pliocene	65
Miocene	65
Oligocene	50
Eocene	40
Upper Cretaceous	40
Lower Cretaceous	20
Turassic	20
Triassic	20
Permian	40
Pennsylvanian	30
Upper Mississippian	40
Lower Mississippian	5
Devonian	5
Silurian	5
Ordovician	15
Cambrian	~5
Precambrian	~5

Petrology

13. Petrology involves the internal relationships, texture, mineralogy, and origin of rocks or, in some cases, partially lithified sediments (transported soils).[7] Certain aspects of the petrology of expansive materials have been discussed,' including internal spatial relationships and texture. Mineralogy was discussed in the previous section of this report. This section will describe the rocklike or sedimentlike nature and the origin of expansive materials.

14. Hardness, durability, and strength determine whether argillaceous earth material should be classed as rock or soil. Generally, material which requires coring and does not disintegrate in contact with water is classed as rock. Weaker material which can be sampled by push-type tubes and slakes freely in water is classed as soil. The expansive sedimentary materials studied in this project included both types, although most of them would be classed as soils by engineers. Geologists, on the other hand, would call these materials "sediments" or possibly "weakly cemented, sedimentary rocks."

15. Sediments or sedimentary rocks which exhibit expansive properties are mainly elastic and fine-grained. This categorization would include materials composed principally of silt- and clay-size particles and would exclude rocks or sediments containing appreciable particles coarser than silt size and carbonate or evaporitic components. Thus, expansive sedimentary materials would be classed as shales, claystones, silts-tones, etc., if rocklike, and as argillaceous, clayey, or silty sediments if poorly lithified.

16. The exclusion of coarse clastic, carbonate, or evaporitic sedimentary rocks or sediments from the class of materials which may be expansive may not always be appropriate and will depend upon the relative amounts of montmorillonite, which may be present in sands, sandstones, limestones, marls, and other rocks or sediments. It will be shown later that some carbonate rocks and sediments containing montmorillonite exhibit expansive behavior which has resulted in considerable pavement damage.

17. The exhibition of expansive properties is undoubtably related, to a certain degree, to the extent that the materials are lithified. Lithification binds or cements the mineral constituents together and either prevents access of water or inhibits expansion if water is able to enter the material. Fine-grained, sedimentary rocks such as shales and siltstones may be lithified by the cementitious effects of mineral cements such as calcite, hematite, or silica, or the lithification may be due to interparticle bonds which developed during diagenesis. These interparticle bonds are called diagenetic bonds. Clay shales are most often lithified by diagenetic bonding, whereas the more permeable siltstones owe their lithification to mineral cements which have been introduced into the material. The mineral cements are also a result of diagenesis. This distinction between cement and diagenetic bonding has resulted in the use of the terms "cementation shales" and "compaction shales" in some classification schemes, wherein the modifier "compaction" relates to materials which have developed diagenetic bonds by the loading and compactive effect produced by the overlying sediments.

18. The expansive sediments and sedimentary rock owe their origin to the accumulation of detrital sedimentary particles in a depositional basin. The sedimentary environments of deposition were controlled by local physiographic and tectonic conditions existing at the time of deposition. These expansive materials occur in both marine and nonmarine sedimentary environments.

19. The detrital sedimentary particles such as the montmorillonite which is the source of the volume change problem are, in part, the result of weathering and climatic conditions in the source area and the depositional characteristics in the basin. The detrital particles may also have been affected by diagenesis, metamorphism, and tectonism after deposition.

20. Another source for the montmorillonite is through the diagenetic alteration of volcanic glass particles or shards which were deposited in the basin along with the material derived from weathering in the source area. This volcanic glass originated during volcanic eruptions either in or beyond the source area and was subsequently

carried by streams or by air currents to the depositional basin. After deposition the unstable, amorphous glass particles are altered by diagenesis to montmorillonite. This process is responsible for the commercial deposits of montmorillonite (bentonite) which occur in South Dakota, Wyoming, Montana, Mississippi, and many other states.

21. The montmorillonite present in noncommercial quantities in other fine-grained sedimentary rock formations also may have been derived from the alteration of volcanic glass which had accumulated in lesser amounts during times of decreased volcanic activity or from volcanic source areas more remote from the depositional basin.

22. The determination of a volcanic origin for montmorillonite found in sedimentary formations is based upon identification of volcanic glass fragments or relict outlines, or the identification of mineral grains commonly associated with volcanic activity. Some common volcanic minerals are sanidine, biotite, and singly terminated quartz.[8] Volcanic glass fragments and relict outlines may be seen in thin-sections and the volcanic minerals may be identified by microscope or by X-Ray diffraction (XRD).

23. It may be concluded that the presence of montmorillonite in expansive rocks and sediments (transported soils) is a function of (a) weathering and parent material in source area; (b) transportation to and within the basin of deposition; (c) vulcanism; (d) diagenesis; and (e) metamorphic and tectonic influences on the sediments in the basin. Also, these influencing factors relate more closely to environmental conditions at the time of deposition than to present environmental conditions. Thus, present climatic conditions are not usually useful indicators for determining the presence of montmorillonite in rocks or transported soils. Present environment is, however, an extrinsic factor which may affect the amount of expansion exhibited by the material and which also controls present-day weathering.

CATEGORIZATION OF EXPANSIVE MATERIALS

24. Any classification scheme for categorizing the distribution of expansive materials should be based upon a combination of intrinsic and extrinsic properties which may be related to observable field performance of highway subgrades and to actual amount of expansiveness exhibited by the material in a particular region. Such a classification, based upon useful properties, must take into account the wide extent of these materials throughout the United States and the fact that they are found in various climatic zones, and that they are associated with many diverse tectonic, geologic, physiographic, and geographic regions.

25. Further classificational complications arise when field performance and amount of expansion are considered. These result from a general lack of uniformity in methods of measuring subgrade performance and testing expansive materials. It is possible, however, to identify materials which have behaved the poorest with respect to subgrade performance and field expansion. Quantitative information such as percent volume change from a specified laboratory test or under uniform field loading conditions is not readily available. However, it is possible to classify materials on the basis of grain size, mineralogy, amount of fine-grained material within stratigraphic units, and geologic history of the area.

26. Witczak[9] discussed the occurrence and distribution of the expansive soils and expansive geologic units* in the continental United States and included an invaluable list of published and unpublished references. Witczak presented his information on expansive materials in terms of physiographic provinces but did not develop any causal or genetic relationships between occurrence and the physiographic province in which the materials are found.

27. Witczak[9] presented distribution maps which show the area1

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* The term "geologic unit" as used by Witczak and used in this report refers to either lithostratigraphic, time-stratigraphic, or geologic time units.

distribution of these materials in terms of a geologic basis, Figure 1, and a pedological basis, Figure 2. Information from these two map types were incorporated with climatic data to form a third map, Figure 3, which delineates areas which are susceptible to expansion problems. The susceptible areas were subdivided into five categories, based upon degree or likelihood of expansion problems to occur. These subcategories were mainly associated with physiographic provinces.[10] It should be emphasized here that Witczak's maps were based on geologic units upon which problems had occurred and on pedological soil classification data.. Thus, expansive geologic units for which there was no engineering experience may have been omitted and the significance of the. pedological soil (which may be quite thin) was not given. Nevertheless, Witczak's maps are a useful first approximation of the distribution and relative expansiveness of these materials.

28. Classification and categorization schemes such as Witczak's, including the one presented here, include a certain degree of bias or subjectivity because of several inherent uncertainties of classification. Probably the most significant uncertainty arises because of the lack of uniformly developed data on the amount of expansion exhibited by various expansive soils and rocks. Related to lack of swell data are questions concerning type and extent of damage and the type of structures which may be susceptible to a given amount of expansion. Also, in some areas there may be no experience on the expansiveness of the local rocks and soils where population densities are low or where there has been no construction of Interstate Highways or other primary roads.

29. The problems of classification and categorization may become more evident by briefly examining three specific materials of more' or less known character and comparing them and relating each to other associated materials in each respective area. The Pierre shale, Chinle Formation, and the Yazoo clay represent highly expansive materials all of which have been the cause of considerable pavement damage and have also been responsible for some structural damage in their respective areas. These three geologic units occur in widely separated parts of the country and are associated with different climatic zones and

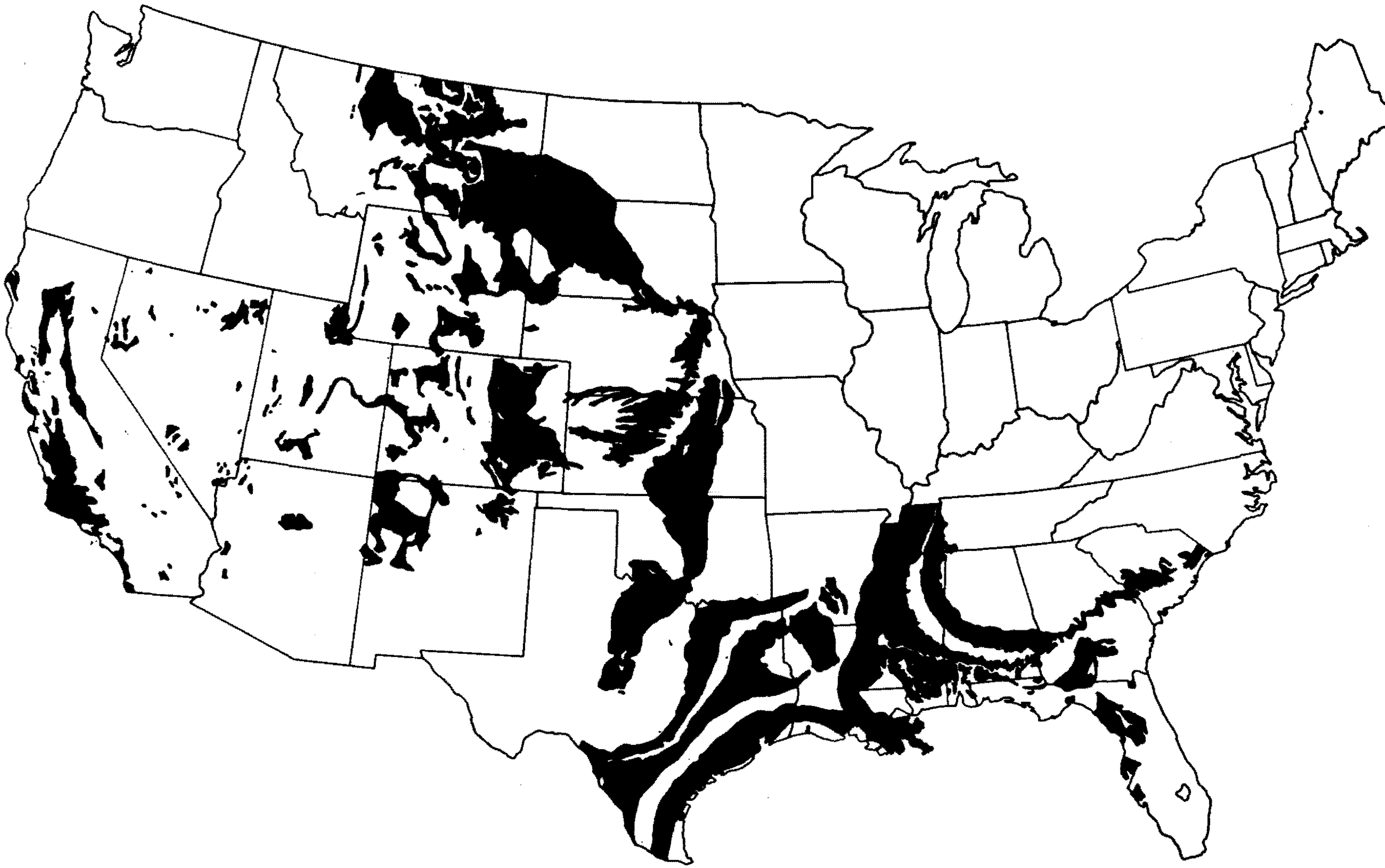

Figure 1. Di of general high volume change soil areas; geologic (from Witczak[9])

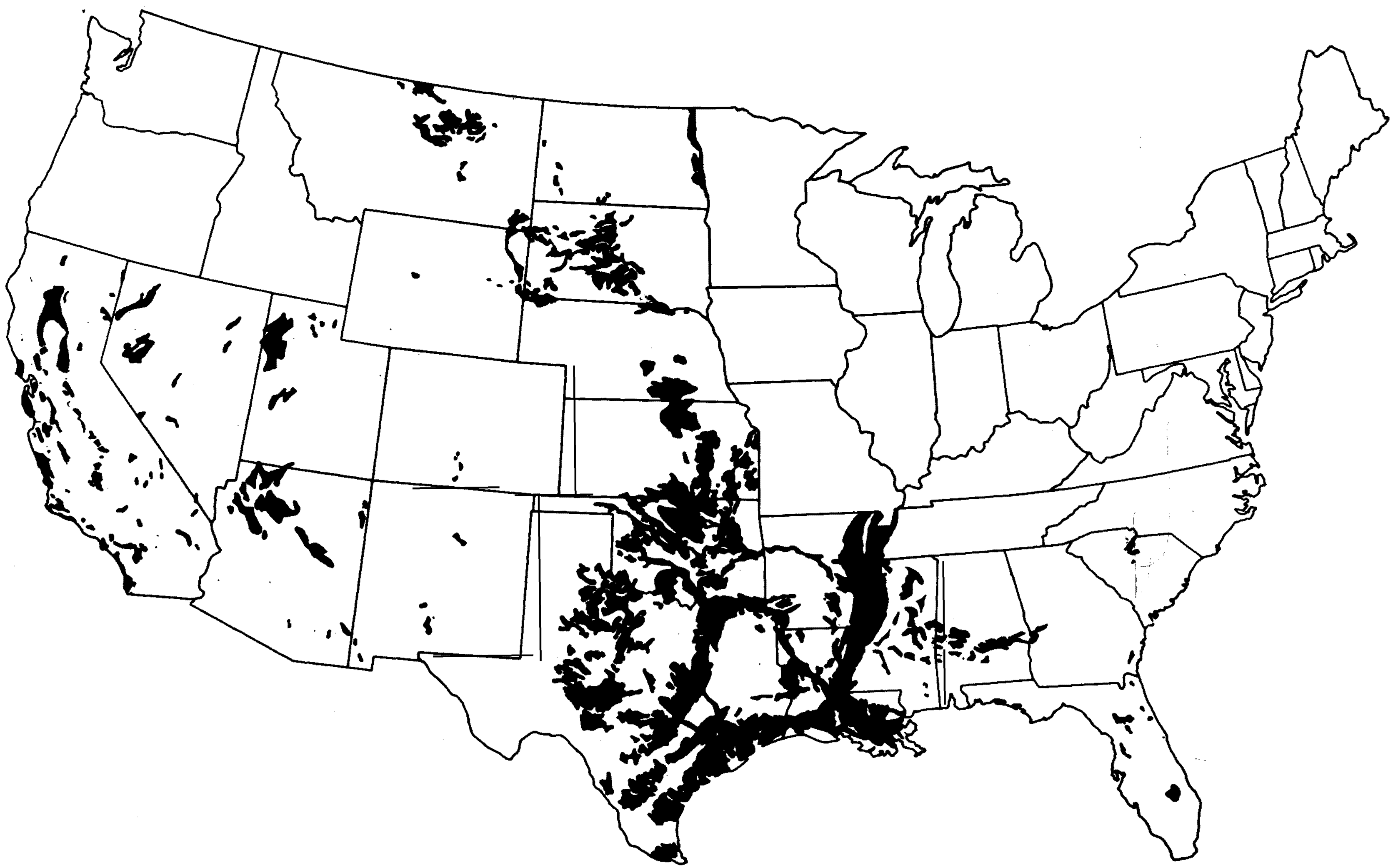

Figure 2. Distribution of general high volume change soil areas; pedologic analysis (from Witczak[9])

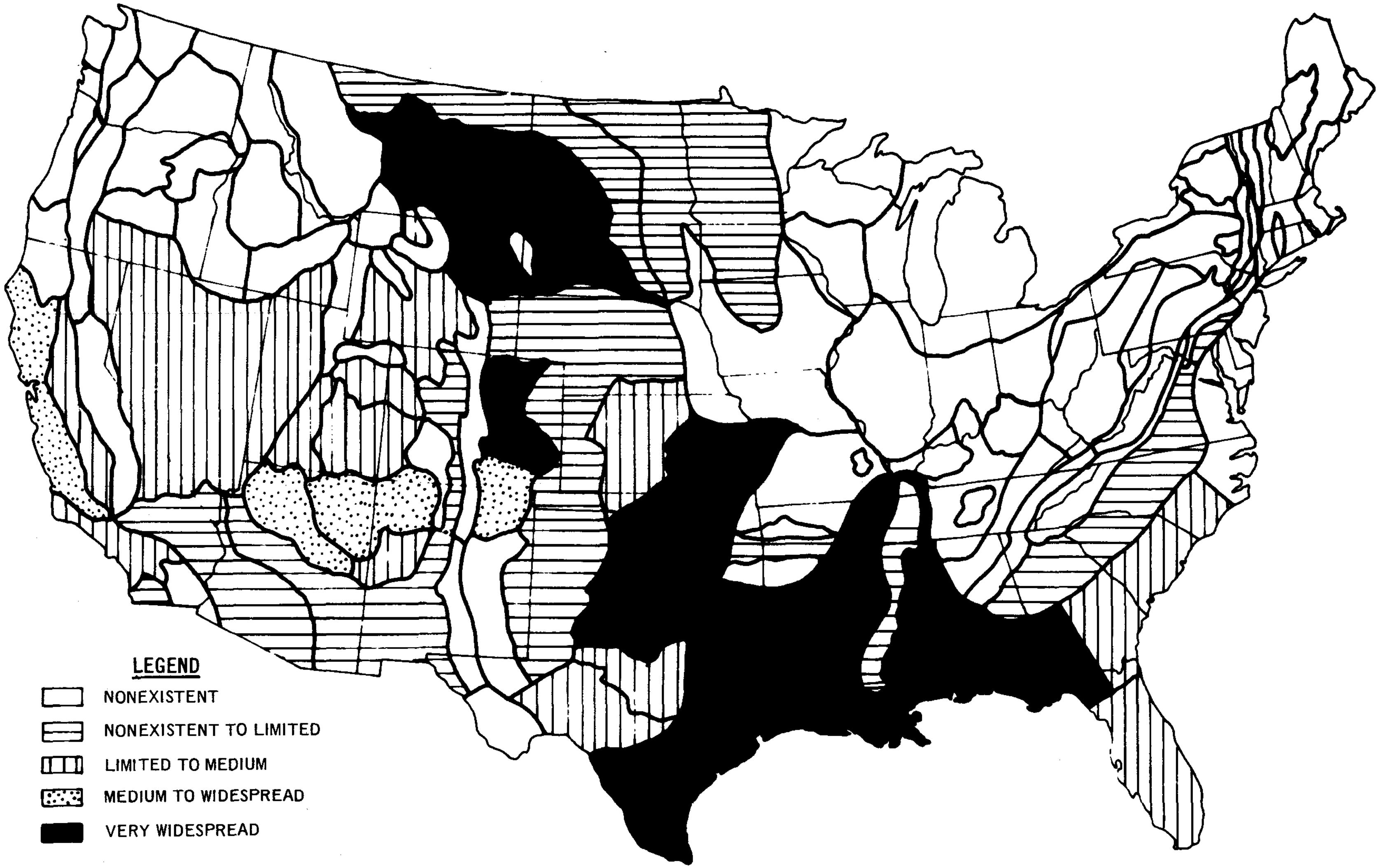

Figure 3. Estimated final adjusted frequency of occurrence rating of high volume change soils, by physiographic unit (from Witczak[9])

comprise more or less different geological environments. Table 2 lists significant characteristics of these three geologic units.

30. An examination of the data given in Table 2 reveals the diversity of general climatic indicators. The geological characteristics are also somewhat diverse, although clay mineralogy and perhaps depositional environment are common to the three units. In view of the diversity and complexity of the geologic, climatic, and performance characteristics of expansive materials, there appear to be no clear-cut factors here which relate these three units.

31. Another approach to identifying common factors is to examine these three materials from a regional standpoint to determine if these highly expansive materials are related spatially, chronologically, or genetically to other expansive materials in the respective regions. In the event that there is any relationship, it would then be possible to classify specific areas as to the extent and origin of expansive material, and possibly, to rate these areas with respect to field performance.

32. There are several ways in which specific regions can be identified and subdivided. Possible bases for subdivision are: climatic zones, major depositional or structural provinces, or physiographic provinces as Witczak has used.

33. The use of climatic zones for identifying and classifying expansive materials would appear to be useful in that such a classification scheme would provide limits on one of the most important extrinsic factors, the moisture regime.. On the other hand, this scheme possesses the disadvantage of not placing any limits on the material itself since a potentially expansive material may occur in several different climatic zones.

34. Depositional and/or structural provinces provide a basis for segregating materials on genetic bases which include source material, depositional environment, diagenesis, and tectonic history. Such a classification may, however, yield little information on climatic influences.

35. Classificational schemes which utilize physiography as a

Table 2

Characteristics of Three Expansive Materials

Characteristics	Chinle	Pierre	Yazoo
Geologic:			
Location	AZ, NM	SD., CO, MT	MS, LA
Age	Triassic	Cretaceous	Tertiary (Eocene)
Type of Material	Mudstone	Clay shale	Silty, sandy clay
Clay Mineralogy	Ca-montmorillonite	Sodium, calcium-montmorillonite	Calcium-montmorillonite
Depositional Environ	Deltaic (mixed, continental, and marine)	Marine	Marine
Physiographic Province	Colorado Plateau	Great Plains	Gulf Coast
Tectonic Province	Colorado Plateau	Williston Basin	Gulf Coast
Climatic:			
Mean Annual Precipitation	8-16 in.	8-16 in.	50 in.
Mean Annual Pan Evaporation	64-80 in.	48-80 in.	∿60 in.
Average Temperature (August)	∿70 deg F	70-80 deg F	>80 deg F
Average Temperature (January)	∿30 deg F	20-30 deg F	∿50 deg F

basis for area subdivision provide some restriction on climate and on the structural and depositional aspects of the materials within the province. This results from the fact that most physiographic province boundaries are based indirectly upon geologic structure and regional depositional patterns, and that some are small enough that the individual areal extent comprises a more or less distinct climatic zone.

36. Most existing physiographic land classifications are based upon differences in landform or topography in different areas. The differences in topography result from climatic differences between provinces and from the effects of different climates on different rock types and geologic structures and on different depositional environments. Thus, a physiographic province is defined as "a region all parts of which are similar in geologic structure and climate and which has consequently had a unified geomorphic history; a region whose pattern of relief features or landforms differs significantly from that of adjacent regions."[11]

37. Generally, it may be concluded from the preceding discussion that expansive materials in a particular area may be conveniently examined and categorized on a physiographic basis and subsequently compared to other expansive materials occurring in other areas. However, this conclusion should not be construed to necessarily mean that all of the rocks or soils in a particular physiographic province would be expected to exhibit the same degree of expansiveness or the same subgrade performance.

38. The first-order physiographic provinces (Figure 4) which contain the Yazoo, Chinle, and Pierre units are respectively, the Atlantic and Gulf Coastal Plains Provinces, Colorado Plateau, and Great Plains. These provinces also contain varying amounts of other units which are also expansive, though to a lesser degree. Genetic relationships between these other expansive units and the highly expansive ones mentioned above result from the following conditions: (a) similar environments, (b) similar source areas, and (c) similar geologic histories.

39. Large areas of the Great Plains Province, including the

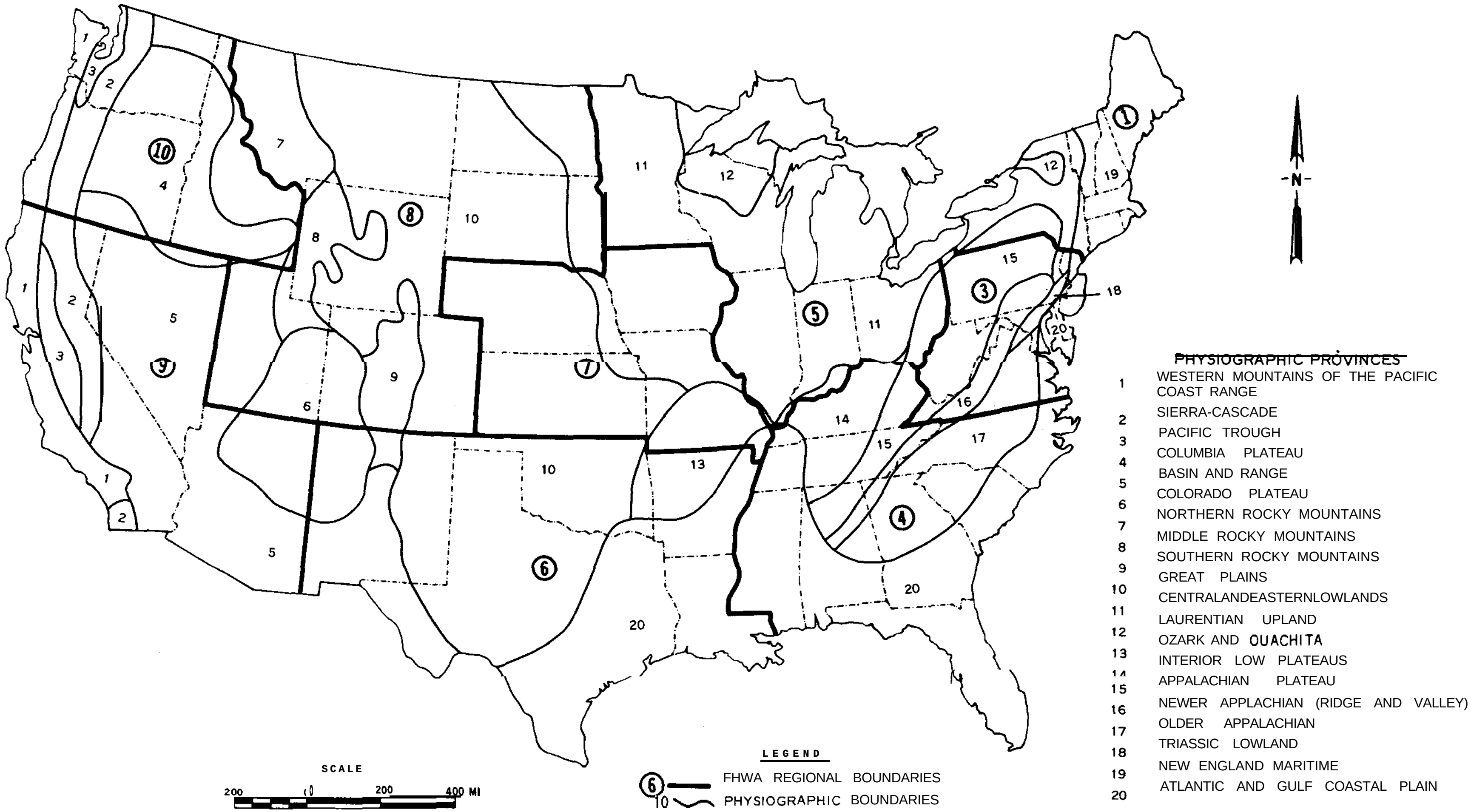

Figure 4. First-order physiographic provinces within-the continental United States (from Atwood[10])

Pierre outcrop areas and the outcrop areas of other units, exhibit expansiveness because of the widespread marine environments which occurred during the Upper Cretaceous time, the nearness to volcanic areas to the west, and the minimal amount of tectonism during subsequent geologic time. Areas which contain relatively nonexpansive material (including nonexpansive Pierre) do so because of the different environmental situations at the time of deposition. Flat topography and the characteristic low dip angles of these units also contribute to their widespread occurrence.

40. Although the Colorado Plateau Province contains the troublesome Mancos and Chinle units, the region as a whole is not particularly expansive. Environmental conditions are responsible for this since the area contains considerable thickness of granular, continental deposits. The Mancos unit is related in time to the shales of the Colorado Group (which includes the Pierre) in the Great Plains Province, which indicates the possibility of environmental similarities between the Mancos unit and the Colorado Group. The Chinle unit does not have extensive expansive time-equivalents in other provinces to which it can be compared and within the plateau area the Chinle itself exhibits sand and carbonate facies. The localization of expansive Chinle shale along the southern part of the plateau is due to a distinct sedimentary environment during the Triassic Period.

41. In the Atlantic and Gulf Coastal Plains Provinces, depositional environments and volcanic activity also have a dominant influence on the presence of expansive materials. Environmental controls determine the areas of expansive behavior of the Yazoo clay which is highly argillaceous with some carbonate to the west and becomes more carbonate-rich to the east, The presence of commercial bentonites in the Vicksburg Group indicates the influence of volcanic activity in this area. Generally, those areas which are much less expansive are so because of the presence of higher energy environments. The sediments found in this province are relatively young and undeformed, thereby, favoring the preservation of montmorillonite.

BASES FOR CLASSIFICATION

42. The categorization and classification methods used in this report are basically the same as those of Snethen et al.[1] The methods are subjective and are based upon the estimated volume change of argillaceous materials within the geologic unit, the presence of montmorillonite, geologic age, and reported problems due to expansive materials. The approach used is essentially geologic in that stratigraphy and mineralogy are considered to be key elements. Pedology on the other hand is not considered to be as important regionally, although it may have local significance.

43. The distribution of expansive materials is categorized by geologic unit on the basis of: (a) degree of expansiveness and (b) expected frequency of occurrence. The degree of expansiveness relates to the expected presence of montmorillonite whereas the frequency of occurrence involves the amount of clay or shale in the geologic unit. Three major sources of information formed the bases for classificational decisions:

a. The reported occurrences of expansive materials as indicated in published literature or other sources of data which revealed actual problems or failures due to expansive materials.[9] These sources were not necessarily limited to highway subgrades.

b. Materials maps provided summaries of illustrated earth material properties pertinent to this study.[12] These materials maps were used to delineate areas of argillaceous materials, and the soils surveys were used to substantiate suspected occurrences of expansive materials.

c. Geologic maps and cross sections were used to identify and delineate areas of argillaceous rocks and sediments which were believed to possess expansive properties.[13-21]

44. These three general sources were combined to produce four mapping categories that reflect the degree of expansiveness in terms of volume change and expected frequency of occurrence. The four categories are as follows:

a. High. Highly expansive and/or high frequency of occurrence.

b. Medium. Moderately expansive and/or moderate frequency of occurrence.

c. Low. Generally of low expansive character and/or low frequency of occurrence.

a. Nonexpansive. These areas are mainly underlain by materials which, by their physical makeup, do not exhibit expansive properties and which, upon weathering, do not develop expansive soils.

45. The following premises guided the map categorization:

a. Any area underlain by argillaceous rocks, sediments, or soils will exhibit some degree of expansiveness.

b. The degree of expansiveness is a function of the amount of expandable clay minerals present.

c. Generally, the Mesozoic and Cenozoic rocks and sediments contain significantly more montmorillonite than the Paleozoic (or older) rocks.

d. Areas underlain by rocks or sediments of mixed textural compositions (e.g., sandy shales or sandy clays) or shales or clays interbedded with other rock types or sediments are considered on the basis of geologic age and the amount of argillaceous material present.

e. Generally those areas lying north of the glacial boundary are categorized as nonexpansive due to the cover of glacial drift. Whether the drift itself is expansive is a function of drift texture and the mineralogy of the source material. The till deposited in Montana and the Dakotas is partially composed of material derived from expansive, Cretaceous shales in this region; thus this till may show considerably more expansive properties than tills in other regions. Also, the argillaceous sediments deposited in Pleistocene lakes may be of such texture and mineralogy that they also possess limited expansive properties.

f. From a regional standpoint, those soils derived from the the weathering of igneous and metamorphic rocks are considered nonexpansive. Such soils may contain some expansive clay minerals but their concentration and the general soil texture preclude appreciable volume change. Also, in temperate areas such soils are usually limited in thickness.

g. The categorization does not consider climate or other environmental aspects. These subjects will be addressed in a later report.

h. Argillaceous rocks or sediments orginally composed of expandable-type clay minerals do not exhibit significant volume change when subjected to tectonic folding, deep burial, or metamorphism.

1. Volcanic areas consisting mainly of extruded basalts and kindred rocks may also contain tuffs and volcanic ash deposits which have devitrified and altered to montmorillonite.

j. Areas along the glaciated boundary may have such a thin cover of drift that the expansive character of the materials under the drift may predominate.

46. The twenty first-order physiographic provinces are shown in Figure 4. The occurrence and distribution of expansive material by FHWA regions are shown in Figures 5-9, and the potentially expansive geologic units are summarized in Table 3. A narrative description of expansive materials within each of the physiographic provinces is presented in the subsequent section of the report.

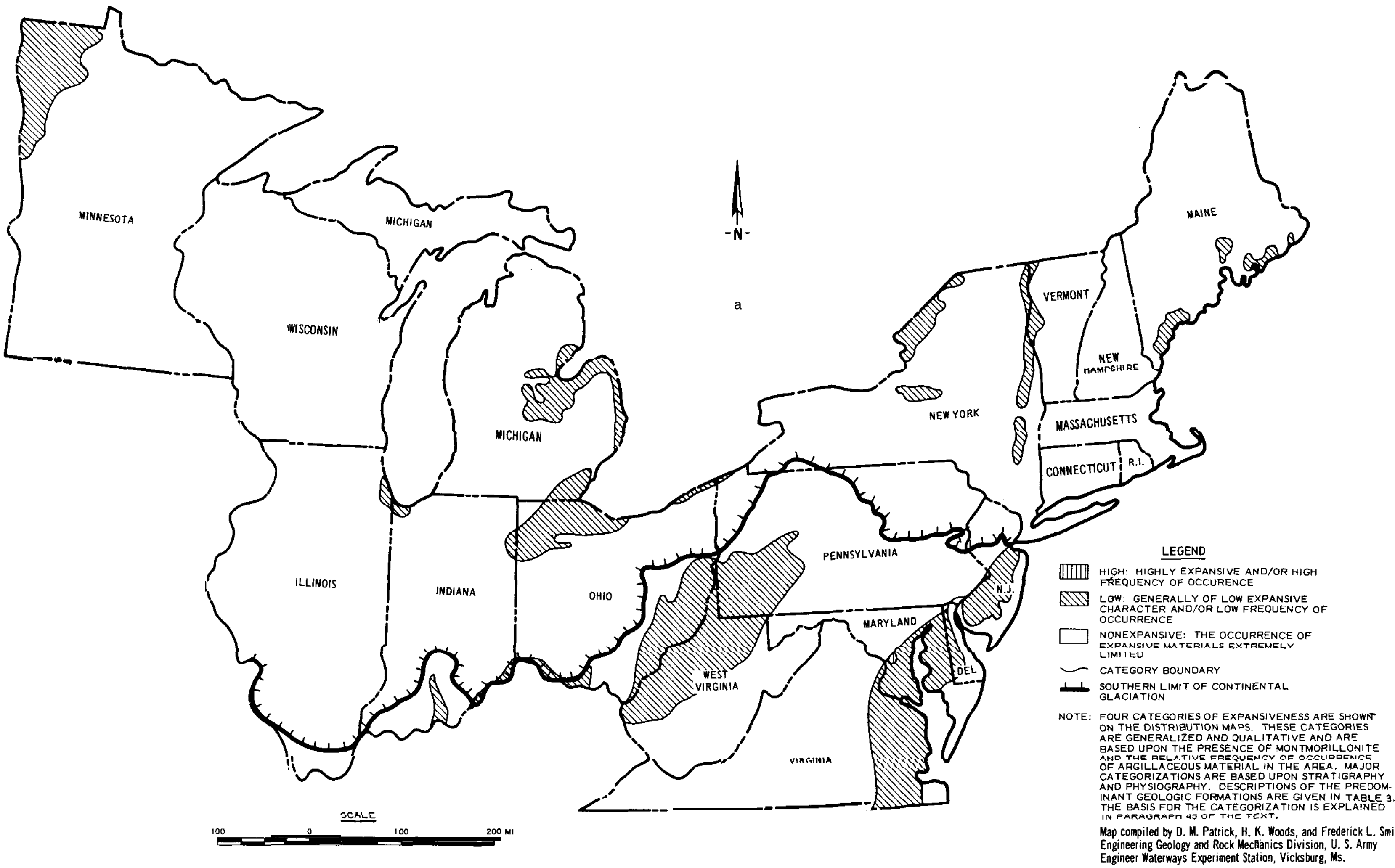

Figure 5. Distribution of potentially expansive materials in the United States; FHWA Regions 1, 3, and 5

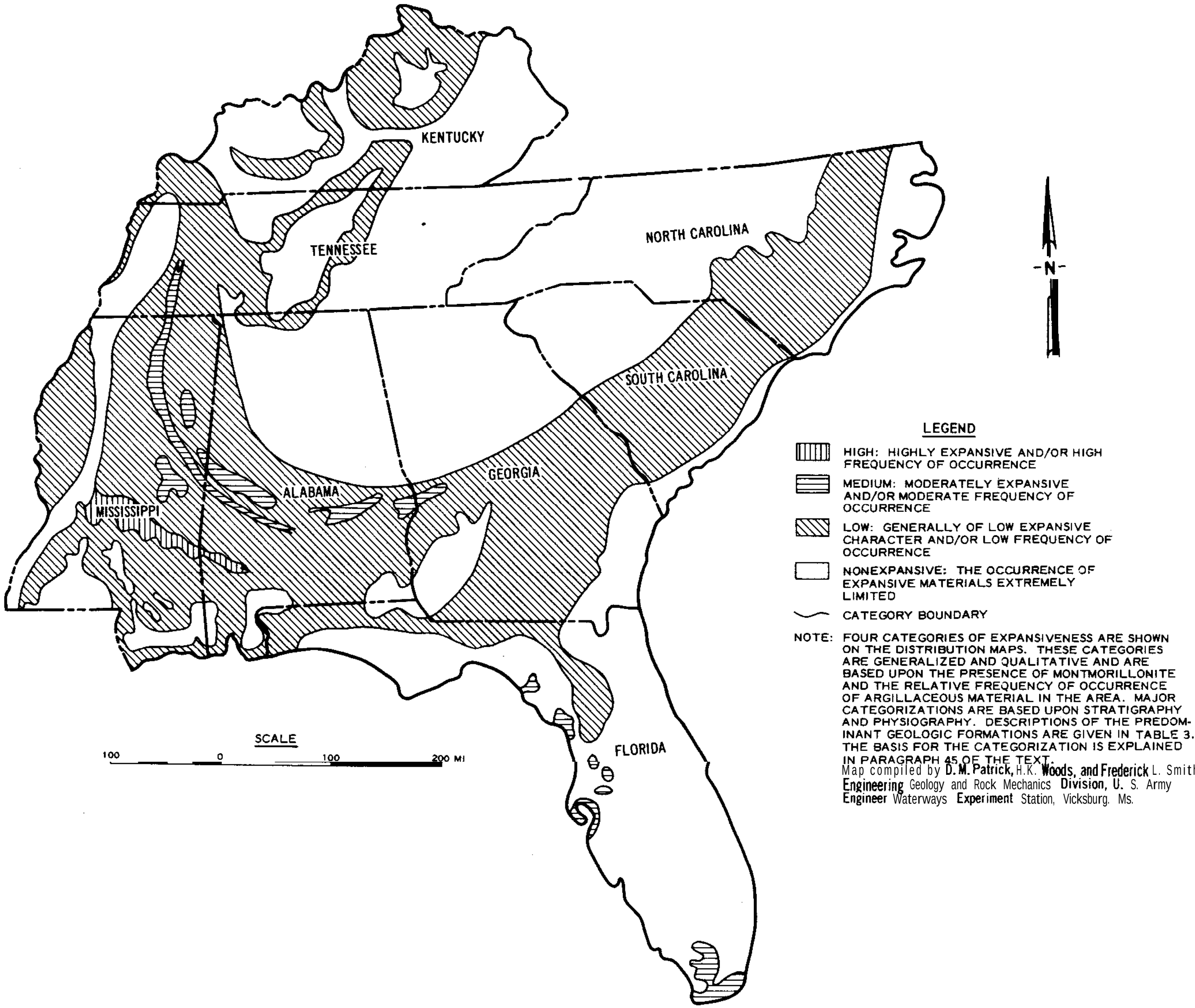

Figure 6. Distribution of potentially expansive materials in the United States; FHWA Region 4

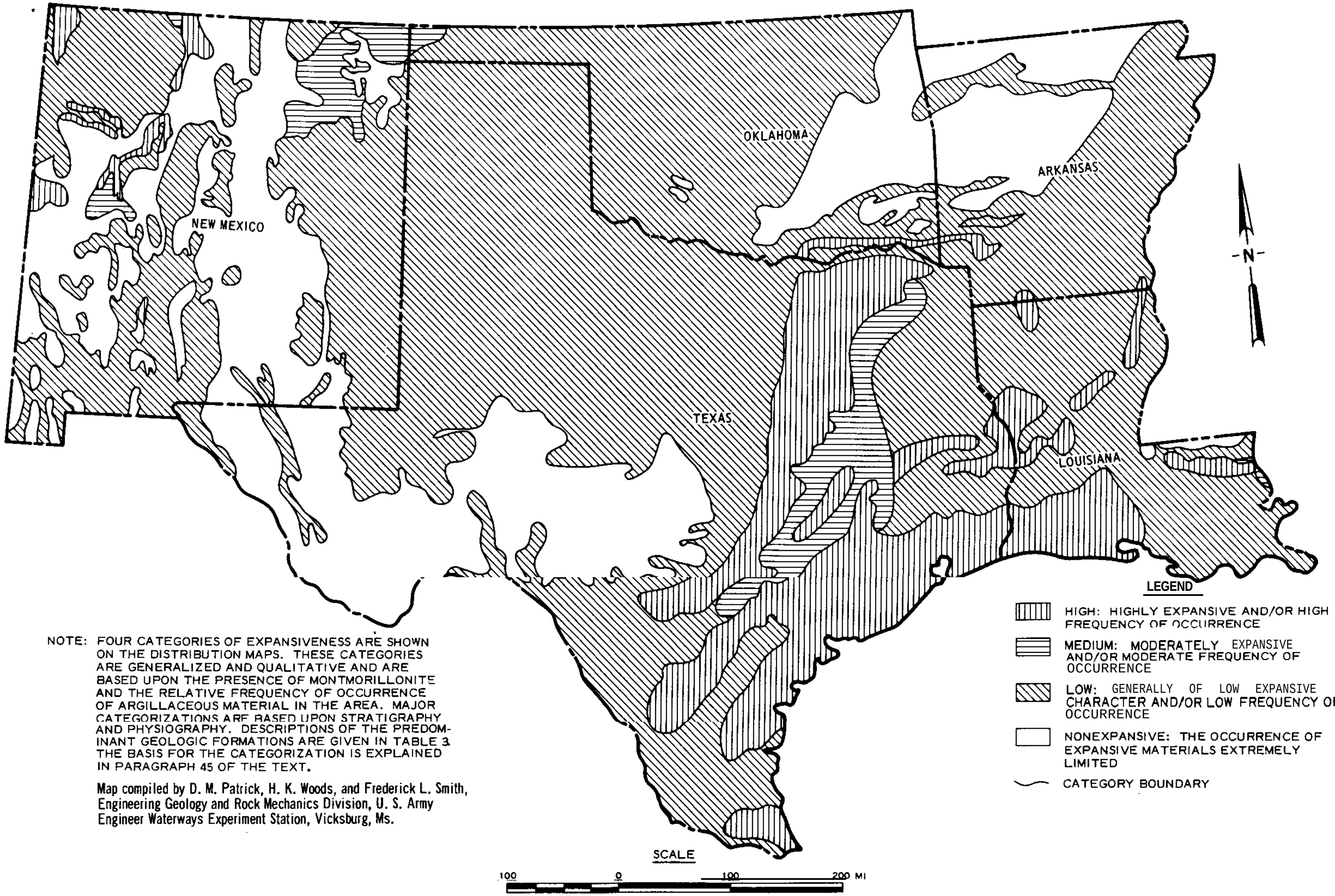

Figure 7. Distribution of potentially expansive materials in the United States; FHWA Region 6

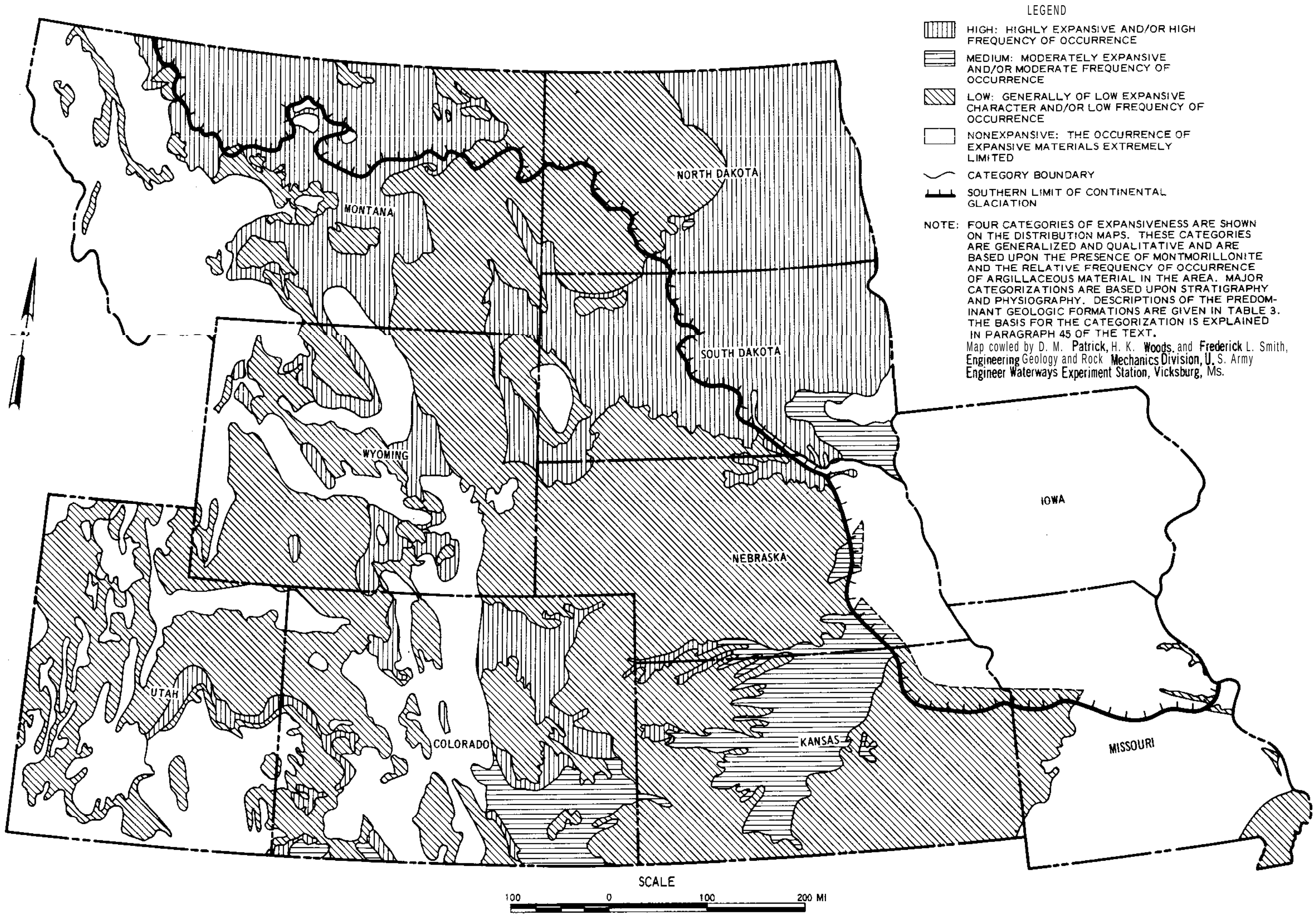

Figure 8. Distribution of' potentially expansive materials in the United States; FHWA Regions 7 and 8

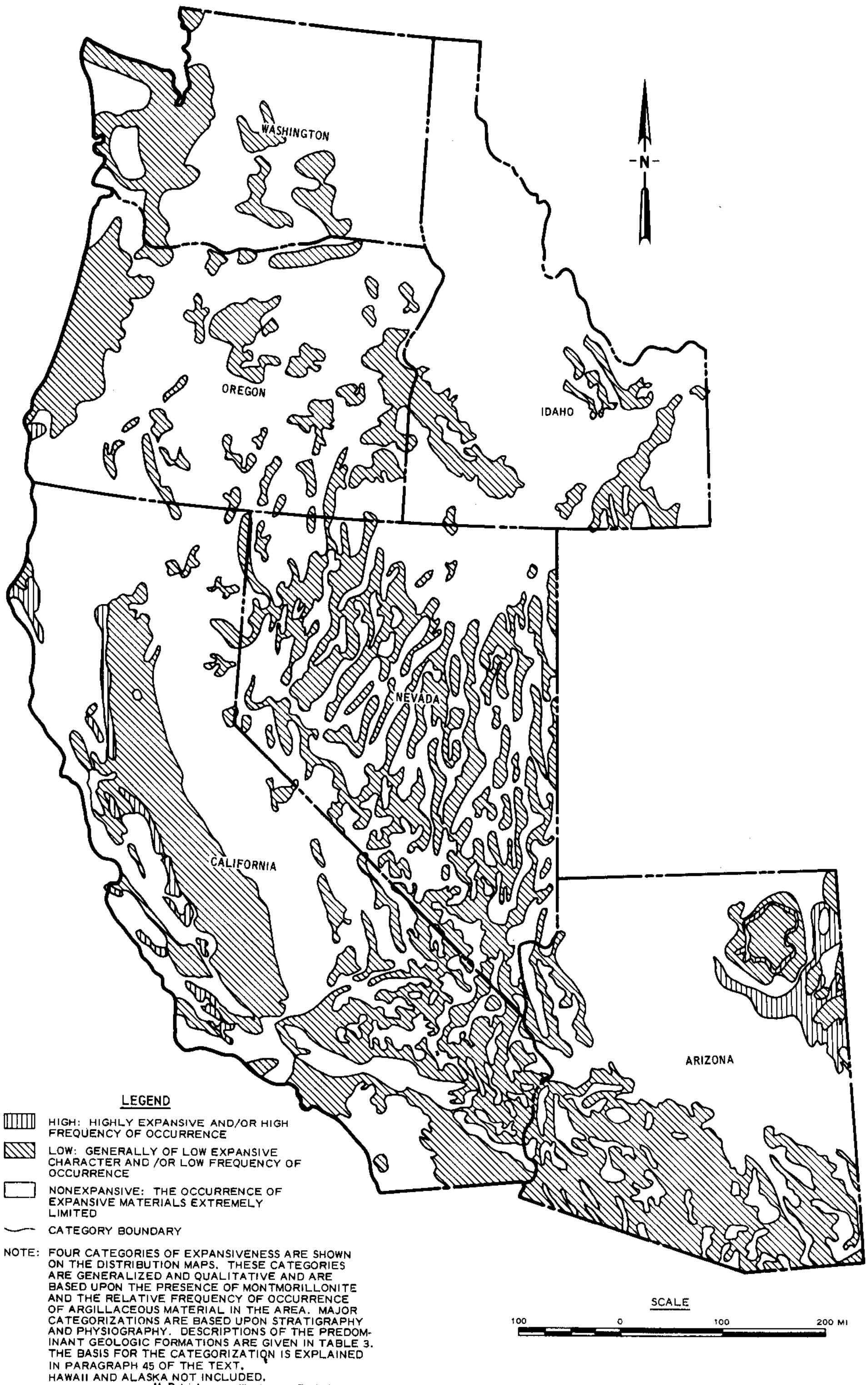

Figure 9. Distribution of potentially expansive materials in the United States; FHWA Regions 9 and 10

Table 3

Tabulation of Potentially Expansive Materials in the United States

Physiographic Province No.*	Physiographic Province Name	Predominant Geologic Unit	Geologic Age	Location of Unit	Map** Category	Remarks
1	Western Mountains of the Pacific Coast Range	Reefridge	Miocene	CA	1	The Tertiary section generally consists of interbedded sandstone, shale, chert, and volcanics
		Monterey	Miocene	CA	1	
		Rincon	Miocene	CA	1	
		Tembler	Miocene	CA	1	
		Umpqua	Paleocene-Eocene	OR	3	
		Puget Gp	Miocene	WA	3	Interbedded sandstones and shales with some coal seams
		Chico Fm	Cretaceous	CA	1	
2	Sierra Cascade	Cascade Gp	Pliocene	OR	4	Predominate material is volcanic
		Columbia Gp	Miocene	WA	4	Interbedded sandstones and shales may occur throughout, particularly in western foot hills
		Volcanics	Paleozoic to Cenozoic	NV	4	
		Volcanics	Paleozoic to Cenozoic	CA	4	
3	Pacific Trough	Troutdale	Pliocene	WA	3	Great Valley materials characterized by local areas of low-swell potential derived from bordering mountains. Some scattered deposits of bentonite
		Santa Clara	Pleistocene	CA	3	
		Riverbank	Pleistocene	CA	3	
4	Columbia Plateau	Volcanics	Cenozoic	WA, OR, ID, NV	4	Some scattered bentonites and tuffs
5	Basin and Range	Valley fill materials	Pleistocene	OR, CA, NV, UT, AZ, NM, TX	3	Playa deposits may exhibit limited swell potential. Some scattered bentonites and tuffs
		Volcanics	Tertiary	OR, CA, NV, UT, AZ, NM, TX		
6	Colorado Plateau	Greenriver	Eocene	CO, UT, NM	3	
		Wasatch	Eocene	CO, UT, NM	3	
		Kirkland shale	Upper Cretaceous	CO, UT, NM, AZ	2	Interbedded sandstones and shales
		Lewis shale	Upper Cretaceous	CO, UT, NM, AZ	2	
		Mancos	Upper Cretaceous	CO, UT, NM, AZ	1	
		Mowry	Upper Cretaceous	CO, UT, NM, AZ	1	
		Dakota	Jurassic-Cretaceous	CO, UT, NM, AZ	3	Interbedded sandstones and shales
		Chinle	Triassic	NM, AZ	1	

(Continued)

* Refer to map of physiographic provinces, Figure 4.

** Numerical map categories correspond as follows: 1 = high expansion, 2 = medium expansion, 3 = low expansion, and 4 = nonexpansive.

Table 3 (Continued)

Physiographic Province No.	Name	Predominant Geologic Unit	Geologic Age	Location of Unit	Map Category	Remarks
7	Northern Rocky Mountains	Montana Gp	Cretaceous	MT	1	Locally some sandstone and siltstone
		Colorado Gp	Cretaceous	MT	2	Locally some siltstone
		Morrison	Jurassic	MT	3	Shales, sandstones, and limestones
		Sawtooth	Jurassic	MT	3	
8	Middle Rocky Mountains	Windriver	Eocene	WY, MT	3	
		Fort Union	Eocene	WY, MT	3	
		Lance	Cretaceous	WY, MT	1	
		Montana Gp	Crgtaceous	WY, MT	1	
		Colorado Gp	Cretaceous	WY, MT	2	
		Morrison	Jurassic-Cretaceous	WY, MT	3	
9	Southern Rocky Mountains	Metamorphic and granitic rocks	Precambrian	WY	4	Montana and Colorado Gps may be present locally with some Tertiary volcanic and minor amounts of Pennsylvania lime-stone (sandy or shaly).
		Metamorphic and granitic rocks	Precambrian	CO	4	
		Metamorphic and granitic rocks	Precambrian to Cenozoic	NM	4	
10	Great Plains	Fort Union	Paleocene	WY, MT	3	
		Thermopolis	Cretaceous	WY, MT	1	
		Montana Gp	Cretaceous	WY, MT, CO, NM	1	
		Colorado Gp	Cretaceous	WY, MT, CO, NM	2	
		Mowry	Cretaceous	WY, MT, CO, NM	1	
		Morrison	Jurassic-Cretaceous	WY, MT, CO, NM	3	
		Ogallala	Pliocene	WY, MT, CO, NM, SD, NE, KS, OK, TX	3	Generally nonexpansive but bentonite layers are locally present
		Wasatch	Eocene	MT, SD	3	
		Dockum	Triassic	CO, NM, TX	3	
		Permian Red Beds	Permian	KS, OK, TX	3	
		Virgillian Series	Pennsylvanian	NE, KS, OK, TX, MO	3	
		Missourian Series	Pennsylvanian	KS, OK, TX, MO	3	
		Desmonian Series	Pennsylvanian	KS, OK, TX, MO	3	
11	Central and Eastern Lowlands	Glacial lake deposits	Pleistocene	ND, SD, NM, IL, IN, OH, MI, NY, VT, MA, NE, IA, KS, MO, WI	3	Some Paleozoic shales locally present which may exhibit low swell

(Continued)

Table 3 (Continued)

Physiographic Province No.	Physiographic Province Name	Predominant Geologic Unit	Geologic Age	Location of Unit	Map Category	Remarks
12	Laurentian Uplands	Keweenawan	Precambrian	NY, WI, MI	4	Abundance of glacial material of varying thickness
		Huronian	Precambrian	NY, WI, MI	4	
		Laurentian	Precambrian	NY, WI, MI	4	
13	Ozark and Ouachita	Fayetteville	Mississippian	AR, OK, MO	3	May contain some montmorillonite in mixed layer form
		Chickasaw Creek	Mississippian	AR, OK, MO	3	
14	Interior Low Plains	Meramac Series	Mississippian	KY	3	
		Osage	Mississippian	KY, TN	3	
		Kinderhook	Mississippian	KY, TN	3	
		Chester Series	Mississippian	KY, IN	3	Interbedded shale, sandstone, and limestone
		Richmond	Upper Ordovician	KY, IN	3	
		Maysville	Upper Ordovician	KY, IN	3	
		Eden	Upper Ordovician	KY, IN	3	
15	Appalachian Plateau	Dunkard Gp	Pennsylvanian-Permian	WV, PA, OH	3	Interbedded shale, sandstone, limestone, and coal
16	Newer Appalachian	See Remarks	See Remarks	AL, GA, TN, NC, VA, WV, MO, PA	4	A complex of nonexpansive Precambrian and Lower Paleozoic metasedimentary and sedimentary rocks
17	Older Appalachian	See Remarks	Paleozoic	AL, GA, NC, SC, VA, MD	4	A complex of nonexpansive metamorphic and intrusive igneous rocks
18	Triassic Lowland	Newwark Gp	Triassic	PA, MD, VA	4	
19	New England Maritime	Glacio-marine deposits	Pleistocene	ME	3	Pleistocene marine deposits underlain by nonexpansive rocks. Local areas of clay could cause some swell potential
20	Atlantic and Gulf Coastal Plain	Talbot and Wicomico Gps	Pleistocene	NC, SC, GA, VA, MD, DE, NJ	4	Interbedded gravels, sands, silts, and clays
		Lumbee Gp	Upper Cretaceous	NC, SC	3	Sand with intermixed sandy shale
		Potomac Gp	Lower Cretaceous	DC	3	Sand with definite shale zones
		Arundel Fm	Lower Cretaceous	DC	1	
		Continental and marine coastal deposits	Pleistocene to Eocene	FL	4	Sands underlain by limestone, local deposits may show low swell potential

(Continued)

Table 3 (Concluded)

Physiographic Province No.	Physiographic Province Name	Predominant Geologic Unit	Geologic Age	Location of Unit	Man Category	Remarks
20	Atlantic and Gulf Coastai Piain (Cont'd)	Yazoo Clay	Eocene	MS, LA	1	A complex interfacing of gravel, sand, silt, and clay. Clays show varying swell potential
		Porters Creek Clay	Paleocene	MS, AI, GA	l-3	
		Seima Gp	Cretaceous	MS, AI, GA	2-3	
		Loess	Pleistocene	LA, MS, TN, KY	4	A mantle of uniform silt with essentially no swell potential
		Mississippi alluvium	Recent	LA, MS, AR, MO	3	Interbedded stringers and lenses of sands, silts, clays, marl, and chalk
		Beaumont-Prairie Terraces	Pleistocene	LA, MS, TX	1	
		Jackson, Claiborne, Midway	Paleocene-Oligocene	LA, MS	l-3	
		Navarre, Taylor, Austin	Upper Cretaceous	TX	l-2	
		Eagleford, Woodbine	Upper Cretaceous	TX	3	
		Washita	Lower Cretaceous	TX, OK	l-3	
		Fredricksburg	Lower Cretaceous	TX	3	
		Trinity	Lower Cretaceous	TX	4	

DISTRIBUTION OF EXPANSIVE MATERIALS BY PHYSIOGRAPHIC PROVINCE

47. In this section the twenty first-order physiographic provinces are discussed in terms of the potentially expansive materials within them. The general lithology, geologic age, stratigraphic association, and mineralogy (if known) are presented and the relative degree of expansiveness estimated. The narrative descriptions should be used in conjunction with Figures 4-9 to qualitatively indicate the extent of potentially expansive materials.

Western Mountains of the Pacific Coast Range Province(l)

48. This physiographic province extends along the Pacific coast from Washington State to California and consists mainly of a series of mountains termed the "Coast Ranges." These mountains are made of folded and faulted Tertiary rocks lying on a Mesozoic and older basement. The lithologies represented by these Tertiary materials include most sedimentary rock types and some igneous and metamorphic material. The Tertiary sequence in the Coast Ranges of Washington State consists of more or less alternating sandstones, shales, and volcanics.[19] The relatively subordinate amount of shale suggests the classification as low. The Tertiary materials in Oregon which may pose limited problems due to expansiveness are confined mainly to Paleocene and Eocene age strata. This sequence consists of shale and sandstone with some interbedded volcanics[19] and is classified as low. In California the potentially expansive materials in this province are mainly restricted to the Upper Cretaceous Chico Formation and portions of the Eocene and Miocene series.[17] Significant Eocene and Miocene units are respectively, the Anita and Cozy Dell shales and the Reef Ridge and Rincon shales. The intermontane Quaternary alluvial deposits may also exhibit expansive properties. The Chico Formation is classified as high and the Tertiary and Quaternary materials are classified as low.

Sierra-Cascade Province(2)

49. This physiographic province lies to the east of the Coast Ranges in Washington and extends south through Oregon into California where it terminates at the Transverse Ranges (an extension of the Coast Ranges). The province continues south of the Transverse Ranges and continues into Baja, California. The materials in the province are considered to be mainly nonexpansive and include a wide variety of intrusive and extrusive igneous, metamorphic, and deformed sedimentary rocks.[17,19]

Pacific Trough Province(3)

50. This physiographic province is a large, noncontinuous, alluvium-filled valley between the Coast Ranges and the Sierra-Cascade Province.[17,19] The valley extends south from Puget Sound to Eugene, Oregon. In California, the valley's northern end is at the Klsmath Mountains and extends south to the Transverse Ranges. In Washington and Oregon, the Quaternary valley materials are mainly granular and are classed as low. The Great Valley of California also contains Quaternary alluvial gravel but the gravels are underlain by Jurassic and Cretaceous shale and sandstone, which outcrop along the margins of the valley. The alluvial fill material in the valley consists predominantly of sand and gravel but finer grained silts and clays may be locally abundant.[22,23] The alluvium is classified as low and the Cretaceous rocks are classified high.

Columbia Plateau Province(4)

51. This physiographic province occupies portions of Washington State, Oregon, Nevada, and northwestern Wyoming. The rocks in these areas consist primarily of volcanic igneous materials of Tertiary and Quaternary age.[15,19] The volcanics are classified as nonexpansive. These volcanics are locally overlain by Quaternary clastic material of

alluvial origin which may contain sufficient fine-grained interbeds or volcanically derived material to warrant classification as low.

Basin and Range Province(5)

52. This physiographic province occupies most of Nevada and portions of Oregon, California, Utah, Idaho, Arizona, New Mexico, and Texas. The region is characterized by uplifted, fault-bounded mountain blocks separated by valley areas containing lacustrine and alluvial materials derived from erosion of the adjacent mountains.[17,20] The mountain blocks consist of a diverse lithologic assemblage of igneous, sedimentary, and metamorphic rocks. Probably the most common surface rocks, in decreasing frequency of occurrence, are Tertiary volcanics; Paleozoic carbonates; Mesozoic carbonates, sandstone, and shale; and Precambrian igneous and metamorphic rocks. Although the volcanic rocks may locally contain some tuffs and related glassy rocks which may be montmorillonitic, the mountain block areas are classified as nonexpansive. The materials in the intermontane valleys are mainly Quaternary in age and consist primarily of sand and gravel with subordinate amounts of clayey silts and occasional bentonite deposits.[24-28] The finer grained material usually occurs either in alluvial deposits, considerably beyond the peripheries of the mountain blocks where coarser material is deposited, or in lacustrine areas. The bentonite is usually restricted to the lacustrine environments. The occurrence of the fine-grained material may locally be quite extensive such as in the depositional areas of the former Pleistocene Lake Searles in southern California, Bonneville in Utah, and Lahontan in Nevada and California.[12] These lake deposits may, however, contain carbonates and evaporites as well as active clays. The overall classification of these alluvial and lacustrine deposits is low.

Colorado Plateau Province(b)

53. The Colorado Plateau Physiographic Province encompasses southeast Utah, southwest Colorado, northwest New Mexico, and northeast

Arizona. Structurally, the strata are relatively undeformed and flat lying. The greater proportion of the exposed stratigraphic section ranges in age from Permian to Tertiary, and the units which possess expansive properties are Triassic, Cretaceous, and Tertiary in age,[20] The Permian units are predominantly limestone and sandstone with minor shale and the Jurassic units consist predominantly of sandstone and'very minor occurrences of shale and limestone. The Permian and Jurassic areas are classified as nonexpansive.

Triassic

54. Triassic units mainly occur in Arizona and Utah. The sequence bears some relationship to the Permian "Red Bed" association in Texas and Oklahoma in that red shales and reddish coarser clastics are conspicuous. These Triassic rocks consist of the progressively older Wingate sandstone, Chinle shale, Shinarump conglomerate, and Moenkopi Formation. The Chinle shale is a red to grey, highly argillaceous mudstone or shale containing some sandy facies.[12] This shale is mapped as highly expansive throughout the Colorado Plateau although the most serious problems with it have occurred in eastern Arizona.

Cretaceous

55. The lower Cretaceous Dakota Formation and the youngest portion of the upper Cretaceous consist mainly of coarse clastics with some shale. These units are mapped as low. However, the lower upper Cretaceous Mancos Formation which is roughly equivalent to the Colorado Group of the Great Plains Province is locally highly argillaceous and is classified as highly expansive.[12] The Mancos shale contains some sandy facies and extends around the north side of the Colorado Plateau in Utah and Colorado.

Tertiary

56. Tertiary units on the Colorado Plateau consist of a diverse sequence of coarse elastics, clays, limestone, coal, and volcanics (including some bentonites). These materials are mainly alluvial and lacustrine deposits derived from the erosion of uplifted areas within but mainly peripheral to the province. Their origin and nature are quite similar to the Tertiary units in the Great Plains Province. The

Tertiary on the Colorado Plateau is classified as low on the basis of the predominant occurrence of sand and gravel. However, some Tertiary units are considerably argillaceous, particularly the Eocene Green River Formation on the north flank of the Plateau in Utah and Colorado and thus locally may be classified as high.

Northern, Middle, and Southern Rocky Mountains Provinces(7,8,9)

57. These three provinces together comprise the Rocky Mountain System or chain which extends from the Canadian border in Washington, Idaho, and Montana into northern New Mexico. The terrane of the Northern Rocky Mountain Province consist primarily of deformed Precambrian metasedimentary, and intrusive and extrusive igneous rocks. These materials are classified as nonexpansive. Small areas of Quaternary alluvial material, however, are present and these are considered to be low. The Middle Rocky Mountain Province is located in western Wyoming and northeastern Utah. This region is characterized by the occurrence of broad, usually elongated, domal uplifts. The uplifted areas consist mainly of Precambrian igneous and metamorphic rocks although younger, Paleozoic and Mesozoic strata are present on the peripheries of the uplifts. These younger materials usually dip away from the uplift and are occasionally deformed. The rocks in the core of the uplifts and the peripheral to the core may generally be classified as nonexpansive. The peripheral rocks, if relatively undeformed, may exhibit expansive properties. The areas in between the uplifts are included in the Great Plains Province. The rocks peripheral to the uplift also occur on the Great Plains and thus the potential for expansion around the uplifts may be determined from the same rocks on the plains depending on the deformation. The lithology and character of the Southern Rocky Province bears a certain degree of similarity to the Middle Rocky Mountain Province with the possible exception of more volcanic rocks in the former. Generally, the rocks intimately associated with the uplifted mountain areas will exhibit low potential for expansion while those strata farther

removed from the uplift will exhibit properties similar to the same material occurring in the adjacent Great Plains and Colorado Plateau Provinces.

Great Plains Province(10)

58. The Great Plains Physiographic Province is a region of gently undulating topography occupying portions of Texas, New Mexico, Oklahoma, Colorado, Kansas, Missouri, Nebraska, Wyoming, Montana, and North and South Dakota. The potentially expansive materials in this large area are diverse with respect to composition, source, distribution, and age. Also, geologic units present in this province occur elsewhere in adjacent provinces but there is no genetic relationship between the source of the expansive materials and this particular province. The ages of these materials range from Pennsylvanian to Tertiary.[16,18,20] Generally, the Mesozoic and Tertiary units contain the highest frequency of occurrence of expansive materials. Mississippian and younger rocks present are much less expansive as a whole although individual units may locally pose problems.

59. Structural deformation of rocks and sediments in this province is minor and the materials are relatively undeformed. Local uplifts within the province and uplifted areas near or at the province borders have produced some degree of deformation which may affect the degree to which these materials exhibit expansive properties.

Pennsylvanian

60. Argillaceous rocks of Pennsylvanian age occur throughout this province; however, the most extensive areas of occurrence are in Oklahoma, Kansas, Missouri, and Texas. The rocks of this age which occur in the other states of this province are generally restricted to areas of uplift where they occupy narrow bands around the uplifted area; elsewhere, they are covered by younger materials. Pennsylvanian rocks occurring in north central Texas comprise a sequence of interstratified limestone and shale with some sandstone.[12,29] In Oklahoma, Kansas, and Missouri, the Pennsylvanian units are somewhat similar to those in Texas

except for some increase in the amount of sandstone and coal. These units are classified as low throughout the province on the basis of amount of shale present in the stratigraphic section and potential amount of montmorillonite present in the shales.

Permian

61. Permian units are widespread in Texas, New Mexico, Oklahoma, Kansas, and southern Nebraska. The overall lithology of the Permian is mixed compositionally although two associations are predominant. One is the "Red Bed" association which consists of red shale, sandstone carbonate, and evaporites. The other is an association of evaporites, carbonates, and shale. The "Red Bed" association extends from Texas through Oklahoma and Kansas into Nebraska. The relatively large proportion of shale, the potential for montmorillonite occurrence, and the clay in the carbonates are the bases for classifying the "Red Bed" association as low. On the other hand, the evaporite-carbonate association, occurring mainly in New Mexico, is classified as nonexpansive.[30,31]

Triassic

62. Triassic units occur in Texas, New Mexico, Colorado, Wyoming, Montana, and South Dakota. These units consist primarily of shale and sandstone and bear some similarity to the "Red Bed" association of the underlying Permian. Stratigraphic names applied to these units are: Dockum Group (Texas), Dockum or Lykins Formation (New Mexico and Colorado), Spearfish Formation (Montana and South Dakota), and Chugwater (Wyoming). Aside from New Mexico and Texas where these Triassic units are relatively widespread, they are more or less restricted in other areas to the peripheries of uplifts and are classified as low.

Jurassic

63. Units of Jurassic age occur throughout the province although they are not particularly extensive. These units are predominantly shale, siltstone, and sandstone and, although they may locally be troublesome, are classified as low. Commonly used stratigraphic names include the Morrison and Sundance Formation.

Cretaceous

64. Probably the most widespread and troublesome units in this

province are those of Cretaceous age. These units consist mainly of shales and limestones, of which many are argillaceous.[12] The reason for the predominance of these lithologies is the widespread inundation of the continental seas during the Cretaceous age. The flooding of the continental interior resulted in the deposition of clay and limestone. Also, during the Cretaceous, volcanoes were active along the borders of these Cretaceous seas. Volcanic debris was carried by air currents and by streams toward the sea basins where it was deposited along with material derived by weathering in the source area. The volcanic debris was subsequently altered to montmorillonite by diagenesis.[32] The amount of volcanic debris deposited in a particular location was dependent upon the location, extent, and duration of vulcanism and various sedimentological aspects of the ocean basin. In any event, under favorable conditions, thick, relatively pure accumulations of volcanic debris were deposited. These accumulations, after diagenesis, resulted in the formation of bentonite. The bentonite may occur as thick (3 ft*) relatively pure montmorillonite; as thinly bedded laminae (a few tenths of an inch); or as disseminations mixed with other sediments. Regardless of purity, size, etc., the overall mode of origin of these deposits is the same. Generally, the Cretaceous units are subdivided into an upper series and a lower series. The upper Cretaceous includes the thick, extensive, and argillaceous Pierre Formation and an overlying sequence of sandstones and siltstones. These units are sometimes called the "Montana Group." Included in the upper series and underlying the Pierre Formation is a sequence of alternating shale and limestone or marl. This sequence consists of the progressively older Niobrara Limestone, Carlile shale, Greenhorn limestone, and Graneros shale and is referred to as the "Colorado Group." Locally, the base of the Graneros shale is the base of the upper series and overlies a sequence of lower Cretaceous sandstones and shales. In other areas there is no boundary between upper and lower Cretaceous which conforms to either top or bottom of a stratigraphic

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page v.

unit; thus, the boundary occurs within a formation. Also, this formation itself may be time-transgressive. This time-transgression of units, the facies changes within units, and the different stratigraphic names applied to formations of the same age in different locations require that the discussion be conducted by region.

Lower Cretaceous

65. The lower Cretaceous of Texas occurs in the region to the north and west of the border between the Great Plains and the Atlantic and Gulf Coastal Plain Physiographic Provinces. The materials consist of limestone with subordinate amounts of sandstone and shale. These materials are classified as nonexpansive, mainly on the basis of the amount of limestone.

66. The lower Cretaceous in New Mexico and Colorado occurs in the eastern part of these states and consists of sandstone and shale (Dakota and Purgatoire Formations). The highly argillaceous Mowry shale overlies the sandstone and shale and transgresses the lower Cretaceous and upper C!retaceous boundary. These units are mapped as medium in these states.

67. In Kansas and Nebraska the Cretaceous is subdivided into three groups: the progressively older Montana, Colorado, and Dakota Groups. The Montana and Colorado Groups are upper Cretaceous, and the Dakota Group is lower Cretaceous at the base and upper Cretaceous at the top. The lower Cretaceous portion of the Dakota Group consists of the Kiowa shale and the Cheyenne sandstone and is classified as medium.

68. The lower Cretaceous in Montana, Wyoming, and the Dakotas is locally highly argillaceous but also contains appreciable sandstone. Highly argillaceous units are the Mowry and Newcastle- Formations which contain commercial grade bentonite. The classification is considered to be medium.

Upper Cretaceous

69. Upper Cretaceous units in this province occur in New Mexico, Colorado, Nebraska, Kansas, Wyoming, Montana, and the Dakotas. The limestone-shale sequence of the Colorado Group has generally been mapped as medium in New Mexico, Colorado, Kansas, and Nebraska on the basis of

the presence of relatively large proportions of limestone or marl. However, the time-equivalents to the Colorado Group' in Wyoming and Montana contain appreciably more clay and less limestone and, in these last two states, are classified as highly expansive. The highly argillaceous, time-equivalent to the Colorado Group in Wyoming and Montana is the Cody Formation. The rocks of the overlying Montana Group are also present in New Mexico, Colorado, Nebraska, Wyoming, Montana, the Dakotas, and Kansas. These rocks are classed as highly expansive and consist predominantly of shale with subordinate strata of sandstone and siltstone. The shale units are the Pierre Formation (Dakotas, Colorado, New Mexico, Kansas, and Nebraska), the Bearpaw shale (Montana), and the Lewis shale (Wyoming). Although classified as highly expansive, these. units exhibit facies variation which include the presence of sandstone or sandy shale, particularly in Montana and Wyoming. Even the highly argillaceous Pierre and Bearpaw shale are locally sandy. Also, the distribution maps include the youngest Cretaceous materials which overlie the Montana Group in the highly expansive category. The uppermost Cretaceous units are mainly granular and include the Fox Hills sandstone, the Laramie Formation, and the time-equivalents of these formations.

Tertiary

70. The Tertiary materials in the Great Plains Physiographic Province consist of a rather mixed lithologic association of coarse gravel, sand, silty clay, coal, limestone, and bentonite. These deposits are all continental in origin and their source area was the uplifted mountain areas to the west of the province or, in some cases, the uplifted domal areas within the province. Generally, the coarser elastics were deposited by meandering streams flowing off of the newly formed mountains. Depressions lying upon these alluvial areas were the loci of deposition of finer elastics, coal, limestone, and bentonite. Vulcanism along the Pacific Coast as well as in New Mexico and Wyoming produced volcanic debris which became incorporated within the sediments and after diagenesis, altered to bentonite.[33] Continental deposits are somewhat more difficult to summarize than marine deposits. This stems

from the heterogeneous nature of the former whereas marine deposits are more uniform and continuous over larger areas. This great quantity of coarse clastics, not withstanding the frequent occurrence of clay and bentonite in these Tertiary units, was the primary basis for classifying these materials as low.

Quaternary

71. Generally the Quaternary deposits in this province consist of Pleistocene glacial deposits (till, outwash, and stratified ice-contact material) and alluvial material of nonglacial origin and alluvial and eolian deposits of Holocene age. The extent to which these materials may exhibit expansive properties is dependent upon the incorporation of the older, Tertiary or Cretaceous, materials within them and the amount of volcanic debris which they contain. Glaciers overriding areas of expansive materials are likely to deposit tills which are also composed of expansive clays derived from the underlying rocks. Likewise, Pleistocene or Holocene age streams draining areas of expansive materials may redeposit these expansive clays. Depressions in alluvial valleys may be depositional sites of volcanic debris which may alter to montmorillonite. The glacial till in the Dakotas and Montana contains expansive clay derived from the Pierre shale and from other formations. However, the till is not nearly as expansive as the older source rocks. The parts of Montana and the Dakotas which are overlain by till are classified on the basis of the nature and composition of the Tertiary or Cretaceous bedrock. The basis for this classification was the variable thickness of the till in these areas as well as the relatively expansive character of the till itself. Pleistocene lacustrine deposits in the Dakotas and Minnesota may exhibit some degree of expansive properties and are classed as low.[12,34-38]

Central and Eastern Lowlands Province(11)

72. This physiographic province comprises a large area of the northern United States between New York State and the Dakotas and consists of a relatively large variety of rock types, environments, and

geologic structures. Perhaps the most common characteristics throughout the region are the lack of structural deformation, the preponderence of Paleozoic rocks, and the extensive cover of glacial drift which overlies the bedrock in most of the area. Aside from areas of expansive glacial materials, the surface exposures of preglacial expansive material are limited to areas where the glacial drift is thin or areas near the southern limit of glaciation. The oldest rocks which may exhibit some degree of expansion are shales and shaley carbonates of upper Ordovician age. These rocks occur in southern Indiana and Ohio and in northern Kentucky and consist of alternating layers of shale and shaley limestones. These materials are classified as low and are discussed in the section on the Interior Low Plateau Province. The Maquoketa shale of upper Ordovician age, occurring in northeast Missouri and mentioned in the section on the Ozark and Ouachita Province, is also classified as low. The Maquoketa shale in northeastern Missouri is partially covered with glacial drift. The upper Ordovician shales in southern Indiana and Ohio may also be so covered. The influence of the glacial material is thin to nonexistant near the glacial boundaries, depending upon the age of the glacial material, the amount of erosion which has occurred, and the topography in the area.* In any event the upper Ordovician and possibly the Silurian, Mississippian, and Pennsylvanian outcrop areas may contain some shales which might exhibit a degree of expansiveness; however, they would be classified as low. The Pleistocene glacial material in this province is considered to be nonexpansive even though some till deposits are quite clayey. A significant exception to this observation is to be found in the Dakotas where the till is highly argillaceous due to the incorporation of the overridden Pierre shale. The distribution map shows the area north of the glacial boundary to be high, principally on the basis of the underlying bedrock but also on account of the clayey till. Areas which are underlain by fine-grained sediments deposited in former Pleistocene lacustrine and marine deposit may, under some circumstances,

* Note that the classification of materials north of the glacial boundary reflects. the bedrock material under the glacial cover in Montana and North Dakota (Great Plains Province).

exhibit expansive properties but would be classed as low. This material occurs in North and South Dakota, Minnesota, along the southeastern shores of Lakes Michigan and Huron, and the southern and southwestern shores of Lake Erie. Similar materials are also found in New York State.[12]

Laurentian Upland Province(12)

73. This physiographic province which includes portions of Minnesota, Wisconsin, Michigan, and New York is a terrane of Precambrian igneous and metamorphic rocks which are not considered expansive.

Ozark and Ouachita Province(13)

74. The Ozark and Ouachita Physiographic Province comprises portions of southern Missouri, northwestern Arkansas, and eastern Oklahoma. The Ozark region consists of relatively undeformed strata dipping away from the Ozark Dome centered in the St. Francois Mountains of southeastern Missouri. The rocks comprise a sequence of lower Paleozoic carbonates (Cambrian through Devonian) followed by a more clastic sequence of Mississippian and Pennsylvanian rocks. The Ouachita region of Arkansas and Oklahoma is a terrane of highly folded and faulted, generally clastic rocks ranging in age from Ordovician to Pennsylvanian." Generally the province should not be expected to exhibit extensive expansive materials; however, some geologic units pose problems. The Maquoketa shale of upper Ordovician age, occurring on the northeast and southeast flank of the Ozark Dome as well as farther north in the Central and Eastern Lowlands Province, is a source of potential and actual expansion and is classified as low. The lower Pennsylvanian, Atokan, and Morrowan Series and the upper Mississippian Chesterian Series contain considerable shale and may exhibit some degree of expansive properties. The stratigraphic names of these shales are: Atoka Formation (contains considerable sand), Morrowan, Bloyd shale, and Chesterian and Fayetteville shale. The Atoka Formation occurs

extensively on the north flank of the Ouachita Mountains and on the south flank of the Ozark Dome. This material is locally mapped as low.[12] The Bloyd and Fayetteville shales are also mapped as low. These occur in an east-west band across northern Arkansas.[12]

Interior Low Plateaus Province(14)

75. The Interior Low Plateaus Physiographic Province comprises most of Kentucky; the unglaciated, southern parts of Indiana and Ohio; and that part of Tennessee between the Coastal Plain and the Appalachian Plateau Province. The terrane consists of an essentially nondeformed, gently dipping sequence of predominant carbonates, sandstones, shales, and coal. Ages range from Cambrian to Pennsylvanian.[14] This sequence of rocks is not believed to be appreciably expansive; however, the sequence does contain certain shales and shaley carbonates. The upper Ordovician series consists of interbedded shaley limestone and shale and occurs in north central Kentucky, southeast Indiana, and southwest Ohio. The shales may contain some mixed-layer illite-montmorillonite and are classified as low. Silurian shales such as the Crab Orchard and Waldron Formations may also pose limited problems. Mississippian shales belonging to the Osagean and Kinderhookian are locally highly argillaceous and are mapped as low in their outcrop area around the Nashville Dome in central Tennessee. Included in this category is the outcrop area of shales belonging to the Mississippian Chester series in northwestern Kentucky and adjacent parts of Indiana.

Appalachian Plateau Province(15)

76. This physiographic province comprises portions of eastern Kentucky and Tennessee, eastern Ohio, most of West Virginia, western and northern Pennsylvania, and southern New York State. The region lies directly northeast of the Newer Appalachian Province and is characterized by a sequence of relatively undeformed sandstones, shales, and carbonates ranging in age from Devonian to Permian. Pennsylvanian

and Permian rock, however, are most abundant. Although shales occur throughout this sequence they are somewhat more common and continuous in the Permian Dunkard series located mainly in West Virginia and adjacent portions of Ohio and Pennsylvania. This series is classified as low and is shown on the distribution map. The Pennsylvanian shales, though not shown, would also be low.

Newer Appalachians (Ridge and Valley) Province(16)

77. The rocks in this physiographic province are predominantly carbonates and sandstone with some shale, and range in age from Cambrian to Devonian. These older rocks, which have been subjected to considerable folding and which do not consist of appreciable shale, are classified as nonexpansive.

Older Appalachians Province(17)

78. The Older Appalachians Physiographic Province, lying to the southeast of the Newer Appalachians and northwest of the Coastal Plain, consists of a heterogeneous assortment of igneous, metasedimentary, and metamorphic rocks. The province is divided into two subprovinces, the Blue Ridge to the northwest consisting of Precambrian igneous rocks, and the Piedmont to the southwest which is predominantly a Paleozoic, metamorphic, and igneous terrane. The Blue Ridge Subprovince is classified as nonexpansive because of the absence of argillaceous rocks and the thinness of pedologic soils. The Piedmont Subprovince consists locally of thick residual soils developed upon many different kinds of igneous and metamorphic rocks. Generally these soils would not be troublesome with respect to expansion, with the exceptions, of the soils developed upon slates, phyllites, and some schists and soils developed upon basic igneous rocks. These metamorphic areas may pose problems due to the fine-grained nature of these soils, and the basic igneous areas may have soils which contain some montmorillonite. These situations are believed to be quite local in extent; thus, the areas of older rocks are classified as nonexpansive.

Triassic Lowlands Province(18)

79. This physiographic province consists of isolated, elongated areas of Triassic age rocks lying in fault-bounded basins generally within the Older Appalachians Province. The rocks consist predominantly of sandstones with shales, and basic igneous rocks. These areas are considered nonexpansive.

New England Maritime Province(19)

80. The New England Maritime Province, consisting primarily of igneous and metasedimentary terrane, is not considered to be an area of significantly expansive materials and is therefore mainly mapped as nonexpansive. However, areas of southern Maine are underlain by Pleistocene marine terraces composed of silt and clay. These fine-grained deposits may exhibit some degree of expansiveness and are classified as low on the distribution map.[12]

Atlantic and Gulf Coastal Plain Province(20)

81. This physiographic province is underlain by a sequence of sedimentary rocks and nonlithified sediments of varying composition, ranging in age from Cretaceous to Holocene. For the most part, these materials are nonlithified clays, marls, silts, and sands and other sediments exhibiting mixtures of these components. Lithified sandstones and limestones also occur but occupy less area than the nonlithified sediments. These sediments and rocks have been subjected to only minor folding and faulting and generally exhibit low dip angles, minimal diagenetic effects, and may be highly weathered.[39]

Lower Cretaceous

82. The oldest expansive material on the coastal plains is Lower Cretaceous in age and extends noncontinuously from Texas to Washington, D. C. Materials of this age are generally of mixed lithologies but contain potentially expansive clay, shale, and marl.

83. The expansive surficial soils of Texas have been described by Carter[29] on the basis of montmorillonite content. The stratigraphic and lithologic approach used in the present report also recognizes the expansive properties of the Washita and underlying Fredericksburg Groups. Both groups are predominantly marl and limestone with interbedded clay or shale. Both groups are assigned to the low category in Texas due to the predominant carbonate component in the stratigraphic section. The Trinity Group which underlies the Fredericksburg is not particularly expansive. The boundary between the Atlantic and Gulf Coast Plain Province and the Great Plains in Texas runs approximately along the contact between the Lower and Upper Cretaceous rocks. However, the approximate position of the boundary has resulted in the presence of Lower Cretaceous rocks in both provinces.

84. In Oklahoma the Washita Group is highly clayey and is classified as highly expansive. This unit is more clay-rich relative to the Washita in Texas, although it too contains considerable limestone or marl. The underlying Fredericksburg consists of clay, sand, and limestone and is classified as low.[12]

85. The Lower Cretaceous Fredericksburg and Trinity Groups are exposed in southwestern Arkansas. Here these materials are mainly sands with some marl and are assigned to the low category. The more expansive Washita Group is not extensively exposed in Arkansas.[12]

86. Lower Cretaceous materials occur in a narrow band between Fredericksburg, Virginia, through the Washington, D. C., and Baltimore areas to a point northeast of Trenton, New Jersey. The sequence consists of silty clays, clays, and sands of the Patasco, Arundel, and Patuxent Formations, respectively. These units are classed as low in swell potential due to the generally coarse-grained nature of the materials. However, the argillaceous character of the Arundel Formation has resulted in the classification of a small area including northeast Washington as highly expansive.[40,41]

Upper Cretaceous

87. The rocks and nonlithified sediments of Upper Cretaceous age occurring on the Gulf and Atlantic Coastal Plain are somewhat similar to

the underlying Lower Cretaceous materials. The Upper Cretaceous is represented by clays, marls, sands, and units of mixed lithologies. However, in Texas and Mississippi, for example, this sequence of rocks and sediments contains highly expansive argillaceous marls which have contributed significantly to poor subgrade performance in these states.

88. The oldest Upper Cretaceous rocks on the Texas coastal plain belong to the Woodbine and Eagle Ford Groups. These two units have mixed lithologies and consist of sand, clay, marl, and limestone. Although locally highly expansive, the generally low clay content of these units leads to classification as low in expansive character. The successively younger Austin, Taylor, and Navarro Groups are generally highly argillaceous and are mapped as highly expansive. These units also contain appreciable carbonate, especially the Austin Group, and, therefore, may be classed as marl or chalk.

89. The Upper Cretaceous unit exposed in Oklahoma is the Woodbine Group. This unit is highly sandy and is classed as low.

90. In Arkansas, the exposed Upper Cretaceous is considered to be of low expansive character with the exception of the Taylor and Navarro Groups, which are clayey and presumed to be highly expansive.[12]

91. The Upper Cretaceous units in Tennessee and Kentucky are predominantly granular materials with minor clay and marl and are thus classified as low.

92. The Upper Cretaceous units in Mississippi, Alabama, and Georgia are compositionally diverse and contain various proportions of sands, clays, and marls. Generally, they lack extensive concentrations of clay and are therefore classed as low. A notable exception is the Selma Group which, although carbonate rich, contains significant amounts of clay and is classified as medium.[12,42-45] Bentonite occur locally in the Eutaw Formation but are not mapped separately.

93. The Upper Cretaceous units in North and South Carolina are mainly sands with small amounts of fine-grain sediments admixed and/or occurring as infrequent members. This outcrop area is categorized as low.[12]

Tertiary

94. The Tertiary units in the Gulf and Atlantic Coastal Plain Province consist of a diverse assemblage of lithologies representing varying degrees of expansiveness. The Tertiary is characterized by considerable facies changes which may be gradual over long distances or quite abrupt over short distances. These facies changes make the summary statements on the degree of expansiveness of a particular unit difficult. Thus, some units may be mapped as highly expansive in one area and medium or low in other areas.

95. Tertiary units in Texas are classified no lower than low. The categorization in this state is based primarily uponthe work of Belcher et al.[12] and Carter.[29] The Paleocene and Eocene are represented by sandy and clayey units and are not considered to be as expansive as the underlying Cretaceous or the younger Tertiary units. The Paleocene and Eocene are mapped as low, medium, or high. The variability is no doubt due to the variable clay content and gradational nature of these units. Oligocene, Miocene, and Pliocene units in Texas are highly argillaceous and have generally been mapped as highly expansive. These units are also gradational and locally may contain appreciable sand, thereby reducing the potential for expansion.

96. The Tertiary of Louisiana mainly consists of sands and clays with minor amounts of marl and units containing admixtures of these components. Generally the Tertiary is classified as low; however, on the basis of Belcher's identification of highly clayey surface materials, the highly expansive category was assigned to some areas.[12] Potentially highly expansive tertiary units in Louisiana include: Porter's Creek clay (Paleocene), Logansport (Paleocene), Yazoo (Eocene), and clay members in the Fleming and Catahoula Formations.

97. The Tertiary in Arkansas is somewhat similar to that in Louisiana and has been classed as low. The Porter's Creek clay in southwest Arkansas has, however, been rated as highly expansive.

98. Tertiary units in Mississippi consist of sand, clay, marl, limestone, sandstone, and admixtures of these components. Generally, the argillaceous nature of many of these units requires that most of

these units be classified no lower than low. Certain units, however, contain appreciably more clay, some of which is montmorillonitic and thus must be classed higher. The Porter's Creek clay, a bentonite in the Midway Group (Paleocene), is locally high in montmorillonite and is classified as medium.[45] Some areas underlain by Wilcox Group (Paleocene and Eocene) and Claiborne Group (Eocene) units also consist of clays and are also classified as medium. The most troublesome Tertiary unit in Mississippi is the Yazoo Clay of the Jackson Group (Eocene) which is classified as high.[12,46]

99. Problems with expansive clays have not posed extensive problems in Alabama and Georgia. Generally the Tertiary strata in this area are predominantly sandy with minor amounts of marl and clay and therefore are classified as low.[47-52] Kaolinite may be more common than montmorillonite.

100. The prevalence of limestone and marl throughout Florida leads to the classification of most of this area as nonexpansive. Argillaceous materials do occur locally and require a higher classification. The Ocala Formation (Eocene) is classified as low and the Tampa Group (Miocene) is classified as medium. These units may weather to moderately clayey soils.[12,53]

101. The Tertiary units in Delaware, Maryland, Virginia, and the Carolinas are predominantly granular and as such are classified as low. Marls and clays do occur but are subordinate in amount.

Quaternary

102. The Quaternary units in this physiographic province are compositionally diverse and consist of granular material on the Atlantic coast (generally nonexpansive); sands, clays, marls, etc., in Florida (also nonexpansive); fine-grained terrace deposits in Texas and Louisiana (highly expansive); and compositionally mixed, although mainly fine-grained, alluvial deposits along the Mississippi Valley and in the delta region of Louisiana.

103. In Texas, the Pleistocene consists of terraces along the Gulf coast of fine-grained materials with appreciable clay. These materials are mapped at the successively younger Bently, Montgomery, and

Beaumont terraces. The quantity of clay present requires that these outcrop areas be classified as highly expansive.[12]

104. Pleistocene terraces (Prairie) in southwestern and northeastern Louisiana are fine-grained and contain montmorillonite. These materials are similar to previously discussed materials in Texas and are classified as highly expansive; although some granular material is also present. The fine-grained materials in the Louisiana delta and in the Mississippi alluvial valley are locally quite clayey and thus are classified as low on the basis of montmorillonite content.[12]

105. The fine-grained materials occurring in swamps and bogs in southern Florida are classified as medium.[12,54]

STRATIGRAPHIC AND ENVIRONMENTAL SYNOPSIS

106. The foregoing discussion of the geology and the distribution of potentially expansive materials has shown that their occurrence is closely related to particular sedimentary rock units and to particular episodes of geologic time. Moreover, it is believed that the stratigraphy and historical geology have a more direct bearing on the occurrence of expansive materials than with relationships between the particular material and the physiographic subdivision in which the material is located. Extrinsic properties also are important but these mainly influence the degree of expansion. Therefore, the following paragraphs attempt to summarize the occurrence of expansive materials with respect to geologic age, stratigraphy, historical geology, and geologic environment.

Precambrian

107. Precambrian rocks are mainly nonexpansive; these rocks do not contain montmorillonite because this mineral is usually destroyed after deep burial and the resulting effects of diagenesis and metamorphism. Residual soils developed upon rocks of this age may exhibit some degree of expansiveness where weathering favors development of montmorillonite.

Cambrian

108. Rocks of Cambrian age are also nonexpansive. This results from the fact that carbonates rather than shales constitute the dominant lithology during this period. Also, those shales which do occur do not contain appreciable montmorillonite.

Ordovician

109. Considerable amounts of shale occur interbedded with

carbonates in the Ordovician Period. These marine shales may contain some mixed-layer illite-montmorillonite and thus pose limited problems. Upper Ordovician units such as the Maquoketa shale of Missouri and the Kope Formation of Kentucky, Indiana, and Ohio are examples of Ordovician units which may be troublesome. The occurrence of thin meta- or K-bentonite zones in Ordovician sequences in the Appalachians and in the Midwest support the contention that the occurrence of expansive materials and vulcanism are related.

Silurian

110. This period is represented by coarse clastics and carbonates, and thus areas underlain by rocks of this age are generally nonexpansive. Possible exceptions are the marine Waldron and Osgood Formations in Indiana, Kentucky, and Tennessee which would be classified as nonexpansive to low.

Devonian

111. The Devonian Period consists of considerably more shale than the Silurian or Ordovician Periods. Devonian shales are marine or deltaic and although they are not extensive enough to be mapped on the distribution maps they would be classified as nonexpansive to low.

Mississippian

112. The Mississippian stratigraphic section consists of considerable amounts of shale interbedded with sandstone and carbonates. The shales are mainly marine and although not particularly extensive areally they may contain appreciable montmorillonite. Note that Weaver[5] (see Table 1) estimated that the Upper Mississippian rocks were the oldest rocks which contain a sizeable proportion of montmorillonite among the clay mineral suite. Mappable areas underlain by Mississippian shales occur in the outcrop areas of the Fayetteville shale (Upper

Mississippian) in Arkansas and the Lower Mississippian of Tennessee and Kentucky. The classification of these areas is low.

Pennsylvanian

113. The Pennsylvanian sequence consists of interbedded sandstone, shale, coal, and carbonates in the Eastern and Central Lowlands, Interior Low Plateaus, Appalachian Plateau Provinces, and Great Plains Provinces. The shales in this sequence may contain mixed-layer illite-montmorillonite, include both marine and deltaic environments, and are classed as low.

Permian

114. Permian shales of the "Red Bed" sequence of Oklahoma, Texas, and Kansas and the Dunkard Series of West Virginia represent ancient, arid continental environments which have resulted in materials of low expansiveness. Vulcanism in Idaho during this time may have provided volcanic ash to the Great Plains area.

Triassic

115. The conditions which typify the Permian were also present during the Triassic. Much of the Triassic record represents continental or deltaic conditions. Considerable shale was deposited during this time. The shales of the Chinle Formation represent some of the most expansive materials in the United States. Considerable vulcanism occurred in California during this time and may have resulted in ash accumulation and the development of montmorillonite.

Jurassic

116. During Jurassic time there was deposition of clay and sand in the western United States; vulcanism occurred in British Columbia.

Expansive materials are not abundant although the Morrison Formation exhibits some expansive properties in the western United States.

Cretaceous

117. One of the maximum inundations of the continent by marine waters occurred during the Cretaceous Period. Although sands and carbonates were also deposited, highly expansive clays are conspicuous during this period. Deposition of this material occurred throughout the Gulf and Atlantic Coastal Plain and in large areas of the western United States. Vulcanism occurred in the Nevadian Orogenic Belt and produced volcanic ash which was subsequently deposited in these marine basins. The shales of the Montana and Colorado Groups in the west and possibly the clays and marls of the Navarro, Taylor, and Austin Groups in Texas owe their expansiveness to the volcanoes in the Nevadian Orogenic Belt. Their widespread occurrence results from their marine environments.

Tertiary

118. The Tertiary is represented by both marine and continental shales along the Pacific coast, by continental deposits in the Great Plains, Basin and Range, and Colorado Plateau Provinces, and by mainly marine deposits in the Atlantic and Gulf Coastal Plain. Vulcanism was common in the western United States following the Laramide Orogeny and Tertiary bentonites are found in Mississippi, Texas, Oklahoma, New Mexico, Colorado, Wyoming, Montana, and the Dakotas. The Tertiary, Yazoo clay of west central Mississippi represents one of the most expansive of these Tertiary materials.

Pleistocene

119. Generally those Pleistocene deposits which possess expansive properties contain material which had originated in older deposits, was eroded out of the older deposit, and transported and redeposited, often

by glaciers during the Pleistocene. Common examples are the tills of the Dakotas and the terrace deposits of southwest Louisiana.

Holocene

120. The expansive material occurring in Holocene deposits also owes its origin to older formations from which it was derived. For example, the montmorillonite in the clay mineral suite of Mississippi River deposits was derived from montmorillonitic formations in the Great Plains Province. The degree of expansiveness of such deposits is in part controlled by the relative amount of montmorillonite being deposited versus the amount of other clays derived from other sources. Thus, the clay mineral suite found in fine-grained Mississippi River deposits is diluted with nonexpansive illite and chlorite derived from the Ohio River Valley.

Environmental Considerations

121. The geologic environments in which expansive materials are found are variable and it is possible to find these materials under diverse geological conditions.[55,56] The previous discussion has shown that expansive clays occur in marine environments (Montana, Colorado, Navarro, Austin, Taylor Groups, etc.), in mixed environments such as deltas (Chinle Formation), and on continental environments such as the Tertiary of the Great Plains. The marine environment is the most significant, perhaps, since these conditions are most suitable for the widespread distribution of a particular deposit. On the other hand, continental environments such as lacustrine, fluvial, or alluvial deposits tend to be more restricted with respect to size. Deltaic environments may be somewhat intermediate in size. Thus, any type of depositional basin may be appropriate for the accumulation of detrital, expansive clays or for volcanic particles which may alter to montmorillonite after diagehesis.

122. The preservation of detrital montmorillonite is a function

of the age of the deposit and its geologic history including loading by supra adjacent sediments and tectonism. Volcanic debris (ash, glass,, shards, etc.) is diagenetically altered under appropriate chemical conditions to montmorillonite, the preservation of which is then controlled by subsequent geologic history.[57]

123. The volcanic debris whidh usually consists of amorphous glass or shards will alter to montmorillonite under most conditions. However, under special conditions the shards may alter to other clay minerals such as illite or kaolinite or to other silicates such as zeolites. The alteration process consists of devitrification of the highly unstable volcanic glass and the crystallization or neoformation of the new mineral, montmorillonite. This process requires the removal of chemical constituents from the system but does not generally require chemical additions.

124. Most volcanic shards which are deposited in basins of accumulation are rhyolitic in composition. This results from the fact that volcanic magmas of rhyolitic composition are more viscous in nature and thus more likely to eject particles explosively. The explosive ejection permits wind currents as well as surface streams to act as transporting agents for the distribution of the ash. Basic magmas tend to be much less viscous and volcanism consists mainly of lava flows. Some volcanic areas may exhibit both rhylolitic and basaltic eruptions.

125. The length of time required for the devitrification of the volcanic material may be variable and dependent upon the environment of deposition. The younger Pleistocene and Tertiary continental ash deposits of the Great Plains Province may locally contain appreciably more ash than montmorillonite, indicating that the devitrification process is incomplete. On the other hand, the marine bentonites in the Mowry Formation (Colorado Group) resulted from devitrification which began shortly after deposition on the sea floor.[32]

126. The rhyolitic ash commonly have silica contents of approximately 70 percent silicon dioxide whereas the silica content of montmorillonite is approximately 57 to 60 percent silicon dioxide. Therefore, in

order for a reaction to occur and montmorillonite to form, there must be the appropriate conditions for leaching of silica from the system. This involves a chemical environment suitable for the solution of silica from the volcanic ash fragments and the removal of the soluble silica beyond the site of alteration. Silica is somewhat soluble at neutral pH conditions but is increasingly soluble under more alkaline conditions. The solubility requirements, with respect to pH, are usually met in most geologic environments. For effective removal, however, there must be sufficient permeability for the water carrying the dissolved silica to move through the system.

127. Alumina, being much less soluble under typical geologic pH conditions, remains to form the octahedral layer of the montmorillonite. Magnesium also remains in the system and will occupy octahedral or interlayer positions in the clay. The alkalis, potassium and sodium, are selectively removed or remain depending upon the chemical character of the aqueous environment. Generally, potassium is removed; if not, the resulting mineral would be illite rather than montmorillonite. The sodium and calcium are selectively removed and that which remains occupies interlayer positions on the montmorillonite.

128. The amount of expansion exhibited by montmorillonite is strongly influenced by the cation occupying interlayer positions, sodium clays being considerably more expansive than clays having either calcium or magnesium in interlayer positions. Therefore, relationships between geologic environments and interlayer cations might provide useful information on expected expansiveness of a particular deposit.

129. It would seem reasonable to assume that volcanic ash deposited in marine environments would tend to retain sodium on the neoformed clay since the marine environment contains abundant sodium. Continental environments, unless evaporitic, usually contain more calcium than sodium and the clay forming here would exhibit calcium on interlayer positions. Deltaic environments would contain both sodium and calcium and the neoformed clay would also exhibit both cations in interlayer positions.

130. Unfortunately, the interlayer cations are rather easily

exchanged, resulting in the removal of the original ion and the substitution of another. This cation exchange could occur during later stages of diagenesis or during present-day (or earlier) weathering cycles. Further, complications arise with respect to concentrations of calcium carbonate in marine environments. Such conditions may result in the dominance of calcium over sodium on the clays of this environment. Thus, the determination of the environment of a particular deposit does not mean that the interlayer cation on the constituent clay minerals is known.

SUMMARY

131. This report, which is based primarily on a review of published information sources combined with the experience of state highway agencies and the WES research team, provides an insight into the geologic influence on the occurrence and distribution of expansive materials. Some of the more important points concerning this geologic influence and related topics are summarized in the following paragraphs.

132. Expansive earth materials consist of expansive, argillaceous, residual, and transported soils and expansive, argillaceous sedimentary rocks exhibiting varying degrees of lithification. The degree of expansiveness exhibited by the soil or rock is controlled principally by the constituent mineralogy. External factors modify the effects of the mineralogy. Expansive sedimentary rocks and transported soils are believed to be considerably more expansive than residual soils, particularly if the parent material of the residual soil is not expansive.

133. Sedimentary rocks older than Mississippian are not generally expansive because of the instability of montmorillonite and its modification in these older rocks. The most highly expansive materials occur in rocks which are Triassic or younger.

134. The distribution of expansive materials is influenced by stratigraphy and geologic history and modified by external factors. The distribution and degree of expansiveness can be determined for various areas by examining the amount of argillaceous material present and the age of material in the area in question.

135. Physiographic delineation is a useful method for discussion and analysis of expansive materials but has no direct genetic implications beyond first-order subdivision.

136. The source of the montmorillonite present in expansive materials is mainly volcanic ash which has been transported by winds, surface streams, and ocean currents from a volcanic region and deposited in a sedimentary basin. After deposition the volcanic ash alters to montmorillonite. Detrital montmorillonite may also be an important constituent in some deposits.

137. Geologic environment does not appear to be a useful criterion for the recognition of potentially expansive materials. Marine, continental, and deltaic environments may contain expansive clays. Marine environments are significant in that these environments cover extensive areas; this results in the widespread occurrence of expansive materials.

RECOMMENDED USAGE

138. The goal of the information presented in this report is to provide the user with qualitative concept for identifying problem areas involving potentially expansive soils. A secondary but significant goal involves planning of field exploration and sampling programs. As with any report of this nature in which subjective information is presented, caution should be used when analyzing the results to avoid misuse of the indicated data. To minimize the hazard of misuse of the information, a recommended decision process is provided, Figure 10, and discussed in detail in the following paragraph. It should be kept in mind that the scale of the included maps is relatively small which does not preclude their use for short distances; however, the maps are best suited to regional planning needs within a particular state or corridor planning through several states. The following description provides a procedure for narrowing the information to specific locations. The decision process shown in Figure 10 is the first step in an overall decision process for dealing with expansive soils in highway subgrades. The remaining portions of the process are subjects of subsequent tasks within the research program and will be further developed as the tasks are completed.

139. Once a tentative route and a basic design have been selected the occurrence and distribution maps are consulted to identify the categories of potential volume change that will be traversed by the route. This provides a first approximation of the potential problem with expansive soils. The "narrowing" process for potentially expansive soil areas begins with the definition of the physiographic province and the predominant potentially expansive geologic unit within the province. Narrative descriptions for all of the physiographic provinces and, in some cases, predominant geologic units are included to provide an insight into the geologic environment. The process continues by locating and defining the distribution of the predominant geologic units using published U. S. and State geologic maps complemented with information from USDA soil surveys. With the area1 limits of the

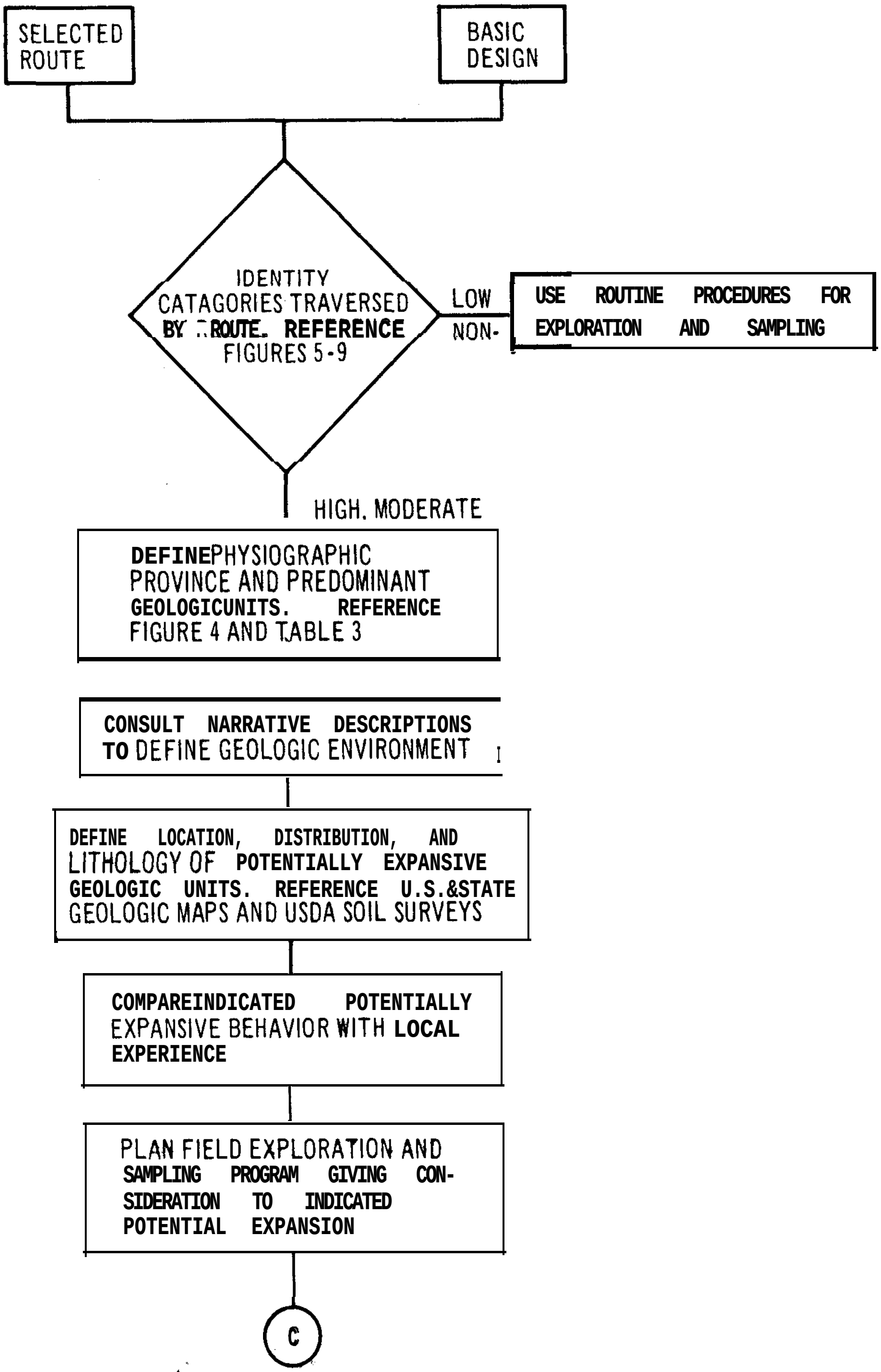

Figure 10. Recommended decision process for qualitative identification of potentially expansive soils

potentially expansive materials reasonably defined, experience with existing highways and structures within the area should be reviewed to verify the indicated degree of expansivity. The planning of the field exploration and sampling program for the selected route is the'next and final step dealing with this phase of the overall decision process. The next step involves actual identification and classification of the expansive materials based on samples obtained in the exploration program. In geologic units characterized as low or nonexpansive, deviations from routine sampling programs will not be necessary to adequately define the properties of the subgrade materials. For the moderate and high categories additional exploration should be conducted to define in detail the extent and variability of the potentially expansive materials.

REFERENCES

1. Snethen, D. R. et al., "A Review of Engineering Experiences with Expansive Soils in Highway Subgrades," Report No. FHWA-RD-75-48, Federal Highway Administration, Interim Report, June 1975.
2. Shamburger, J. H., Patrick, D. M., and Lutton, R. J., "Design and Construction of Compacted Shale Embankments," Vol 1, "Survey of Problem Areas and Current Practices," Report No. FHWA-RD-75-61, Federal Highway Administration, Washington, D. C., 1975.
3. Grim, R. E., Applied Clay Mineralogy, McGraw-Hill, 422 pp, 1962.
4. Grim, R. E., Clay Mineralogy, 2nd Edition, McGraw-Hill, 1968.
5. Weaver, C. E., "Potassium, Illite, and the Ocean," Geochim. Cosmochim. Acta, Vol 31, pp 2181-2196, 1967.
6. Keller, W. D., The Principles of Chemical Weathering, Lucas Bros, Columbia, Mo, p 65, 1962.
7. Pettijohn, F. J., Sedimentary Rocks, 3rd Edition, Harper and Row, Chap. 3, 1975.
8. Folk, R. L., Petrology of Sedimentary Rocks, Hemphill's, Austin, Tx, p 93, 1968.
9. Witczak, M. W., "Relationships Between Physiographic Units and Highway Design Factors," Report 132, 1972, National Cooperative Highway Research Program, Highway Research Board, Washington, D. C.
10. Atwood, W. W., The Physiographic Provinces of North America, Ginn and Co, 1940.
11. Glossary of Geology, American Geological Institute, Washington, D. C., p 538, 1972.
12. Belcher, D. J. et al., Map - "Origin and Distribution of United States Soils," 1946, The Technical Development Service, Civil Aeronautics Administration, and the Engineering Experiment Station, Purdue University, Lafayette, Ind.
13. U. S. Geological Survey, Geologic Map of North America, 1965, Washington, D. C.
14. American Association of Petroleum Geologists, Geologic Highway Map: Mid-Atlantic Region, 1970, Tulsa, Okla.
15. __________, Geologic Highway Map: Northern Rocky Mountain Region, 1972, Tulsa, Okla.
16. __________, Geologic Highway Map: Mid-Continent Region, 1966, Tulsa, Okla.
17. __________, Geologic Highway Map: Pacific Southwest Region, 1968, Tulsa, Okla.
18. __________, Geologic Highway Map: Texas, 1973, Tulsa, Okla.

19. American Association of Petroleum Geologists, Geologic Highway Map: Pacific Northwest Region, 1973, Tulsa, Okla.

20. __________, Geologic Highway Map: Southern Rocky Mountain Region, 1967, Tulsa, Okla.

21. __________, Geologic Highway Map: Southeastern Region, 1975, Tulsa, Okla.

22. Watson, E. B., et al., 'Soil Survey of the Merced Area, California, 1914, U. S. Department of Agriculture, Washington, D. C.

23. Gowans, K. D., 'Soils Survey of Tehama County, California,' May 1967, U. S. Department of Agriculture, Washington, D. C.

24. Langan, L. N., et al., 'Soil Survey of the Lovelock Area, Nevada," Series 1958, No. 31, June 1965, U. S. Department of Agriculture, Washington, D. C.

25. Strahern, A. T., "Soils Survey of the Fallon Area, Nevada," 1911, U. S. Department of Agriculture, Washington, D. C.

26. Strahern, A. T., et al., "Soil Survey of the Delta Area, Utah," 1922, U. S. Department of Agriculture, Washington, D. C.

27. Sanchez, A. M., "Soil Survey of the Provo Area, Utah," 1904, U. S. Department of Agriculture, Washington, D. C.

28. Erickson, A. J., et al., "Soil Survey of Davis-Webber Area, Utah," July 1968, U. S. Department of Agriculture, Washington, D. C.

29. Carter, W. T., "The Soils of Texas," Texas Agriculture Experiment Station, Bull. No. 431, 1951.

30. Bourlier, B. G., et al., "Soil Survey of the Torrance Area, New Mexico," Jan 1970, U. S. Department of Agriculture, Washington, D. C.

31. Chugg, J. C., et al., "Soil Survey of Eddy Area, New Mexico," March 1971, U. S. Department of Agriculture, Washington, D. C.

32. Slaughter, M. and Early, J. W., Mineralogy and Geological Significance of the Mowry Bentonites, Wyoming, Geol Soc Amer Spec Paper 83, pp 116, 1965.

33. Swineford, Ada and Frye, J. C., 'Source Area of Great Plains Pleistocene Volcanic Ash," Jour Geol Vol 57, pp 307-311, 1949.

34. Cobb, W. B., et al., 'Soil Survey of Bottineau County, North Dakota," 1915, U. S. Department of Agriculture, Washington, D. C.

35. Knobel, E. W., et al., "Soil Survey of McHenery County, North Dakota," 1921, U. S. Department of Agriculture, Washington, D. C.

36. Hutton, F. Z. and Nichols, E., "Soil Survey of Traill County; North Dakota," 1920, U. S. Department of Agriculture, Washington, D. C.

37. Watkins, W. I., et al., "Soil Survey of Beadle County, South Dakota," 1924, U. S. Department of Agriculture, Washington, D. C.

38. Smith, W. G., et al., 'Soil Survey of Pennington County, Minnesota,' 1914, U. S. Department of Agriculture, Washington, D. C.

39. Murray, Grover E., Geology of the Atlantic and Gulf Coastal Province of North America, Harper and Bros, pp 692, 1961.

40. Kirby, R. M., 'Soil Survey of Prince Georges County, Maryland," April 1967, U. S. Department of Agriculture, Washington, D. C.

41. Kirby, R. M., Matthews, E. D., 'Soil Survey of Anne Arundel County, Maryland," Feb 1973, U. S. Department of Agriculture, Washington, D. C.

42. Burgess, L. H., et al., "Soil Survey of Montgomery County, Alabama," Series 1957, No. 7, Sep 1960, U. S. Department of Agriculture, Washington, D. C.

43. Stroud, J. F., et al., "Soil Survey of Green County, Alabama," 1926, U. S. Department of Agriculture, Washington, D. C.

44. Schoenman, L. R., et al., 'Soil Survey of Lowndes County, Alabama,' 1918, U. S. Department of Agriculture, Washington, D. C.

45. Kerr, P. F. (Editor), Preliminary Reports, Reference Clay Minerals, Research Report 49, American Petroleum Institute, pp 39-41 and pp 44-47.

46. Bonsteel, J. A., et al., "Soil Survey of the Yazoo Area, Mississippi,' 1901, U. S. Department of Agriculture, Washington, D. C.

47. Smith, H. C., et al., "Soil Survey of Monroe County, Alabama," 1918, U. S. Department of Agriculture, Washington, D. C.

48. Harris, D. M., Jr., "Soils Survey of Houston County, Alabama," Feb 1968, U. S. Department of Agriculture, Washington, D. C.

49. Allen, R. T. and Grimes, E. J., "Soil Survey of Miller County, Georgia,' 1914, U. S. Department of Agriculture, Washington, D. C.

50. Middleton, R. C., 'Soil Survey of Dougherty County, Georgia,' Jan 1968, U. S. Department of Agriculture, Washington, D. C.

51. Long, D. D., Baldwin, M., "Soil Survey of Terre11 County, Georgia," 1915, U. S. Department of Agriculture, Washington, D. C.

52. Long, D. D., Hall, E. C., 'Soil Survey of Early County, Georgia,' 1921, U. S. Department of Agriculture, Washington, D. C.

53. Mooney, C. N., et al., 'Soil Survey of Hillsborough County, Florida,' 1916, U. S. Department of Agriculture, Washington, D. C.

54. Vanatta, E. S., Jr., 'Soil Survey of Pinellas County, Florida," Sep 1972, U. S. Department of Agriculture, Washington, D. C.

55. Keller, W. D., 'Clay Minerals as Influenced by Environments of Their Formation," Ainer Assoc Petrol Geol Bull., Vol 40, pp 2689-2710, 1956.

56. Weaver, C. E., "The Clay Petrology of Sediments," Clays and Clay Minerals, Proc of the Sixth National Meeting, pp 154-187, 1959.

57. Weaver, C. E. and Beck, K. C., Clay Water Diagenesis During Burial: How Mud Becomes Gneiss, Geol Soc Amer Spec Paper 134, p 96, 1971.