The Logic of Geological Maps, With Reference to Their Interpretation and Use for Engineering Purposes

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 837

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By DAVID J. VARNES

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A discussion of the definition and classification of map units, with emphasis on the problems presented by maps intended for use in civil engineering

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By DAVID J. VARNES

ABSTRACT

A map is a spatial classification that transmits information about features at or near the earth's surface for a defined purpose. Transmission is effective only if map maker, map, and map user are so coordinated that the maker's concept is transferred to the user's mind without significant alteration. Map purpose lies between the two extremes of showing the area or distribution of one or more attributes or showing the attributes of a selected area or point. Attributes are of four basic kinds, which refer to time, space, the inherent properties of real matter, and the relations between objects. In common with all classifications, maps involve the definition of classes or units by grouping or division, logical synthesis or analysis, induction or deduction. The resulting map units consist of two parts that cannot be considered separately: graphic portrayal of the position or areal distribution, and the definition in words of what the graphic portrayal means. One of the most fundamental problems in the construction and use of maps is the isolation and identification of those attributes that are essential to the definition of map units.

Maps are both prepared and modified through four principal types of operations: generalization, selection, addition or superposition, and transformation. The derivation from a conventional geologic map of information or other maps applicable to the needs of civil engineering is dominantly an operation of transformation in which some or all of the lines of the geologic map are reused but in which the delineated units are assigned new essential attributes of engineering performance, behavior, or use. The success of this transformation depends on what accuracy and reliability are required, on how closely the properties of interest covary with the originally mapped boundaries, and on how heterogeneous the geologic units are with respect to these properties. More generally, each type of special-purpose engineering geological map requires for its preparation specific operations of addition, selection, generalization, and transformation of spatial information that concerns not only lithology and structure of soils and rock but also hydrology, geomorphology, and geologic processes.

Real examples of engineering geological and related maps are analyzed regarding identification of essential attributes of map units. The principal operations on map units are regrouping, transformation, and addition and superposition with and without generalization. Some map units are based on geometric or age relations. Some maps converge in intent but differ in content. Examination of the logic, or lack of it, in maps is aided by various kinds of plots and graphical analyses. Among the more useful and easily constructed are the data matrix, tree of logic, table of logical division, and three-dimensional map unit matrix.

Thoughts on needed improvement in the preparation of engineering geological maps are contained in a discussion of concern, clarity, critical evaluation, and creativity. A look at the future suggests an increasing need for precise information and growing sophistication in acquiring and processing of data. Thus, maps that show only one or a few attributes, whose boundaries may overlap and are not necessarily coincident with boundaries of geologic units, may become the dominant and most useful mode for transmitting spatial engineering geological information.

INTRODUCTION

Maps and Maidens —

They must be well-proportioned and not too plain;
Colour must be applied carefully and discreetly;
They are more attractive if well dressed but not over dressed;
They are very expensive things to dress up properly;
Even when they look good they can mislead the innocent;
And unless they are very well bred they can be awful liars!

(Willatts, 1970)

Much of this paper pertains to the last two lines of verse, that is, to the integrity and good breeding of maps, for which I consider proper construction an essential. Its purpose is to examine the process of spatial classification as it operates to define map units, to discuss how maps function as instruments of communication, to indicate some problems of map communication through analysis of actual examples, and to suggest some improvements in the way we think about making engineering geologic maps and their derivatives.

Some of the discussion is abstract, philosophical, and admittedly difficult, because the language needed to discuss the thought processes used to make maps is strikingly different from that needed to discuss their scientific content. In any event, this report is expected to be of more interest and use to those with some experience in applied geologic mapping than it will be to the beginner seeking guidance. The paper is more specifically directed toward geologists who are interested in the process of defining map units, and particularly toward those engaged in the derivation, from general geologic or engineering geologic maps, of interpretations regarding the performance, behavior, or use of geologic materials.

Although the discussion is mostly about engineering geological maps, it includes a look at characteristics of maps in general. We are often too close to our work to always be aware that some of our goals and many of our difficulties are not peculiar to geology but are common to any science that deals with the spatial distribution of things and their properties. Advances in allied fields, such as geography or biology — either in the manner of acquiring and presenting information or in the development of principles to guide selection of information to be presented — may be applicable to our own activity in geology. We must see how our work relates to the work of others, not so much in our ends as in our means; and the means employed are primarily those of thought.

Awkward necessity requires that maps are here discussed more with words than by means of the maps themselves. Direct references are made to some examples, and simple drawings are presented as aids, but words must serve as the principal vehicle for ideas. Hence, the meanings of some common terms, as they are here used, are defined or discussed at appropriate places.

This paper is an outgrowth of several related activities and interests: a continued concern with the subject of engineering geological mapping through more than 20 years' work in the engineering geology investigations by the U.S. Geological Survey; present participation in the project on Research in Geologic Mapping directed by H. W. Smedes; membership in the Association of Engineering Geologists Ad Hoc Committee on Mapping, whose chairman is E. E. Lutzen; and a desire to further the aims of the Working Group on Engineering Geological Mapping of the International Association of Engineering Geologists, whose chairman, Milan Matula, and secretary, Dorothy Radbruch-Hall, have shown interest that encouraged me to prepare this paper. The advice and criticism given by Professor Matula, John S. Scott of the Geological Survey of Canada, and my colleagues Mrs. Radbruch-Hall, D. L. Schleicher, J. E. Harrison, and C. M. Wentworth have been very helpful.

GENERAL CHARACTERISTICS OF CLASSIFICATION AND MAPS

A particular field of knowledge is a body of structured, patterned, ordered, or interrelated information. Inquiry into such a body must consider first what makes up the units or individual building blocks of information, and second, what arrangements of these units are possible, feasible, or useful. Much of this paper concerns the processes of classification, so the terms "classification" and "identification" must be distinguished. Sokal (1966, p. 108) put it this way:

> When a set of unordered objects has been grouped on the basis of like properties, biologists call this "classification." Once a classification has been established the allocation of additional unidentified objects to the correct class is generally known as "identification."

The process of classification can be reduced to examining the validity of a series of elementary categorical propositions in which something is asserted or denied about a subject or individual. In formal logic, that which is asserted or denied is called a "predicate." Thus, a complete proposition might be of the form: Most (qualifier) of the Pierre Shale (subject) is (copula or verb) unsuited for dimension stone (predicate). Predicates, according to Carnap (1962, p. 58), may be of degree one, in which they designate properties or characteristics of individuals, or of degree two or higher, in which they designate relations between individuals. Carnap grouped properties and relations together under the term "attributes." I adopt this meaning and use the term repeatedly because it has such a broad meaning. The way this term is used among authorities seems to be uniform, whereas other similar words, such as "property" or "characteristic," are sometimes used in varied and more restrictive senses.

UNITS OR INDIVIDUALS

Ideally, an individual or unit is defined by a unique attribute or a unique set of attributes. Clearly, the construction of classes from individuals is meaningful only if the individuals are generically similar — the sum of a horse and a radish is not horseradish.

A basic and pervasive problem in making maps is the isolation and identification of the attributes that are necessary and sufficient to define the units to be mapped. An attribute may be absolute, that is, either present or absent, or it may exist in degrees that are measurable in qualitative or quantitative terms, or it may be immeasurable. Attributes may be constant or variable in space or time, and one attribute may covary in space or time with another, with or without a dependent or cause-effect relationship.

Complex material objects, such as a unit of rock or a landslide, are commonly defined by a suite of attributes, and among these is generally at least one that is both essential to the classification and identification of the object and unique to the body. Other attributes may be essential but not unique, some may be unique but nonessential, and some may be neither essential nor unique but simply present or accessory. If no unique properties can be found in a broad group of individuals, a class can be constructed of individuals that have only gross similarity. Such a class is defined by the clustering of its members in some sort of data plot or by a statistical or nonstatistical measure of similarity that demonstrates the existence of a group distinct from the population from which it was selected. No attribute is necessarily common to all components that form such a unit or is necessarily unique to the group thus formed. Many geologic map units are so constructed, which helps to explain why they commonly are heterogeneous rather than homogeneous.

Four fundamental categories of attributes apply to maps; these pertain to time, space, the inherent qualities or properties of real matter, and the relations between objects. Correspondingly, four kinds of units can be referred to as temporal, spatial, typological, and relational. Geologic units commonly are defined by combinations of these four kinds of attributes. Because many possible combinations of these categories are not covariant, we geologists can readily get into logical difficulties unless care is taken in our definitions of map units.

The four categories of attributes generally require different treatment. Temporal units on a map are defined solely by time lines that are established, for example, by the fossil record, geochronology, or the high-water marks of a major flood. Likewise, a purely spatial map unit is defined by physical boundaries only. In contrast, typological and relational units are defined, respectively, by a great variety of properties or by various geometric or time relations. Specific attributes pertaining to time, space, inherent qualities, and relations can be superposed, but whether any "individual" actually possesses all these attributes may then become a serious question. We may have created a complex pigeonhole that closely fits no real pigeon.

If not only typological but also relational, temporal, or spatial attributes are combined to define a new class, the areas of the new class are not necessarily contiguous. For example, we may wish to define an engineering geologic map unit as having the following attributes: (1) Lithology *A*, (2) slope within a range designated *S*, and (3) ground-water condition *I*.

These attributes may be distributed as shown in figure 1. The map unit is shown as two ruled noncontiguous areas of coincidence of all three attributes. If A_1, A_2, and A_3 represent strata of different ages but of essentially the same lithology, rocks in the two shaded areas are also noncontiguous in time.

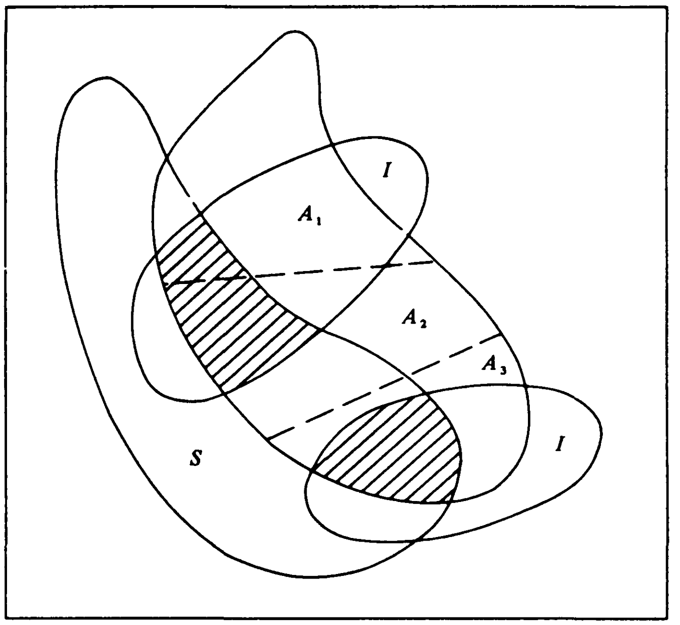


FIGURE 1.—Map unit (ruled) defined by overlapping attributes of lithology *A*, slope *S*, and ground-water condition *I*.

Lack of spatial contiguity should not be troublesome if the attributes involved are clearly not genetically related. Strong forces, however, work in the mind to create regions if there is spatial coincidence of typological attributes. If *A*, *S*, and *I* in figure 1 were somewhat similar physical properties or slightly different landforms, then many mappers would tend to join the shaded areas (depending on scale) to make them contiguous, which infers that all the area in and between the shaded areas embraces a significantly large group of genetically related covariant attributes. These are the "natural" regions thought of by geographers, and the philosophy of their discrimination has been much discussed (Armand, 1965; Grigg, 1965, 1967; McDonald, 1966; Rodoman, 1965). Geologic formations are often so regarded; although the Code of Stratigraphic Nomenclature (Am. Comm. Stratigraphic Nomenclature, 1970) allows only lithology to be considered in defining a rock-stratigraphic unit, attributes of genesis and time or geometric relations with other units almost inevitably and properly enter in. Similar trends occur in the search by many mapping organizations for "integrated" terrain, landform, or soil units of significance for engineering and for land use and development.

The importance of careful definition of map units cannot be overemphasized. First, the purpose of the unit must be identified, and the unit must be assigned to one or more of the fundamental categories — temporal, spatial, typological, or relational. Second, a formal statement of the essential attributes in each of the applicable categories must be composed. The statement must specify what characters and properties are necessary and sufficient to identify the unit or an individual in the class; and if many essential attributes are specified, care must be taken that they are not mutually exclusive under some conditions. The third step is to determine the degree of internal heterogeneity that can be permitted and yet fulfill the purpose of the map.

Homogeneity, or the lack of it, is so important to concepts in natural science and to engineering geology in particular that homogeneity will be considered as absolute in this report; that is, an attribute either is absolutely homogeneous or possesses degrees of heterogeneity. One of the measures of heterogeneity which is relevant to mapping is that given by the ratio V_R/V_1, where V_1 is the total volume of the body and V_R is the smallest representative size of sample taken from anywhere in the body such that the measure, within V_R, of the attribute being considered does not range beyond preselected acceptable limits. This is the inverse of the measure of homogeneity proposed by Bjerrum (1954). The concept presumes that the smallest sample of significance to the engineering geological attributes of a given homogeneous body will have attributes identical to those of the body as a whole.

Homogeneity must be considered for each attribute separately, because any physical object or body of rock or soil may be homogeneous with respect to one or more attributes and heterogeneous with respect to others. In geology, as in other spatially oriented sciences, boundaries usually can be drawn around real parcels of ground such that, with respect to a certain named set of attributes, the defined parcel is not unacceptably heterogeneous, and the measure of one or more of its essential characters changes abruptly or with steep gradient at the selected borders.

The essence of mapping is to delineate areas that are homogeneous or acceptably heterogeneous *for the intended purpose of the map*. The resulting map consists of two parts that should never be considered separately: (1) the two-dimensional plan showing the outline of identified areas and (2) the explanation that tells in words and symbols what the essential attributes are that the enclosed areas exhibit. In a purposefully constructed map, a selected characteristic or set of attributes appears as an areal entity or group of areas that has the minimum heterogeneity obtainable—that is, the inclusion of additional area would increase the net heterogeneity, and the delineation of a smaller area or areas would fail to include parts similar to those within the remaining unit.

Because a map is constructed by classifying data and outlining class boundaries, the methods of classification are prime factors in mapmaking, and a look at various procedures and their logic is pertinent to both the construction of a new map and the evaluation of an existing one.

METHODS OF CLASSIFICATION

According to Beckett (1968, p. 53), a map is made "in order to be able to make more precise statements about the mapped subdivisions of the region than we can about the region as a whole." This is true, but it is only half the story. Mapping also includes the operation of grouping small areas into larger units so we can make statements about the group that are more general than those we can make about its components. In these two intents, and their combinations, lie all the reasons for mapping. Every map occupies some part of a field of contest that has at one end the goal of attainment of perfectly detailed information about the attributes that are possessed by specified areas and at the other end the goal of complete knowledge of location of all areas that have one or more attributes of interest. (See fig. 2.)

A close look at the countercurrents shown in figure 2 shows that operations tending to go to the right (grouping, synthesis) presuppose the existence of defined individuals that can be welded into new, more inclusive individuals. Operations tending to the left (analysis, logical division) consist largely of a

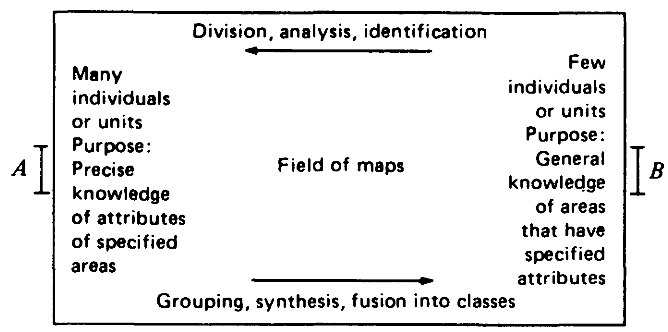


FIGURE 2. — Field of purposes of maps. The two goals — *A*, attainment of precise knowledge of attributes of specified areas, and *B*, general knowledge of the areas having specified attributes — are generally approached by opposing methods of classification: division and grouping.

search for, and precise definition of, manageable, useful individuals; and this search presupposes the existence of concepts by which individuals can be defined or recognized.

The two opposed operations of subdivision and grouping are subject to well-known rules of logic (Grigg, 1965, p. 481–482; Searles, 1956, p. 61–67; Armand, 1965, p. 22–26, 33). In a very illuminating way, Armand pointed out specific instances in Russian geologic and geographic studies where inattention to logic led to faulty classifications.

Logical grouping and subdivision can proceed on the basis either of concepts or of the attributes of real subjects. Use of concepts for classification is perhaps more consistent with the historical development of mathematical logic and was advocated by Knox (1965, p. 79) and by Schelling (1970) for the classification of soils, even though some classes may be empty. Similar philosophy was followed in geography by Milovidova (1970), who explained that certain classes, although logically and factually possible, are unrealized in the area under consideration. In contrast, Cline (1949, p. 81) held that a class is a group of individuals which is exemplified by the actual median individual. A geologic formation is a product of Cline-type classification, for it requires a real example — a lithostratigraphic unit, or stratotype (Hedberg, 1970).

Much of the modern technique of arranging field data and establishing classes, especially in the United States, is based more on manipulating the quantitative measures of the properties of physical units or samples and forming empirical groups than on fitting them into abstract class concepts. In Europe, especially eastern Europe, the Milovidova procedure prevails.

Three types of relations must be considered in the arrangement of information:

1. Object to attribute. (The terms "object" and "subject" are here regarded as synonyms.)
2. Attribute to attribute, over a span of objects.
3. Object to object, over a span of attributes.

The relation of object to attribute, or sample to property, can be expressed most simply by specifying whether the property is present or absent. More commonly, the property has a range or degree, and some system of measurement permits more precise descriptions of all three kinds of relations.

Measurement is the assignment of numerals to events or objects according to rules. The rules are of four kinds, as listed in table 1 in increasing complexity (Abler and others, 1971, p. 93–110; Stevens, 1946, 1958; Searles, 1956, p. 278–282).

TABLE 1. — *Kinds of measurement*

Scale	Basic operation	Typical example
Nominal	Assignment of a number (or name) to each object.	Numbered rock specimens.
	Assignment of a number (or name) to each class.	Rock specimens named by lithology.
Ordinal	Determination of greater or less.	Hardness of minerals. Street numbers. Strata ranked by age.
Interval	Determination of the equality of intervals or differences.	Temperature on Fahrenheit or Celsius scale (arbitrary zero). Calendar time.
Ratio	Determination of the equality of ratios.	Length, mass, altitude, velocity, or size. Temperature on Kelvin scale (zero point identified).

The formal name of an object is in this paper regarded as an attribute, perhaps the most fundamental attribute, because a name represents, generally, a specific identification or classification. Identifying a formation in the explanation of a map involves not only a nominal measurement by specifying it as the "Jones Pass Sandstone" but also an ordinal measurement by assigning it to the "Lower Cretaceous" and by placing its analog box in the explanation in proper relation to the other units.

MATRICES

If more than a very small number of objects and their attributes is being considered, use of a matrix to display the data is very helpful in constructing or analyzing classifications. Figure 3*A* shows a matrix in which the symbols *a*, *b*, and so forth express, according to one of the modes of measurement, the relation between the corresponding object and attribute. Any of the symbols can be replaced by 1 or 0, a nominal measurement denoting presence or absence of the relation, as shown in figure 3*B*; this may be convenient in mathematical or computer treatment (Laffitte, 1968; Dixon, 1970). Gradational attributes can be partitioned into classes or ranges so that the presence or absence of any range, now within specified limits, can also be indicated by 1 or 0. If more information is available, the objects can be assigned ordinal numbers in each column, as in figure 3*C*, or given numerical values on an interval or ratio scale, as in figure 3*D*.

The objects referred to in figure 3 may be samples that are tied to some spatial or temporal frame of reference, or they may be the spatial or temporal individuals themselves, regarded as homogeneous and having no variation of attributes.

The geographic matrix presented by Berry (1964, fig. 2), slightly modified here as figure 4, shows various ways in which information on spatial, temporal, and typological attributes may be arranged. The matrix can be used in two fundamentally different ways. If we wish to know the attributes of an area,

ATTRIBUTES

OBJECTS	1	2	3	4	5	6
A	a_1	a_2	a_3	a_4	a_5	a_6
B	b_1	b_2	b_3	b_4	b_5	b_6
C	c_1	c_2	c_3	c_4	c_5	c_6
D	d_1	d_2	d_3	d_4	d_5	d_6
E	e_1	e_2	e_3	e_4	e_5	e_6

A

	1	2	3	4	5	6
A	1	1	1	1	1	1
B	1	1	1	1	1	0
C	1	1	0	1	1	1
D	1	1	1	1	0	1
E	1	1	1	1	1	1

B

	1	2	3	4	5	6
A	1	2	1	1	2	1
B	2	3	3	2	4	5
C	3	1	5	3	1	3
D	4	5	2	5	5	2
E	5	4	4	4	3	4

C

	1	2	3	4	5	6
A	500	16	40	0.73	1500	+6.2
B	400	13	25	0.62	300	n.a.
C	300	17	0.0	0.57	2670	-1.1
D	200	10	30	0.39	0	+3.6
E	100	12	5	0.43	1200	-2.3

D

FIGURE 3. — Matrices relating objects and attributes according to scales of measurement: *A* and *B*, nominal; *C*, ordinal; and *D*, interval or ratio.

we scan the particular row of interest, noting the measures in each column; if we wish to know the areas that exhibit an attribute, we scan the column of interest, noting the measures in the rows (places or areas).

Maps are a method of representing such matrices graphically, in a spatial format, so that the places are not simply ordered serially but are displayed in correct relations having topologic similarity to the real world. Hence, the two modes of use of the matrix are the two basic ways in which maps are used, and the design of maps reduces to devising means to display one or the other of these two matrix modes.

A map's logic, or lack of logic, and the ways in which maps can or cannot be used can often be examined more easily with reference to the underlying matrix than to the maps themselves. Berry (1964, p. 5–9) discussed 10 ways of treating the data matrix; the first two are the basic approaches mentioned above:

1. Examine the arrangement of cells within a row or part of a row.
2. Examine the arrangement of cells within a column or part of a column.
3. Compare pairs or series of rows; that is, compare places or areal differentiation on the basis of characteristics.
4. Compare pairs or series of columns; that is, examine spatial covariations or associations of attributes.
5. Study a submatrix. (See fig. 4.)
6. Compare a row or part of a row through time; that is, study changing character of some particular area through a series of stages.
7. Compare a column or part of a column through time; that is, study changing spatial distribution of attributes.
8. Study changing differentiation of areas through time.

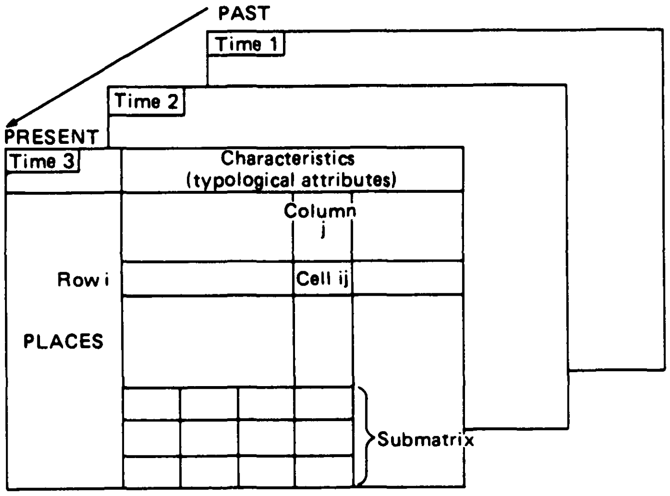


FIGURE 4. — Geographic matrix. Modified from Berry (1964, fig. 2).

9. Study changing spatial association of attributes through time.
10. Compare a submatrix through time by rows or columns.

TEMPORAL VARIATIONS

The importance of the temporal aspects of areal variation was emphasized by Duncan, Cuzzort, and Duncan (1961, p. 160ff). They pointed out that some scientists

* * * believe that genuine causal knowledge can be established only on the basis of longitudinal or diachronic [through time] observations, or at least by using information on the temporal relationships among variables. The need to understand the course of change and to forecast the direction of future change often is felt to be so great that the research worker is constrained to make some inference about change even though he lacks time series data. Thus the tacit assumption frequently is made that temporal relationships can be surmised from relationships holding in cross-sectional data.

For example, suppose, as shown in figure 5, that units or individuals A, B, C, and D of various ages show at an instant of time, t_0, a property X that is greater the older the individual, as indicated by points A_0 through D_0. It is very easy to infer from these "cross-sectional" data that a relationship between X and age is defined by the heavy line and that any one individual, as time passes, will move up along the line from the position of A to that of B, and so on. This may be false if the actual paths pursued by the individuals from time t_0 to time t_2 are given by the dashed lines. Obviously, some factor other than the simple passage of time is operating on the individuals.

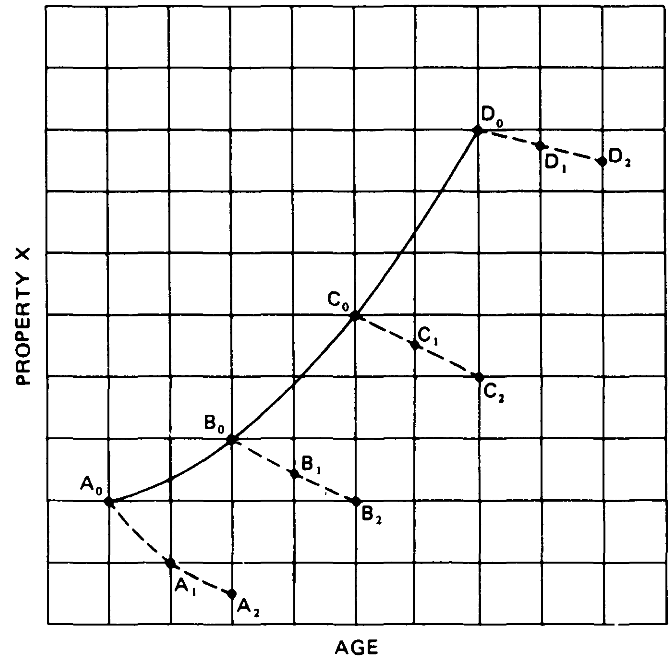


FIGURE 5. — Relation between property X and age might be inferred from data pertaining to individuals at a particular instant, as given by the points A_0 through D_0, implying that as each individual ages it moves up along the solid line. However, with passage of time, each individual may follow a path such as A_0 to A_2 because of the influence of a factor not recognized.

GROUPING

A matrix is highly useful to study covariance, for the columns or rows can be manipulated to help establish groupings that can be used to define classes. For example, regrouping of the rows (places) of figure 6*A* into those of figure 6*B* identifies two new classes (map units) having similar but not identical attributes. If grouping of these places into slightly inhomogeneous map units does not violate the purpose of the map, then the areas to be shown have been reduced from 9 to 5. This kind of study is areal (grouping of places having similar attributes).

A topical study can be made, as shown in figure 6*C*, by regrouping columns. This operation identifies two pairs of attributes that covary — 3 and 7 perfectly, 1 and 9 almost perfectly. The reason for the covariances can then become the subject of investigation.

A historical study would examine the relations of the various matrices through a span of time. The comparison and grouping of objects over a span of attributes (grouping of rows in fig. 6*B*) is termed correlation in the *Q* mode, and the grouping of attributes or variables (grouping of columns in fig. 6*C*) is called correlation in the *R* mode (Krumbein and Graybill, 1965; McCammon, 1968). By natural extension of this nomenclature, grouping according to time might be termed correlation in the *T* mode.

As grouping proceeds, statements that can be made about the increasingly agglomerated groups become fewer and more generalized but presumably more significant to the purpose and use of the classification system. At some point we arrive at groups that have a maximum acceptable heterogeneity with respect to the statements we wish to make about them for the purpose of the map, and the process is terminated. The techniques by which either objects (places) or attributes, or both, are grouped to make the most meaningful units for the purpose at hand commonly involve specialized statistical methods that are beyond the scope of this paper. The interested reader is referred to work by Abler, Adams, and Gould (1971), Berry (1961, 1964), Berry and Marble (1968), Cole and King (1968), Hautamäki (1971), Johnston (1968), King (1969), Klovan and Billings (1967), Krumbein and Graybill (1965), McCammon (1968), Pocock and Wishart (1969), Rhodes (1969), and Spence and Taylor (1970).

ATTRIBUTES

PLACES	1	2	3	4	5	6	7	8	9	10
A		X	X	X		X	X	X		X
B	X	X	X		X	X	X		X	X
C	X			X		X		X	X	
D			X	X		X	X	X		X
E	X	X	X		X	X	X		X	
F		X		X				X		X
G	X	X	X		X		X		X	X
H		X	X				X			
I		X	X	X		X	X	X	X	

A

ATTRIBUTES

PLACES	1	2	3	4	5	6	7	8	9	10
A		y	X	X		X	X	X		X
D			X	X		X	X	X		X
I		X	X	X		X	X	X	X	
B	X	X	X		X	X	X		X	X
E	X	X	X		X	X	X		X	
G	X	X	X		X		X		X	X
C	X			X		X		X	X	
F		X		X				X		X
H		X	X				X			

B

ATTRIBUTES

PLACES	3	7	1	9	2	4	5	6	8	10
A	X	X			X	X		X	X	X
B	X	X	X	X	X		X	X		X
C			X	X		X		X	X	
D	X	X				X		X	X	X
E	X	X	X	X	X		X	X		
F					X	X			X	X
G	X	X	X	X	X		X			X
H	X	X			X					
I	X	X		X	X	X		X	X	

C

FIGURE 6. — Matrices showing: *A*, attributes of places; *B*, places grouped by similar attributes (*Q* mode); *C*, attributes grouped by similar places (*R* mode).

Overlapping of map areas formed by grouping generally is not allowed (Grigg, 1965, p. 486; Rodoman, 1965, p. 6), but contiguity or adjacency is another matter. Some geographers require that "regions" comprise only contiguous places (Johnston, 1968, p. 575, 578; Grigg, 1965, p. 476, 480); others recognize two types of regions in which one type requires contiguity and the other does not (Berry, 1968, p. 424; King, 1969, p. 199; Armand, 1965). Armand called the first "individual regions" and the second "typological regions." He recognized also that whereas typological regions can be precisely defined, individual regions often cannot. He noted that individual regions derive their uniqueness and integrity from predominance of a certain terrain or regular pattern of land types, but they may include alien enclaves.

Grigg (1965, p. 477) likewise distinguished generic and specific regions by, in effect, placing emphasis either on a suite of typological attributes or on specific spatial attributes (in the form of boundaries or location). The different types of geometric relations that may hold between regions defined by various kinds and combinations of factors were well illustrated by McDonald (1966).

DIVISION

The search for classes, individuals, mappable units, or natural regions can proceed, as shown in figure 2, by division rather than by grouping. Both processes are subject to similar rules of logic, they are often used in concert, and each usually results in a hierarchy of classes. But there is no assurance that their end products would be the same if the two processes were applied to the same information independently.

In division, the classes most significant to the purpose of the classification are produced at the beginning, and the most trivial, at the last. Therefore, the choice of criteria and attributes for the first few divisions is extremely important, for these determine the principal characters of the resulting hierarchy. Successive divisions are made in the order of increasing focus on details.

In mapping, logical division consists only of the addition of boundaries, without erasure or alteration of those already drawn. The process continues to reduce within-unit variance and produce smaller units until further division cannot usefully reduce heterogeneity with respect to the chosen essential concepts or attributes or until practical cartographic or economic problems become overriding. At this point we have a practical typological individual. Criteria applied at the successive stages of logical division must be defined as early in the course of study as possible to achieve economy of effort. Ideally, a hierarchy of criteria can be established on the basis of incomplete but representative spatial surveys; in geologic mapping, such surveys involve reconnaissance, widely spaced traverses, preliminary photogeologic work, or interpretation of other imagery. This naturally leads to the classification of type areas that exemplify those attributes or groups of attributes deemed important to the study. From here on, with the classification scheme begun, the proper categorization of new places, as unmapped areas are filled in, can proceed by successively applying discriminating criteria, starting with the highest rank of attributes and proceeding by the logical process of dichotomy. In the actual practice of geologic mapping, discovery of new properties and recognition of new map units are common, so a continuing revision of criteria and remapping of some areas are expectable as the study proceeds.

MAPPING OF FUNDAMENTAL ATTRIBUTES

Attributes are themselves structured into hierarchies. The attribute "suitable for liquid waste disposal" comprises others that are more fundamental, such as porosity, permeability, susceptibility to specific chemical or physical alteration, properties of the waste liquid, degree of saturation, thickness, and direction of ground-water movement. Some of these, in turn, can be broken down into still simpler components; permeability, for example, depends upon the size distribution, shape, and connectedness of voids. Eventually we should be able to define a set of n largely independent attributes of a basic nature (excluding position), which in various combinations would form the essential components for a larger number, N, of other attributes or statements.

Because fundamental attributes are the basic building blocks, we hope that they can be identified, and described or measured, in mapping, much as the elements are used in chemistry. In mapping, as in chemistry, the fundamental attributes can be structured in many ways. Unfortunately for the mapper, particularly in a natural science such as geology, the almost infinite combinations of physical, chemical, and structural properties of earth materials make determination of fundamental attributes elusive. Even where fundamental attributes can be identified in a single sample, the tendency for all earth materials to be heterogeneous requires that projection of these attributes beyond the sample be done with care and skill.

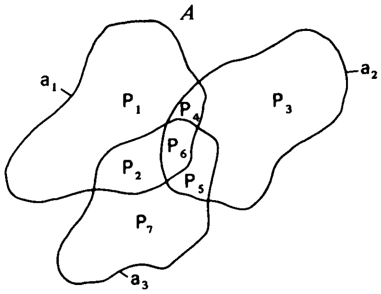
The geologic mapper can and should identify and map attributes pertinent to the purpose of his map. Obviously, if truly fundamental attributes can be identified and mapped, more uses can be made of the map, because many properties and qualities depend on the basic attributes. In actual practice, some of the properties known to be pertinent to the map purpose are selected for mapping. These, plus others collected along the way, can be tested for pertinence via such devices as an attribute-attribute matrix (fig. 7), which helps identify the most common attributes that may be important or even fundamental.

ATTRIBUTE	A_1	A_2	A_3	A_4	A_5	A_6
A_1		X		X		
A_2	X		X	X	X	
A_3		X		X		X
A_4	X	X	X		X	X ←
A_5		X		X		X
A_6			X	X	X	

FIGURE 7. — Attribute-attribute correlation matrix. Crosses indicate attributes that correlate. Degree of correlation and directed sense of dependence or causal relation could be shown by other symbols. Arrow indicates attribute A_4 correlates with more attributes than any other.

PLACE \ ATTRIBUTE	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
P_1	X							
P_2	X		X					
P_3		X						
P_4	X	X						
P_5		X	X					
P_6	X	X	X					
P_7			X					

A



B

FIGURE 8. — *A*, Attribute-place matrix. *B*, Superposed maps formed by plotting the information of the matrix and using the known position of the places; overlap is permitted.

The map distributions of various properties, qualities, and units commonly overlap, as shown in figure 1. In fact, it is the areas of overlap of various characteristics pertinent to the purpose of the map that define areas for particular performance, use, or behavior. Boundaries on true multiattribute maps are determined only by the areal distribution of the attributes shown. Such boundaries may or may not coincide with those of geologic map units. Where they do coincide, the geologic units can be used for cautious projection of information from the measured areas into other areas of concern, particularly where the geologic unit is only slightly heterogeneous with respect to the projected attribute. However, some pertinent attributes, such as slope or depth to water table, may at best be only crudely covariant with geologic formations. A compound map, formed by the superposition of several simple maps, in which overlap is allowed and integration and generalization are not imposed, can be regarded as a plot of an attribute-place matrix of the kind shown in figure 8.

PURPOSEFULNESS IN CLASSIFICATION

However constructed, a map requires the application of logical division and logical grouping, neither of which can proceed effectively without well-defined purpose. Yet we have long accepted the idea that engineering geological information, for special purposes, can be extracted from conventional or general-purpose geologic maps (Eckel, 1951; U.S. Geol. Survey, 1949). This concept is useful only to the degree that one can take a conventional geologic map, which is itself a synthesis — a special-purpose map for certain kinds of geologists — and make from it another synthesis corresponding to the needs of civil engineers, without drawing new lines or analytically decomposing the geologic map units into more basic components and reassembling them in another form.

The basic assumptions are (1) geologic map units are "natural" units, (2) components of these units have a common genesis and have been subject to similar environmental factors and processes, and (3) therefore, all parts of such units have so many attributes in common that the units can be regarded as homogeneous for diverse or general purposes.

As Searles (1956, p. 66–67) said,

> Classification is guided both by the nature of the materials to be classified and by the purpose of the classifier. This two-fold aspect may serve to introduce us to the distinction which is usually made between *natural* and *artificial* classification. Natural classification ideally is dictated by the discoverable natural structures, properties and attributes of the materials under investigation. Artificial classification, on the other hand, is dictated by some practical human purpose, such as convenience in handling and saving of time and energy * * *.

Harvey (1969, p. 331) pointed out that a general classification can be designed to serve many purposes, but it is unlikely to serve all those purposes with more than a low level of efficiency.

Grigg (1967, p. 486) discussed eight rules for classification, of which the first is *"Classifications should be designed for a specific purpose; they rarely serve two purposes equally well."*

Board (1967, p. 707), quoting Gombrick, said, "The form of representation cannot be divorced from its purpose and the requirements of the society in which the given visual image gains currency."

Cline (1949, p. 81) said,

> The purpose of any classification is so to organize our knowledge that the properties of objects may be remembered and

their relationships may be understood most easily *for a specific objective.* The process involves formation of classes by grouping the objects on the basis of their common properties. In any system of classification, groups about which the greatest number, most precise, and most important statements can be made *for the objective* serve the purpose best. As the things important for one objective are seldom important for another, a single system will rarely serve two objectives equally well.

Orvedal and Edwards (1941) made a distinction between technical and natural grouping of agronomic soils, and what they wrote years ago has direct relevance to engineering soils and engineering geologic mapping today:

By the term *technical grouping* we mean, in general, the placing of soils into groups for immediate practical objectives — objectives that pertain to the use and management of soils * * *.

* * * If soils are properly classified into a system of natural classification, they can be grouped in many ways for specific objectives. Almost any conceivable technical grouping for agricultural purposes can be derived from a sufficiently detailed fundamental natural classification; and this fact, incidentally, is one of the strong arguments for first classifying the soils according to a natural classification, even for immediate practical objectives. * * *

The first requisite for any technical grouping, as well as any other grouping, is a clear understanding of the objective for which the grouping is made * * *.

Everything hangs, of course, on whether the classification is sufficiently detailed and fundamental enough to serve several purposes.

The preparation of a derived or interpretive map from a geologic map depends on the thesis that two or more objectives *can* be served by a single system of classification. From a geologic map showing units based upon criteria of genesis, age, and lithology, we infer the boundaries of units having a satisfactory degree of homogeneity with regard, say, to lithology. Only the boundaries shown on the geologic map, or parts of them, together with supplementary information in the text can be used; no new field data are necessary. From the lithologic units, we infer units having particular properties, and from the units having particular properties, we infer units having the characteristics of performance, use, or behavior in which we are interested.

The success of such serial inferences depends primarily upon whether the original map depicts the required information in the necessary detail. The final probability that the derived map is acceptably accurate depends upon the product of the probabilities involved at each stage of inference. Suppose a geologic map unit "quartzite" is transformed into a use unit "suitable for building stone," without alteration of boundaries. Suppose also that the geologic unit actually is 0.8 quartzite and 0.2 shale and, further, that even if the rock is quartzite, the chances are only 8 in 10 that it is "suitable for building stone." The final average probability that any randomly selected part of the suitability unit actually fulfills the description is $0.8 \times 0.8 = 0.64$. Thus, although rather high probabilities are involved at each stage of inference, repeated inference may ultimately result in an unsatisfactory degree of accuracy for the stated purpose of the map. Unless new supplementary data are obtained, the final description of the unit must be made loose enough that it is true or accurate, although it then may become so broad, imprecise, and loaded with qualifying phrases as to be useless.

The whole matter is one of high current interest among geologists, geomorphologists, soil scientists, ecologists, environmentalists, and others concerned with land use in many parts of the world. Because of this interest, and need, and because we should be concerned about the possibility of misinforming our audience, some of the functions of and operations with maps, as specific means of communication, are briefly examined in the next two sections.

MAP INFORMATION

Maps are primarily instruments for arranging, storing, transmitting, and analyzing information about the spatial distribution of attributes. The term "information" itself needs explanation, for it has three principal aspects, of which any one or all may be exhibited by a geologic map.

The first aspect of information is syntactic: information is a quantity that can be measured by messages used in various means of communication, such as telephony, codes, or common language. This aspect involves the statistical rarity of signals quite apart from their truth, precision, meaning, value, or importance. Rare signals, having a lower probability, are regarded as being more informative, when they occur, than common ones. This is the "surprise" aspect of information (Cherry, 1966, p. 14, 50–51), which is closely connected with the concept of order-disorder and entropy in thermodynamics. In the context of maps, we might regard a gravity, geochemical, or geothermal anomaly, which appears in an unexpected place and whose meaning, significance, or cause is yet unknown, as an item of syntactic information. Likewise, a topographic map that shows a lone conical hill on an otherwise nearly featureless plain clearly contains information that the neighboring sheet does not, even though the hill's

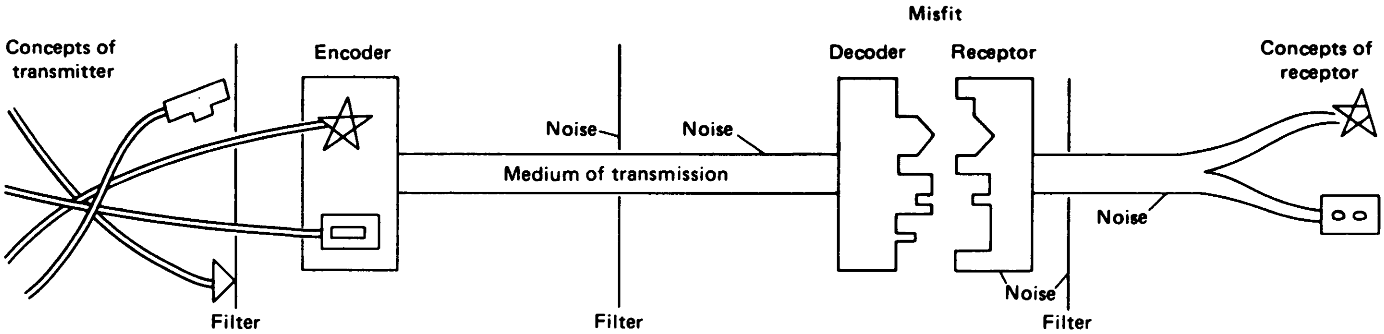


FIGURE 9. — Schematic diagram of some features of a communications system.

composition, origin, or significance to land use is completely unknown.

The second aspect is semantic: information concerns something other than statistical relations among signs or within language; it is *about* something. This aspect of information involves the validity of propositions, the construction of classification systems by grouping and division, and the progressive removal of uncertainty concerning the attributes of individuals and units apart from consideration of who the user may be and of the value, purpose, or use of the information. This kind of information forms a large part of the body of geological knowledge.

The third aspect is pragmatic: information refers to a completed communication process. Pragmatic information is measured by the change in state of an identified receptor produced by the receipt of a message. The change may be zero or catastrophic for any given message, depending upon the ability of the receiver to understand the message, upon his interest, and upon the resulting change in his previous assessment of probabilities concerning the subject of the message. Pragmatic information, like beauty, exists only in the eye and mind of the beholder. Cherry (1966, p. 245) stated that

> * * * what people value in a source of information (i.e., what they are prepared to pay for) depends upon its *exclusiveness* and *prediction* power * * *. "Exclusiveness" here implies the selecting of that one particular recipient out of the population, while the "prediction" value of information rests upon the power it gives to the recipient to select his future action, out of a whole range of prior uncertainty as to what action to take.

For example, a map showing a gravity anomaly might mean nothing to me except just that — an anomaly exists at such and such a place, and I am completely disinterested. To me this is syntactic information, of no value. But the same data arriving at the mind of a petroleum geologist already familiar with adjoining areas might have an enormous impact — completely altering his previous assessment, if any, of the attributes of the map area — and result in some decision or overt action.

The fields of applied science, of which engineering geology is one, seek constantly to convert semantic information to pragmatic information, to put knowledge in the abstract to use, to make it relevant. This requires a complete and operating communication system, such as shown in figure 9, with a transmitter, medium of transmission, and receptor, all having known pertinent characteristics and, to the degree practicable, all designed for the most efficient operation of the system. The process of transmitting cartographic information was examined in detail by Kolacny (1969).

OPERATIONS ON MAPS

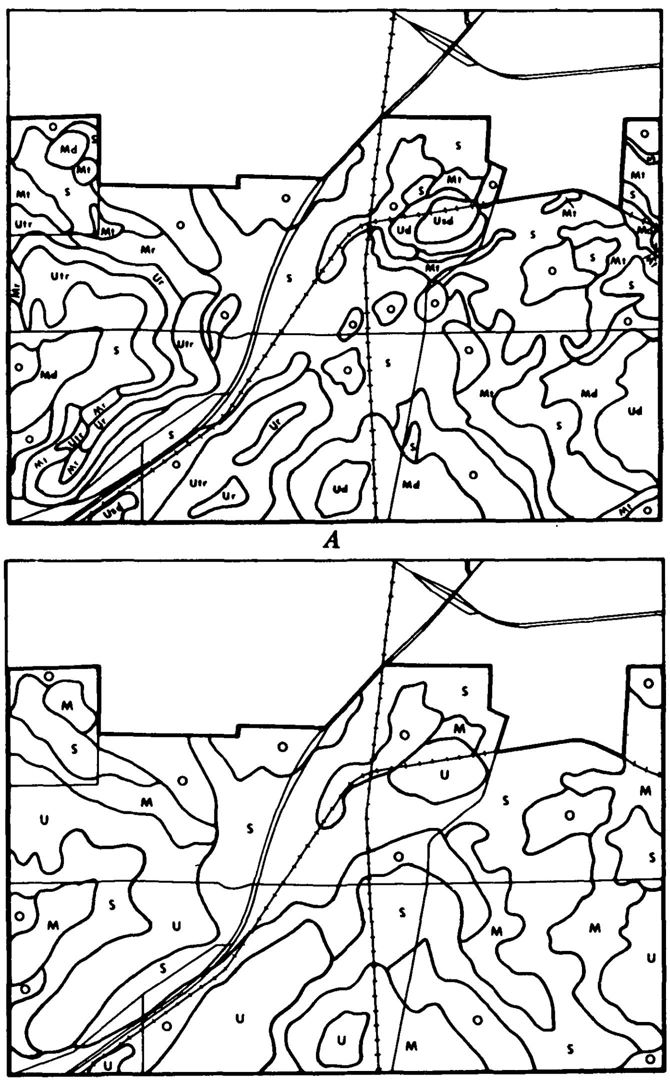
One may go beyond the reading and use of a map simply for the information on it and manipulate this information by performing an operation on the map for a new purpose. The four most common operations that can be performed on maps are generalization, selection, addition or superposition, and transformation.

GENERALIZATION

To generalize a map requires the preexistence of something more detailed. One does not a priori produce a generalized map unless he has at hand a map that is more detailed, or has at least a mappable mental concept of how things are really arranged in a more complicated manner than he is making them out to be.

As implied in the word itself, generalization is a simplification; and, because maps involve both areal and typological attributes, the simplification can occur in either or both types of attributes. The two types of attributes were recognized by Orvedal and Edwards (1941), who distinguished cartographical and categorical generalization. Although I do not agree completely with some of their examples, their concept is useful, and the paper as a whole is an excellent contribution to the philosophy of mapping.

In spatial or cartographic generalization, the boundaries between units are made smoother, tortuosities are simplified, and small inliers of one unit in another, if not important to the purpose of the generalized map at the scale intended for use, are absorbed by the surrounding unit. The number of typological classes remains unchanged, but class heterogeneity, particularly near the borders, may be greatly increased.



A

B

FIGURE 10. — Detailed and generalized versions of a rural residential land-use-suitability map. *A*, detailed, showing units as small as 5 acres and indicating ratings of optimum (O), satisfactory (S), marginal (M), and unsatisfactory (U), and limiting factors of slope (t), soil class (s), drainage (d), and depth to bedrock (r). *B*, Generalized, showing units larger than 10–20 acres, without indication of limiting factors. Map *B* is generalized both cartographically and typologically from map *A*. From Kiefer (1967, figs. 4, 5).

In categorical or typological generalization, classes are fused. If map units that are to be fused are contiguous, a boundary is removed; otherwise, boundaries are not altered. Noncontiguous units that are fused take on a single new color, symbol, pattern, or other label that designates the new unit. The classes are redefined on the basis of a new set of essential attributes. The new set may include some of the old attributes, but inevitably others are less specific than before. Thus, although categorical generalization can result in decreased heterogeneity, some information is lost. Both kinds of generalization may be required if information is recompiled at a much smaller scale.

Kiefer (1967) showed a generalized land-use map that involves both cartographic and typological generalization of a more detailed map. (See fig. 10.)

Generalization is not usually reversible. Degeneralization is not commonly a logical procedure, for once the details of boundaries are smoothed, or the details of attributes are lost in fusion of units, the original boundaries can be recovered only by reference to original data. This procedure is, in effect, a new start, not a reverse of generalization. Nevertheless, degeneralization is employed in making derivative maps, but its success depends upon the use of inference and experience concerning covariance of attributes.

SELECTION

Selection is the process by which a discriminating choice of information is achieved. It is an operation that must permeate mapmaking from initial concept to printing and be directed toward presenting a final product that shows the desired information effectively. The need to fulfill a newly recognized special purpose may, however, arise after the map is finished. Further selection of map units is then based upon one or more of the attributes stated to be present (or absent) in the description of the units. If the attribute upon which selection is to be made, say A, is not mentioned in unit description, then one must infer the presence or absence of A from experience and judgment about its covariance with expressly stated attributes. Obviously, then, selection commonly precedes the other operations of addition and transformation.

Selection may be semimechanical. For example, it may involve modifying the information-carrier base so that only certain information is transmitted. Suppose that a map showed typological attributes by means of colors produced by halftone dots and that

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each dot reflected light of a certain narrow band of wavelengths. If some attribute, A, was designated by color "a," then theoretically, those areas exhibiting attribute A could be selectively displayed either by illuminating the map with light of color "a" or by illuminating the map with white light and selectively filtering out all but color "a" from the reflected light.

The power to select may exist also, of course, in a receptor, such as the human mind, which can receive all sorts of stimuli from a map through the eyes but react only to some preselected one, rejecting or ignoring to a large degree all others. The process of selection is, however, somewhat more complicated than may appear, according to Treisman (1966, p. 610). She suggests that selective attention is achieved by reducing unwanted sense data to a mere trickle; but at the same time, in order to reduce the risk of missing something really important through inattention, the criterion for recognizing essential sights and sounds is set very low. Thereby, unwanted stimuli are not wholly blocked, and selection appears to be a complex and probably taxing mental process. No doubt the transmission of information is made more simple, accurate, rapid, and reliable, even from a map that is not very complicated, if the material is preselected or prefiltered before presentation to the user.

ADDITION AND SUPERPOSITION

A simple map is a map that shows the spatial distribution of one attribute or its class intervals. Many maps are compound; they consist of several or many

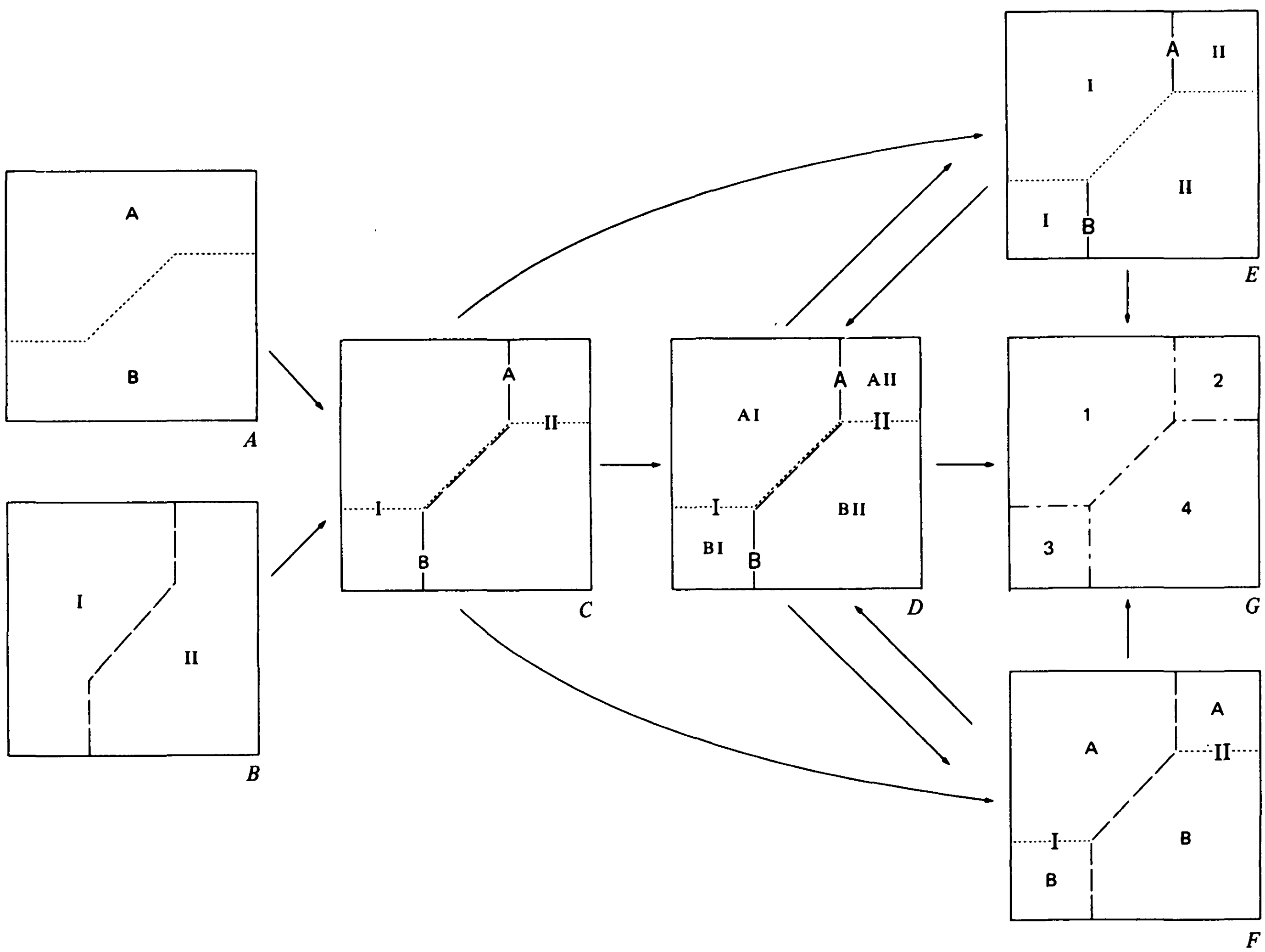


FIGURE 11. — Superposition of maps and regionalization. *A* and *B*, two simple maps; *C*, superposed; *D*, regionalized, with identifying names retained, equal weight to letter and numeral nominations; *E*, Roman numeral regions subordinate to lettered regions; *F*, lettered regions subordinate to Roman numeral regions; *G*, complete renaming of the four units, using Arabic numerals. From Rodoman (1965, fig. 1).

simple maps superposed and printed together. Each mapped attribute may, of course, have a rather simple definition or a relatively complicated one.

The addition of information to a map may involve any or all the processes by which maps are constructed; but basically, addition can be reduced to one or a combination of three processes:

1. Relating existing attributes to an added place or heretofore-unmapped part of area considered.
2. Relating additional attributes to an existing place.
3. Adding information concerning spatial or typological attributes at new times.

The second of these processes, adding attributes, can be accomplished over extended areas by addition of one whole map to another. This is perhaps more clearly indicated by the word "superposition" than by "addition." Superposition can be illustrated by a diagram (fig. 11) from Rodoman (1965).

The distinction is fundamental between superposition of simple maps and typological generalization of a compound map by fusion; recognition of this distinction is essential to understanding the present state of engineering geologic mapping. Typological generalization by fusion, as in figure 11*G*, results in a new spatial-typological individual, some of whose attributes are usually less precisely defined than were those of its components. If overlap can be tolerated, the maximum information load is carried by simple superposition, as in figure 11*D*, where all the original areal and typological data are still shown.

Superposition has been used very effectively in environmental planning. McHarg (1969), for example, showed what areas exhibit combined attributes to the maximum degree, by using film transparencies that record each attribute in degree by steps of decreasing optical density, the clearest areas having the attribute to the highest desirable degree. When the separate negatives are superposed, laying "truth on truth on truth" as he puts it, the clearest areas in the composite are those that show the combination of the desired attributes to the greatest degree. Grabau (1968, p. 218) used a similar technique of superposing "factor" maps to derive a "factor complex" map. The Kansas Geological Survey Study Committee (Kansas Geol. Survey, 1968) superposed factor maps to derive a combined single-purpose suitability map. An analogous system using punched cards that code the features or attributes exhibited by items (which can be areas) was described by Brink, Mabbut, Webster, and Beckett (1966, app. G). Haans and Westerveld (1970) superposed recommendations for soil use to derive a soil-suitability map in which the spatial distribution of each recommended use remains identifiable. (See fig. 12.)

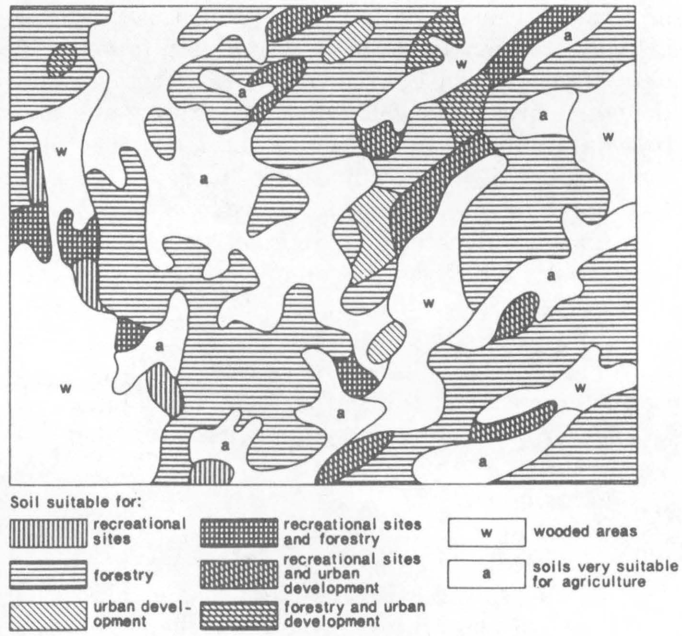


FIGURE 12. — Soil-suitability map showing superposition of recommendations for uses of areas. From Haans and Westerveld (1970, fig. 12*B*).

TRANSFORMATION

Very often communication is not achieved in a system such as shown in figure 9, because of a misfit at the junction between the transmission medium and the receptor. To so change the receptor that transmission is possible may require considerable effort and may result in so altering the receptor that other desirable qualities are adversely affected. It is easier to change the transmission side of the junction; that is, it is generally easier, quicker, and better for all concerned (if we are dealing with human beings rather than machines) to change the character of a map to fit the needs of the user than to modify the user so that he can extract information from a map which he does not initially understand.

Transformation is the process of changing the character and generally the meaning of lines, areas, and symbols of a map to make it more understandable and meaningful to the reader and more easily applicable to his purpose. The addition or acquisition of new data is not involved; the changes are in the symbolization, identification, arrangement, and, especially, description or grouping of existing information. Six kinds of transformation, generally in order of increasing complexity, are given below. The first three transformations are elementary mechanical ways to transform or modify a map to better fit user needs. The last three transformations relate to the whole process of gathering, classifying, and plotting data and are more fundamental, for they alter the meaning of previously drawn lines.

1. *Change in the medium for storage or display.*

   This involves interchange between paper, film, magnetic tape, negative and positive scribe sheets, and so forth.

2. *Change in symbolization.*

   This involves changes in character of lines, patterns, or colors; translation from one language to another; or change in symbols used for quantitative data.

3. *Change of metric.*

   A. Of spatial attributes; that is, change in the scale or type of projection.

   B. Of typological attributes; that is, alteration of class interval limits or change of variable, such as from X to log X.

4. *Spatial extrapolation.*

   This involves the assertion that place P_2 has the same set of attributes, A, known at place P_1 even though not all of A were measured or observed at P_2. This may come about because (1) P_2 is simply near to P_1; (2) a subset "a" of attribute set A was observed at P_2, and "a" having been recognized as a constant inclusion in A at P_1 and elsewhere, the presence of the full set A is inferred at P_2; or (3) both P_1 and P_2 fall within a boundary which is drawn around an area more or less homogeneous in a set of attributes, B, which commonly includes set A or has a satisfactory degree of correlation with it. All this sounds like rather sloppy logic, and it is, but these are some of the ways maps are drawn and some of the ways they can become misleading.

   Spatial extrapolation is the very common and very important process by which information at points of observation is changed to statements about areas or by which a user extends information from a mapped area into nearby unmapped areas of greater interest to him. Extrapolation includes also the process of interpolation, that is, the inference that the value of an attribute at an unsurveyed point can be estimated through knowledge of its value at neighboring points.

5. *Typological extrapolation.*

   This involves the assertion that because point P_1 is known to exhibit essential attributes A, B, C, and D, the probability that P_1 also exhibits unobserved and unessential attributes E and F is sufficiently high to allow E and F to be regarded as essential in lieu of A, B, C, and D in classifying other points. The validity of this operation depends entirely on the existence of a relation between set A–B–C–D and set E–F such that A–B–C–D implies or requires E–F.

   This process can be used for areas rather than points, with the added complication that spatial extrapolation is also involved. Typological extrapolation is commonly used in two circumstances:

   A. One or more of the essential attributes, say A and B, of a geologic unit may be much less easily observed than E and F; so E and F are used in mapping, but the map purports the presence of A and B.

   B. Attributes A, B, C, and D are not of interest to a user, but E and F are; that is, they are essential to definitions of new classes in which he has interest. Therefore, although mapping may proceed on the basis of attributes A through D, the map omits reference to them and shows only that the map unit has attributes E and F.

6. *Temporal extrapolation.*

   This involves using a map prepared at one time for making decisions or interpretations at another time. The error involved may be so small as to be negligible if the attributes shown are essentially static. But if the attributes are changing, such as those connected with processes and their rates, then errors may be large. Temporal extrapolation is always required in using a map unless the communication system operates virtually instantaneously, from data acquisition, through portrayal, to decision for use.

SUMMARY OF OPERATIONS

Some operations are not wholly independent, and they have been somewhat artificially separated to clarify discussion. For example, cartographic or spatial generalization involving the erasure of a small inlier can be regarded also as a radical typological transformation in which the attributes of the inlier are transformed from those it originally had to those of the host.

Table 2 summarizes factors in the more important operations that are performed on maps.

ANALYSIS AND PROBLEMS

Engineering geologic maps or maps intended to show some properties important to civil engineers and land-use planners have been constructed in many ways. The following pages are devoted to analyzing how some such maps are made and presenting

TABLE 2. — *Operations performed on maps*

Operation	Cause, reason, or purpose	Effects on graphic portrayal	Effects on language statements
Generalization:			
Spatial	To achieve emphasis or clarity; may be required cartographically after reduction in scale.	Boundaries made straighter; inliers erased; several symbols in a given area replaced by one.	Changes generally not necessary; can be made less specific to fit increase in heterogeneity.
Typological (same as grouping)	To clarify concepts, add emphasis, or remove detail unimportant to purpose.	Lines erased; fewer symbols used	Must be recast to make broader.
Selection:			
Spatial	To limit area of interest to user	Units outside of boundaries deleted	Some may require modification.
Typological	To emphasize or to fit particular needs.	Some units deleted	Some statements deleted.
Division:			
Spatial	To divide area for examination, sampling, or scanning.	Lines added	No effect on typological units; areal units defined.
Typological	Need for detail of new kind	Lines added	New units defined.
Addition:			
Spatial	To extend areal coverage or increase detail.	Map enlarged or information made denser.	None.
Typological			
Same map	To add related information	None	New attributes added.
Superposed maps	To add information of a different kind.	All map elements superposed	Statements still refer to identifiable areas for each attribute.
Transformation:			
Cartographic	Change of medium	None	None.
Spatial	Change of scale or projection	Size or shape of units altered; may require generalization.	None.
Temporal	Use in future	Depends whether attributes are constant or changing.	Depends whether attributes are constant or changing.
Typological	Change in actual or potential use for map.	Lines erased but not added without new field study.	Minor to complete change in definition of map units.

a few of the logical difficulties that may be encountered in their construction and use.

IDENTIFICATION OF ESSENTIAL ATTRIBUTES DURING OPERATIONS ON MAPS

The identification of essential attributes of a geologic map unit can be difficult even during mapping. A lithostratigraphic geologic formation is defined by lithology and mappability. Thus, it may be a distinct, perhaps only slightly heterogeneous, rock unit large enough to be mapped at the scale being used, or it may be a highly heterogeneous unit of many lithologies that is mappable only because it is sandwiched between two more readily identifiable units. The only essential attribute of such a unit may be that each part, by definition, lies between drawn boundaries. When the meaning of such a map unit becomes changed by an operation such as typological transformation — when attributes of use or behavior are ascribed to areas defined by lithostratigraphic criteria that may not require homogeneity — then the attributes essential to the new definition of the transformed unit may be even more difficult to isolate. This problem can be highlighted by looking at a number of examples that display operations involving a more or less regular increase in logical complexity.

A map consists of the elements of linework, pattern and color, symbol, unit name or identification, and word description. These elements of map language range from purely graphic to purely verbal, and the various operations on maps generally follow a course of metamorphism that affects first the words and then the graphics.

ADDITION OR REGROUPING WITHOUT REDEFINITION

The addition of numbers and words that give, say, the results of tests and that present inductive inferences concerning the engineering behavior of the mapped units does not affect the essential attributes of the map units. These attributes remain as they were, as do the names, symbols, and linework. There are many such maps, of which a map of the Oakland East quadrangle, California, by Radbruch (1969) is a good example.

The second operation that can be made, also without removal or change of lines on the basic geologic map or of the description of its units, involves a supplementary identification of the engineering behavior of specific lithologies and the geologic map units in which they occur. An excellent example of this type of treatment is a map of the Orocovis quadrangle, Puerto Rico, by Briggs (1971).

The geologic-genetic formation units of Briggs' map are grouped into tiers A through N on the basis of common engineering geologic characteristics. Each tier includes lithologically similar rocks from the various formations. As shown in a key, each geologic map unit, because it is heterogeneous, can be placed in several different tiers (some are in as many as four), and the principal tier to which a geologic unit belongs is shown by boldface type. (See fig. 13.) The engineering geologic tiers are not specifically shown on the geologic map, nor are they formally defined.

KEY FOR RAPID REFERENCE FROM MAP TO ENGINEERING GEOLOGY TABLE

Geologic map symbols in alphabetical order

Capital letters refer to tiers of table.

Letters in boldface refer to predominant rock types and characteristics

Map symbol	Tier	Map symbol	Tier	Map symbol	Tier	Map symbol	Tier
ha	**J**	Kmt	**H**	Kpw	**F**	Kva	**A**
Ka	**D**,G	Kmu	**H**,E	Kr	G,B,C,H	Kvm	**A**
Kc	**D**,A,B,E	Ko	**A**,C,G	Krf	**A**	Qa	**K**
Kct	**C**,A	Kpb	**D**,F	Krla	**A**	Ql	**L**
Kma	**B**,A,C,G,	Kpo	**H**	Kt	G,A,B,C	Qt	**K**
Kmaf	**A**	Kpr	**H**	Ktb	C,G	TKd	**I**
Kmd	**E**	Kprb	**H**,D	Kto	**B**,A,C,G	TKp	**I**
Kmh	**H**	Kpv	**D**,A	Kv	G,**B**,A,C	Tt	**N**

HOW TO USE THE ENGINEERING GEOLOGY TABLE

Columns are divided horizontally into tiers lettered A to N

Table to map—If the reader is looking for rock suitable for riprap, for example, he will search column 3 and find that tier B lists "Riprap—Good." Columns 1 and 2 of tier B show the rock types involved, the geologic map symbols, and the general area of the map in which these rocks are found. With these data the reader can then locate on the geologic map the sites where the desired material probably will be found.

Map to table—If the reader wishes to know, for example, the excavation and stability conditions along a proposed highway route, he can plot the route on the geologic map, find the geologic map symbols of the units crossed, and check with the key accompanying the table. Thus, if the area in question is labelled Kto, opposite this letter symbol the key lists **B**,A,C, and G, with the **B** in boldface. These letters refer to tiers and the desired information appears in column 3 of these tiers. The boldface **B** indicates that most of the Kto rocks will have the characteristics listed in tier **B**, while some of the Kto rocks will have the characteristics listed in tiers A, C, or G.

A

FIGURE 13.— Part of explanation for geologic map of the Orocovis quadrangle, Puerto Rico. From Briggs (1971). *A*, Key relating geologic map units to engineering geologic tiers, and directions for use of engineering geology table. *B*, First three columns and first five tiers in the engineering geology table.

Note that the lithologic descriptions for tiers B and E are nearly identical. If the engineering geologic classification depends on lithology, the essential attributes that distinguish these two tiers are unexpressed, at least in the first column of the tabular description. Inasmuch as tier B includes 80–90 percent of formations Kma and Kto but no Kmd and tier E includes 100 percent Kmd but no Kma or Kto, the unexpressed essential differences must somehow be linked to the definition or areal distribution of these formations. The engineering characteristics are somewhat different, but patterns of similarity in engineering characteristics do not seem to have wholly controlled the grouping or division into tiers. (Note similarity in the engineering characteristics of tiers C and D.)

Incidentally, Briggs' paragraphs on "How to Use the Engineering Geology Table" are exactly parallel to the two basic uses of engineering geological maps previously emphasized. His directions for going (1) from table to map are essentially those to find the areas of an attribute, and (2) from map to table are those to find the attributes of an area.

TRANSFORMATION UNEMPHASIZED

The next more complex operation involves actual typological transformation. This operation, which was discussed in an earlier section in somewhat abstract terms, is at the heart of many problems with real maps. The operation consists essentially of doing one thing and saying that it is, or amounts to doing, something else. The shift can be abrupt and very apparent, but it also can be so subtle and unob-

ENGINEERING GEOLOGY

Characteristics of fresh rock unless specifically stated otherwise (see column 1, tier M)

Tier	1. ROCK TYPES AND GEOLOGIC MAP SYMBOLS (Percentage indicates proportion of the rock type within each map unit)	2. DISTRIBUTION	3. GENERAL ENGINEERING CHARACTERISTICS (see text below this table)
A	Very thick lava and lava breccia: 100% of Kmaf, Krla, Kvm, Kva, dikes shown by red with x's, blue, and blue with x's 70-80% of Ko. 10-20% of Kto. <10% of Kc, Kct, Kma, Kpv, Kt, Kv.	Chiefly in the east-central and central parts but locally present in most parts of the quadrangle.	Excavation—Difficult. Stability—Good. Strength—Good (A). Aggregate—Excellent. Riprap—Fair (B). Fill—Fair. Permeability—Low. Tunnel requirements—Minimum.
B	Very thick and thick-bedded pyroclastic breccia and tuff, chiefly of marine origin: 80-90% of Kma, Kto. 30-40% of Kv. 10-20% of Kt. <10% of Kc, Ko, Kpv, Kr.	Widespread in east-central, central, and west-central parts of the quadrangle, locally near the southern border.	Excavation—Difficult. Stability—Good. Strength—Good (A). Aggregate—Good (A). Riprap—Good. Fill—Fair. Permeability—Low. Tunnel requirements—Minimum.
C	Very thick bedded hyaloclastic breccia and tuff: >90% of Kct, Ktb. 10-20% of Kt, Kv. <10% of Kma, Ko, Kr, Kto.	Chiefly in the area south of the Cordillera Central, locally elsewhere south of the Damián Arriba fault, which is near the northern edge of the map area.	Excavation—Intermediate. Stability—Fair. Strength—Good (B). Aggregate—Poor (A). Riprap—Poor. Fill—Good. Permeability—Moderate. Tunnel requirements—Minimum to moderate.
D	Very thick and thick-bedded pyroclastic breccia and tuff, chiefly subaerial in origin, and very thick and thick volcanic conglomerate: >90% of Ka, Kpv. 70-90% of Kc, Kpb. 10-20% of Kprb.	Widespread along the northern edge of the quadrangle north of the Damián Arriba fault; otherwise chiefly in the southern part of the quadrangle.	Excavation—Intermediate. Stability—Fair. Strength—Good (B). Aggregate—Poor (A). Riprap—Poor. Fill—Good (especially Ka). Permeability—Moderate. Tunnel requirements—Moderate.
E	Very thick and thick-bedded pyroclastic tuff and breccia, marine: 100% of Kmd. 20-40% of Kmu. 10-20% of Kc.	Almost entirely in the southern one-third of the quadrangle.	Excavation—Moderately difficult. Stability—Good, locally fair. Strength—Good (A). Aggregate—Fair (A). Riprap—Fair (A). Fill—Fair. Permeability—Low to moderate. Tunnel requirements—Minimum.

B

trusive that it appears to have occurred in the mind of the writer almost without his being aware of it. For example, Rockaway and Lutzen (1970), in their excellent report on the Creve Coeur quadrangle, Missouri, state (p. 5) that

Boundaries of map units were drawn based on engineering geologic characteristics of the bedrock rather than on geologic position or age, as on a conventional geologic map. * * * Because engineering parameters are the basic criteria used to denote the units, different geologic formations may be mapped as one unit. * * * In this system the bedrock formations and extensive surficial deposits of Missouri have been classified according to engineering properties into different units identified by Roman numerals. * * * Major units identified in the Creve Coeur area are:

Unit I — Alluvium
Unit II — Carbonate bedrock
Unit X — Cyclic deposits

Parts of stratigraphically separated formations were indeed included in single engineering geologic map units, but the statement that the mapping criteria were engineering parameters or properties seems unwarranted. Longer description of map units and subunits in the text indicates that the classification criteria actually used in mapping were genetic process (as in alluvium), lithology (as in carbonate bedrock), age ("Unit X denotes areas underlain by Pennsylvanian age bedrock," p. 11), and topographic position or form. Although the units adopted are less heterogeneous with respect to engineering properties and behavior than time- or rock-stratigraphic units would be, the criteria actually used for drawing the boundaries were not engineering but geologic.

A similar transformation appears in a figure presented in a very useful report on the pilot study for land-use planning and environmental geology of an area near Lawrence, Kansas (Kansas State Geol. Survey, 1968, fig. 10), here reproduced as figure 14. The shift from statements concerning lithology, slope, thickness of soil, and genesis to the statement "based on engineering properties" occurs rapidly and unobtrusively between the explanation for the map and the caption that immediately follows.

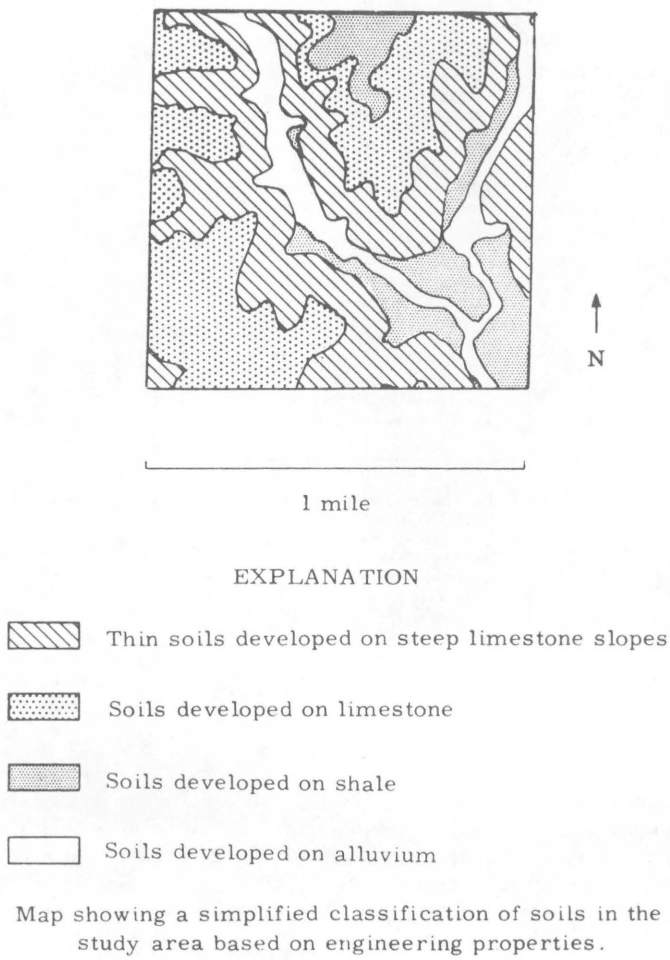


FIGURE 14. — Transformation of meaning between explanation and caption. From Kansas State Geological Survey (1968, fig. 10).

These examples may appear trivial to some geologist readers, who might be expected to infer, through long experience with our methods of induction, the whole meaning intended by the words. But what of the engineer or planner? If we say that our map boundaries are drawn on the basis of engineering properties, the nongeological reader has some reason to expect that we actually tested engineering properties and drew boundaries based on their values — that our map units are delineated in the field by homogeneity with respect to the engineering properties ascribed to them in our explanations—not that we are estimating engineering properties within a unit whose boundaries were drawn on the basis of other criteria.

UNITS REDEFINED

Typological regrouping assembles previously mapped geologic units into fewer use or behavior groups, identifies the regrouped units by new symbols or colors, and presents new descriptions. A good and typical example is the foundation- and excavation-conditions map of the Burtonville quadrangle, Kentucky, by Dobrovolny and Morris (1965). They used for this map all but one of the lines shown on the basic geologic map made earlier by Morris and added one line (requiring new fieldwork) that subdivided a geologic map unit according to lithology; these changes are indicated in a part of the stratigraphic column reproduced here on plate 1*D*.

The description of one of the four lettered map units for the Burtonville foundation and excavation map is also given on plate 1*D*. The new essential attributes of the units, as I would interpret them, are in the first line beneath the explanation box. That is, the essential attributes of unit A are now "Poor foundation material, easily excavated," and that is all; the remaining descriptive material is accessory — informative and useful, but not essential.

The grouping (and division) at Burtonville took place in an ordered vertical sequence involving a considerable thickness of stratified material, both bedrock and alluvium, and it was determined solely by the inherent lithological attributes of that material.

Grouping of units and transformation of descriptions for particular purposes is commonly performed on soils maps. In an article that often has been cited as the origin of the "stoplight" map system, Quay (1966) summarized the problems relating to a residential development by means of a map that shows units according to degrees of capability. The boundaries of the capability units are the previously mapped soil boundaries; his description of the capability units is shown below.

Map unit	*Description of capability*
A	No temporary or continuing problems.
B	Temporary problems, no continuing problems.
C	Significant temporary problems, no continuing problems.
D	Significant temporary problems, with continuing problems.
E	Significant temporary problems, significant continuing problems.
F	Significant temporary problems, complex continuing problems.
G	Temporary and continuing complex problems, imposing extra design requirement.
H	Temporary and continuing complex problems, imposing unusual design requirements.
I	Temporary and continuing complex problems, imposing such design requirements that conventional urban uses are impractical.

The classification of capability map units according to the kinds of problems involved lends itself to diagraming in a three-dimensional array, as shown in figure 15. This figure was constructed in the hope that geometric representations of classifications might be as helpful to the reader as they have been to me. I made two assumptions in constructing figure 15: (1) design requirements were classified as "conventional" unless otherwise specified and (2) the word "complex" was interpreted as a fourth class extending the continuous series that progresses from "absent" through "significant" to indicate seriousness of problems. The arrangement shows a progression directed from one corner of the array to its diagonally opposite corner, although not along the shortest path. Mapped categories lie wholly in the conventional or complex faces; that is, design requirements are not regarded as extra, unusual, or impractical unless both temporary and continuing problems are complex.

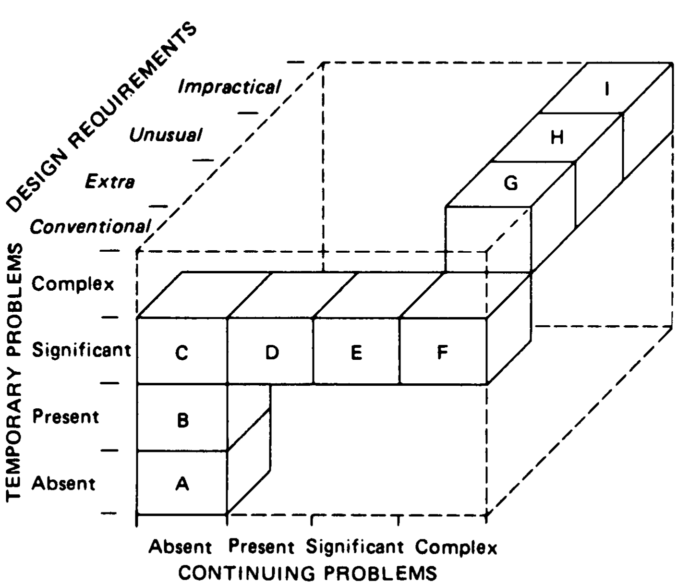


FIGURE 15. — Three-dimensional matrix of map units *A* through *I*. Units are defined by capability in terms of design requirements resulting from temporary and continuing problems of various degrees of severity. Based on Quay (1966, pl. 11).

Grouping, for a particular purpose, of a number of surficial units that occur within a limited vertical range but that are largely defined by inherent lithologic properties is illustrated by two maps in Hackett and McComas (1969): plate 1*A* (Surficial deposits) and plate 2*C* (Geologic conditions relating to waste disposal). Equivalent parts of these maps and their explanations are reproduced here as plates 1*E* and *F*. The map sheet has ample space for explanation of the units, so perhaps one can assume that the explanations contain all the essential attributes of the units in both the surficial-deposits and the waste-disposal maps.

Figure 16 shows the distribution of surficial geologic units among the suitability-for-waste-disposal units for the full area of the original published maps by Hackett and McComas (1969). The proportion of many geologic units assigned to a given suitability unit is very small. I estimated (by eye) that 15 of the 26 geologic units have 95 percent or more of their area assigned to 1 suitability unit. Other geologic units are more equitably divided among as many as 5 suitability units. Probably more than 95 percent of the lines on the suitability map coincide with or closely follow boundaries on the surficial geologic map. Because many geologic units occur in several suitability units, various individual patches of a particular geologic unit must have been assigned, undivided, to a variety of suitability units (which, of course, is apparent by inspection). Thus, suitability units have essential attributes whose changes in value closely follow geologic contacts but whose absolute value is not specifically determined by the material in the geologic unit. Hence, in this transformation we must be dealing with attributes that are accessory to the geologic unit and yet essential to the interpretive behavior unit. Such attributes can easily pertain to topography, geomorphology, hydrology, or even vegetation. In what follows, the

SUITABILITY-FOR-WASTE-DISPOSAL UNIT

GEOLOGIC UNIT	G2	G3	Y1	Y2	Y3	R1	R2	R3
1		X						
2			\			\	\	
4			X					
5A				\		\	\	
5B							X	
5C							X	•
5D		\			\	\		
6			\		\	\		
6/7			\	\	\	\	\	
6/9					X	•		
6/16				•	X			
7				\	\	\	\	
8		\			\			
9	X		•		•		•	
9-10			X					
10-9			X					
11					X			
12					\		\	
13-16					\	\	\	
14	X							
15			•				X	
16	\		\	\			\	
16G			\		\			
19	X							
21	X					•	•	
30								X

X > 95 percent of geologic unit is in indicated suitability unit
\ Geologic unit present
• Suitability unit present in amount < 5 percent of geologic unit

FIGURE 16. — Distribution of geologic units among suitability-for-waste-disposal units. Estimates by eye from maps in Hackett and McComas (1969, pls. 1*A*, 2*C*).

description of the suitability units is examined in more detail.

The statements made about the units on the waste-disposal map can be analyzed in two ways: by a data matrix (fig. 17) and by a tree of logical division (fig. 18). Each method serves a different purpose. The matrix indicates not only what is said about each established unit in relation to what is said about other units but also, by blanks or other means more clear than running text, what is not said, not known, or irrelevant to the classification process. The matrix is unwieldy, however, to use for placing a new area into the existing scheme or for reclassifying any small selected area that may not appear to fit the classification shown for it and its surroundings. The instrument needed for this operation is an identification key, which may conveniently take the form of a logical tree.

Both methods of analysis use answers to questions to determine the presence of attributes. If the same question is asked of all individuals or groups, the answers will not always be yes or no; the answer "yes or no" (equals "maybe") must be allowed. The answer to one or more questions may logically imply the answer to another; for example, a yes answer to "used as a ground-water source?" implies a no answer to "impermeable?" Such relations are, however, generally not symmetric; that is, a no answer to "impermeable?" does not imply a yes answer to "used as a ground-water source?"

In the data matrix (fig. 17), those attributes that I think may be necessary for division into classes are indicated by an underline. One attribute that seems to be both essential and unique is given a double underline.

In constructing a tree of logical division, one should consider the relative importance of the criteria to the purpose at hand and apply the criteria in order of decreasing priority or effectiveness in discrimination. The nine criteria shown in figure 17 can be arranged in factorial nine ways. After trying various schemes, I chose to arrange the criteria, in both the matrix and the logical tree, in order of decreasing number of map units to which the answer to the question appeared possibly necessary for classification. Thus, the presence of peat in a closed basin appeared, from study of the maps, to be a decisive characteristic — all areas of peat are G3 and almost all areas of G3 are peat — hence, the answer to question 1 creates a clear separation of G3 from the rest of the geologic units. Permeability of the surficial material appeared essential to the definition of seven of the eight classes, and therefore a question regarding that property was placed next, and so on.

The tree, better than the matrix, illustrates two points. First, often one can place a geologic unit in its proper class without having to answer more than a small fraction of the questions in the classification system. For example, G3 is isolated after one question, G2 after two, and R3 after three. All additional information given in the explanation about these units is redundant for identification, although it is certainly informative and useful. But how is one to determine which among many statements made about a map unit are really essential to its definition? A

	G2	G3	Y1	Y2	Y3	R1	R2	R3
1. Is the material peat in a basin?	No	Yes	No	No	No	No	No	No
2. Is the surficial material impermeable?	Yes	No	(Maybe)	No	(Maybe)	No	No	(Maybe)
3. Is ground water shallow or discharging?	(No)	Yes	( )	No	( )	Yes	Yes	( )
4. Are there ground-water sources at depth < 500′?	No	(Maybe)	(Maybe)	Yes	(Maybe)	Yes	Yes	Yes
5. Is material saturated at depth of disposal?	( )	Yes	( )	No	( )	(Maybe)	Yes	( )
6. Is the surficial material thick?	Yes	( )	Maybe	Yes	( )	( )	Yes	No
7. Is the surficial material highly variable?	(No)	(No)	(Maybe)	(No)	Yes	( )	( )	( )
8. Is the material subject to flooding?	( )	Yes	( )	(No)	( )	( )	Yes	( )
9. Is the bedrock permeable?	No	( )	( )	( )	( )	( )	( )	Yes

FIGURE 17. — Data matrix for classifying geologic units into units of suitability for waste disposal. Constructed from statements in map explanation for plate 2C of Hackett and McComas (1969). Underline indicates that statement seems essential to classification (if questions are asked in the order shown). Double underline indicates that statement seems both essential and unique. Parentheses indicate that statement is not specifically made, and the answer is an inference.

logical tree is helpful for this purpose, but its construction may be difficult, particularly in the choice of sequence of questions that lead to the most efficient division. The other point is that many empty sets hang on the logical tree. Although some of these may represent logical impossibilities, many do not. Should we infer that none of those possibilities are actually present in the area? What are the chances that some possible units, because they are rare or small, were incorporated in other units?

DIFFERING MAPS OF SIMILAR INTENT

This section began with examples of how easily new words and new meanings can be applied to existing map units, with scarcely a ripple in the smooth current of thought. Indeed, most problems in typological transformation stem from the statistical accuracy of applying new words to previously delineated areas. But this is not the only possible source of difficulty. One can transform two different maps of the same area and arrive at interpretive maps in which descriptions of the transformed units are remarkably similar yet the spatial picture (and therefore the meaning) is very different. This convergence and confusion is illustrated on plates 1*A* and *B*, where part *A* is a map showing suitability of *soils* for *septic fields* and part *B* is a map of the same area showing suitability of *formations* for *septic sewage disposal.* Map *A* is a transformation made by grouping units on a soil series map; map *B* was constructed by grouping units on a geologic map (both bedrock and surficial), except that one division was made that does not appear on the geologic map. The two transformed maps could hardly be more different. The distinction between "soil" and "formation" as the source of original data is crucial; yet this easily might escape the attention of a developer or planner, who may see only one of these maps and who is probably more concerned with suitability of the ground for a standard operation than he is with whether the material involved is a "soil" or a surficial or bedrock "formation." Such instances are apparently rare — so far. But many different groups —geologists, geomorphologists, soil scientists, physical geographers, and general environmentalists— are increasingly engaged in deriving special purpose maps from their own basic data and maps. We may perhaps see more maps, of different origin, that con-

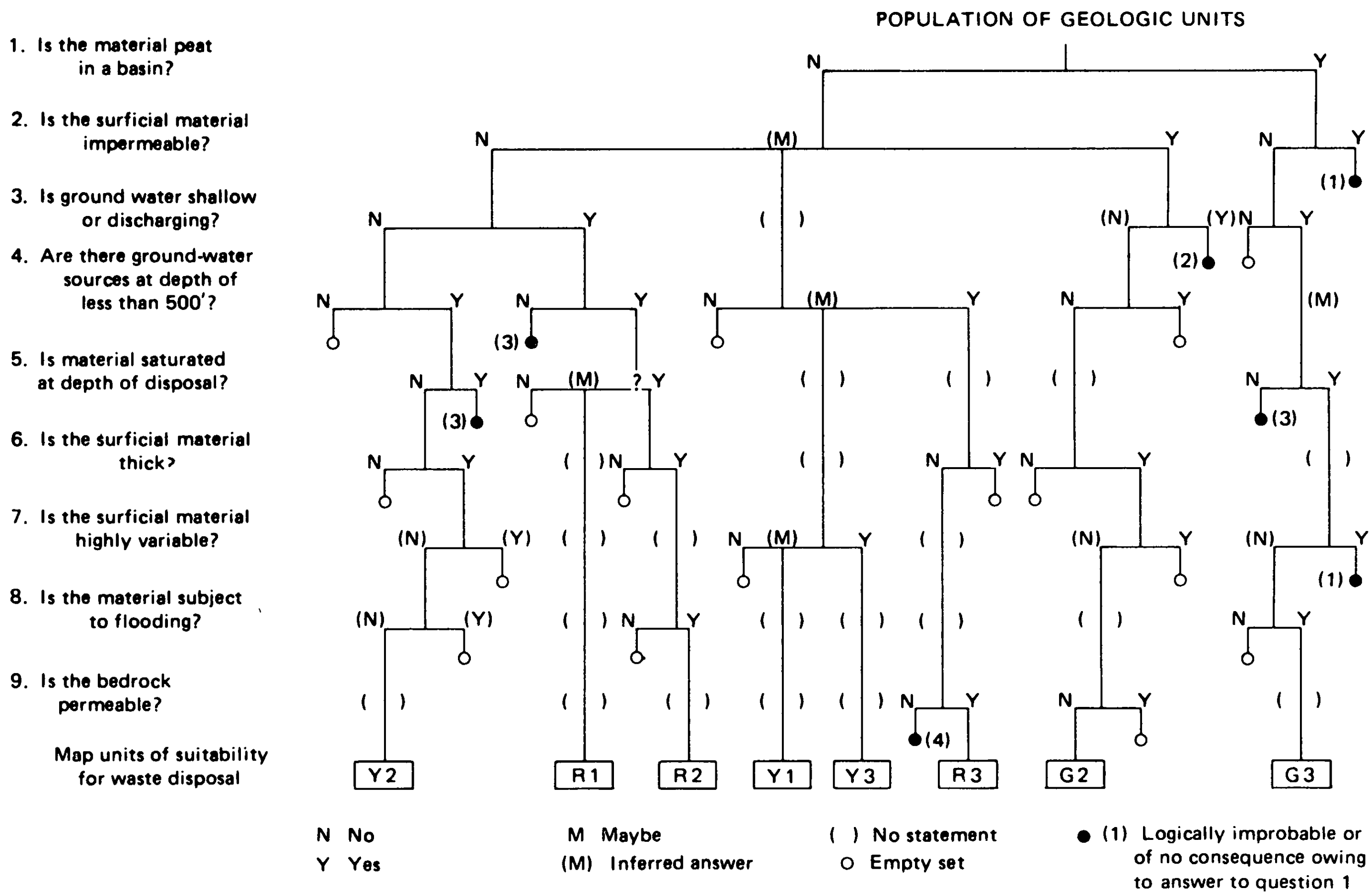


FIGURE 18. — Tree of logical division for classifying geologic units into units of suitability for waste disposal. Constructed from statements in map explanation for plate 2*C* in Hackett and McComas (1969).

verge in intent to show the same or similar attributes of the same area but which turn out to be confusingly different.

ADDITION AND SUPERPOSITION

Many derived or interpretive maps cannot in practice be obtained from the geologic map alone, as were the foundation- and excavation-conditions map by Dobrovolny and Morris (1965) and the waste-disposal map by Hackett and McComas (1969). Some types of derived maps require the addition of much other information or the use of other maps to create useful new classes of data.

COVARIANCE NOT REQUIRED

Classes of additional information may or may not be genetically related to the classes of geologic units with which they are to be combined. If classes are not genetically related, then generally they are not spatially covariant. A map showing units formed by the various possible combinations of two sets of genetically unrelated criteria will have a distinctive appearance. This appearance, in detail, can be similar to the costume of a harlequin, with four colors or patterns meeting at a point, as shown in figure 19, in which areas having attributes 1, 2, and 3 of one kind and A and B of another cross and overlap. If the criteria are not wholly independent, a change in one set will be accompanied by covariant changes in the other set, as shown at locality I, where the contact between lithologies 2 and 3 follows the boundary between slope categories A and B.

An attribute map that illustrates noncovariant contacts very well is the slope-stability map of the San Clemente area, California, by Blanc and Cleveland (1968), of which a part is reproduced on plate 1*C*. This map was constructed by superposition of two other maps: one showing four strength categories (essentially lithologic) formed by grouping geologic formations without adding new lines (Blanc and Cleveland, fig. 2); the other showing two slope categories, below and at or above the critical angle for stability (Blanc and Cleveland, fig. 4). This leads to eight map units, which are arranged in order of increasing stability as below:

Map unit	*Description*
8	Strength unit I, above critical angle.
7	Strength unit I, below critical angle.
6	Strength unit II, above critical angle.
5	Strength unit II, below critical angle.
	And so on.

The n $(=8)$ units taken p $(=2)$ at a time could lead to M distinct kinds of contacts between units, where

$$M=\frac{n!}{p!(n-p)!}=28.$$

Of these possibilities, 24 are actually realized in the whole area mapped; examples appear on plate 1*C*.

Figure 20 is a contact-criteria matrix for the San Clemente map that shows what attributes must change at the contact between units identified in the rows and columns. More than one attribute can change across a contact, but that type of contact on this kind of map either is rare or has a simple and probably significant geologic explanation, such as common coincidence between break in slope and bedrock-alluvium contact. The San Clemente map, besides being very useful for its subject matter, is thus a fine example of superposition of two simple maps of attributes to form a combined or compound map. It shows, without generalization during superposition, not only the areas that have specific attributes and the two classes of attributes that apply at any point but also a new set of characteristics regarding stability that are inferred from the combination of the attributes of slope and strength.

The superposition of maps of attributes that are generally not spatially covariant is most common in maps designed to show areas suitable for multiple use or areas of conflicting possible use. McHarg (1969, p. 114) presented such a compound map for Staten Island which shows areas suitable for conservation, recreation, or urbanization in four degrees each, together with areas in which these three potential uses overlap and compete equally, in all the various combinations and in four degrees.

If the added information required in transformation is not markedly spatially covariant with the units of the geologic map, if it is dominant over the criteria used for geologic mapping, and if it is given much greater weight than the geologic criteria in defining new units resulting from the transformation, then the boundaries on the new map will, of course, generally look much different from those on the geologic map. A good example is taken again from Hackett and McComas (1969); parts of their

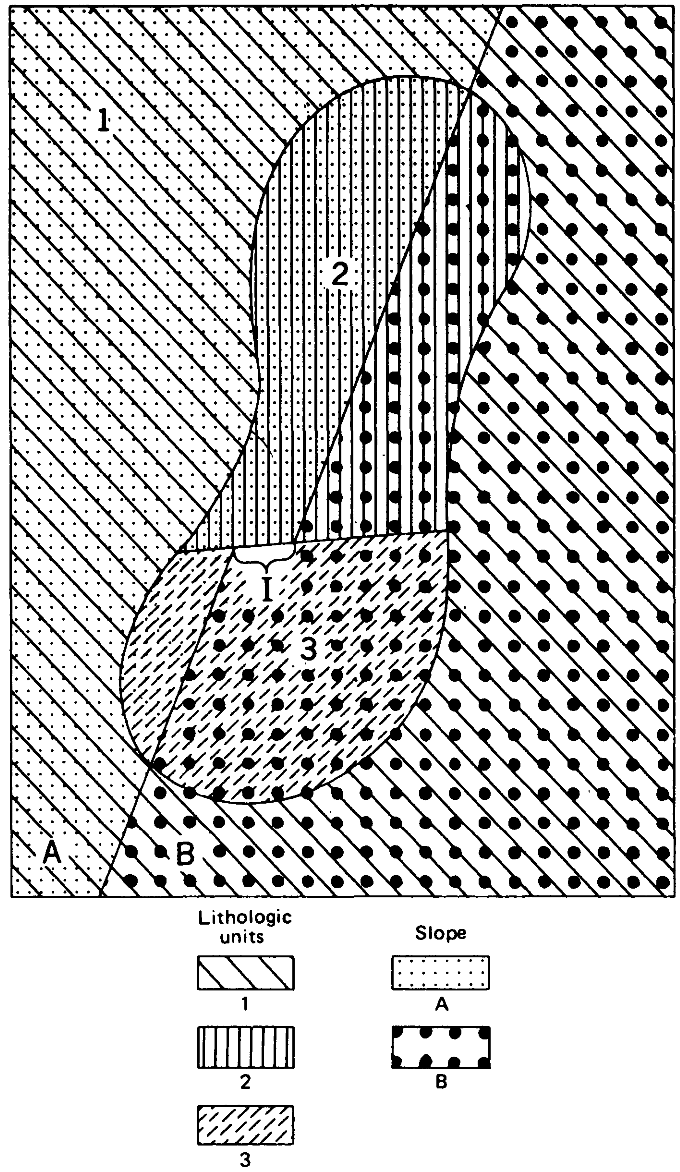


FIGURE 19. — Map units resulting from superposition of maps of two sets of attributes, such as lithology and slope, that are genetically independent and not covariant except at locality I.

plate 2*A* (Ground-water conditions) are reproduced on plate 1*G*. Note that the map unit boundaries bear only local resemblance to those on the map of surficial deposits (pl. 1*E* of the present report), because thickness, depth, and water yield of buried bedrock units as well as exposed near-surface surficial units were all considered.

The statements in the explanation are unusually informative, so a table of logical division could be made that uses not only yes and no answers but also the quantitative ranges of attributes. The table is shown in figure 21. As divisions are achieved going

STRENGTH GROUP	SLOPE ANGLE	I		II		III		IV	
		At or above critical (pink)	Below critical (tan)	At or above critical (yellow)	Below critical (pale yellow)	At or above critical (green)	Below critical (pale green)	At or above critical (blue)	Below critical (pale blue)
I	At or above critical		C	S	SC 2	S	(SC)	S	SC 2
	Below critical			SC 1	S	SC u	S	SC r	S
II	At or above critical				C	S	(SC)	S	SC 2
	Below critical					SC r	S	SC 3	S
III	At or above critical						C	S	SC 2
	Below critical							(SC)	S
IV	At or above critical								C
	Below critical								

FIGURE 20.— Contact-criteria matrix for slope-stability map, San Clemente area, California (Blanc and Cleveland, 1968, pl. 1, part of which is illustrated as pl. 1C of this report). Contacts between map units in rows and columns require changes in attributes of strength, S, and (or) criticality of slope angle, C. Some types of contacts are rare, r, uncommon, u, or absent, ( ). 1, occurs at head or foot of landslide; 2, occurs at foot of landslide or at break in slope at foot of valley side; 3, shown in contact on map, but apparently in error.

down the table, vertical lines are inserted, and the end result is the scheme of classification into six sets of conditions which are transformed into grades of suitability.

Note in the explanation for unit G3 the dual statement combining the two attributes "more than 50 feet thick below a depth of 50 feet," which is linked by the connective "or" to another dual statement. This complex appears to have helped distinguish G2 and G3 from Y1, Y2, and Y3, but the lack of definitive statements in G2 concerning buried sand and gravel aquifers leaves the distinction between G2 and G3 to be drawn on differing thicknesses of underlying dolomite. Perhaps this was the authors' intent.

Inferences must be made, or specific information is lacking, at quite a few places in figure 21. No doubt a complete logical tree would indicate empty sets whose existence is unspecified. A matrix in which each box contains yes, no, or maybe (or irrelevant), or an explanatory text constructed upon such a matrix, might add measurable clarity to these very useful derivative maps and texts.

COVARIANCE IMPOSED

The McHenry County ground-water map more than hints at further complexities in analyzing and presenting multivariable data usable for a specific purpose. Some purposes involve requirements that a map unit be defined by several attributes, which may not, actually and strictly, have the same boundaries. Such a unit is "regionalized" in the geographer's sense. Some units on the McHenry County ground-water map are at least in part defined by geometric relation—for example, units such as G2 or G3 consist of one stratigraphic unit over another. Also, there are distinctions between units according to specific ranges of continuous variables.

	G-1	G-2	G-3	Y-1	Y-2	Y-3
1. Are there permeable sandstone aquifers at depths of 500-2,000 feet?	Yes	Yes	Yes	Yes	Yes	Yes
2. Are there shallow aquifers (depth < 300 ft)?	Yes	Yes	Yes	Yes	Yes	Yes limited
3. Are the shallow sources suitable for all uses?	Yes	Yes	Yes	No	No	No
4. Are the shallow sources suitable for small requirements?	(Yes)	(Yes)	(Yes)	Yes	Yes	No
5. Do the shallow sources include surficial aquifers						
> 50 ft thick?	Yes	No	(No)	No	No	No
15-20 ft thick?	(No)	Yes	Yes	(No)	( )	( )
6. Are the buried sand and gravel aquifers						
> 50 ft thick below 50 ft depth? or > 25 ft thick above 50 ft depth?	( )	( )	Yes	(No)	No	(No)
25-50 ft thick below 50 ft depth?	( )	( )	No	Yes	No	( )
< 25 ft thick?	( )	( )	No	No	Yes	( )
7. What is thickness of underlying dolomite?	( )	> 100 ft	50-100 ft	> 50 ft with shale	< 50 ft	( )

FIGURE 21. — Table of logical division for map units of ground-water conditions, McHenry County, Ill. (Hackett and McComas, 1969, pl. 2*A*). Empty parentheses indicate no information in statements in the explanation; answer in parentheses is inferred.

The problems that may arise from these kinds of complexities are illustrated by the engineering geological zonation map of the Zvolen Basin, Czechoslovakia (Matula, 1969, app. 3). This excellent map is among the very few of its kind in English, of a real area, in full color, and generally available outside of central and eastern Europe. It is largely derived from information presented on a more conventional geologic map — a map of engineering geologic conditions (Matula, 1969, app. 2). The geologic map was prepared with the knowledge and intent that the zonation map could and would be derived from it. This sort of planning greatly increases the probability that a derivative map will be satisfactory for a specific purpose.

Parts of the Zvolen zonation map and its explanation are shown on plate 2*A*. Each map unit is defined by essential attributes concerning geomorphic form, slope, thickness of cover, and lithology or degree of consolidation of the underlying material. Figure 22 is a contact-criteria matrix developed from the statements made in the explanation of the Zvolen map. The matrix indicates what defining attributes must change at a contact represented by the intersection of map units listed in the rows and columns.

When units are defined by more than one essential attribute, a contact represents a change in one or more of the attributes. Only if they have close spatial covariance can all the essential attributes change at a contact. One type of contact shown on the full Zvolen map requires in three different areas covariation among three variables: slope, thickness of deluvia, and type of underlying material. This may be perfectly possible, but both the mapmaker and the mapreader need to be aware of the expressed or implied need for multiple covariation. If the mapmaker does not require strict covariation and he uses some averaging, sketching, or stretching of the nominal ranges to draw a "line of best fit," then he has employed typological generalization. No doubt this is very commonly necessary, but the mapreader needs to be advised by the mapmaker concerning the extent, possible significance, and effect of generalization upon the heterogeneity of the unit.

The three essential attributes used to define map units III, IV, and V on the Zvolen map can be represented in a Venn diagram (fig. 23). This diagram adequately illustrates the logical relations of the classes, but it portrays spatial relations less well. That is, units such as VA and IIIC that can actually be in physical contact are shown in this diagram as separated by other regions. However, representing both the logical and the spatial or topologic interrelations of three variables by using only two dimensions may be too much to expect.

A portrayal of the classification that shows some topologic similarity to the map is the three-dimensional matrix in figure 24. This is similar to but more complex than the matrix presented previously (fig. 15) in analysis of the classification used in a map by Quay (1966). The category boxes represent map units. Possible and actual contacts between most of the units may here be visualized as surfaces,

	I-A	I-B	II	III-A	III-B	III-C	III-D	IV-A	IV-B	V-A	V-B
I-A		G	G	G			G	G	G		
I-B			G	G		G	G	G	G		
II				G	G	G	G		G		
III-A						T					
III-B						L	T L		*	G T	
III-C							T		G T	G T L	G T
III-D								G (L)	G (L)?	G (L)	G (L)?
IV-A									L		
IV-B										G L	G (L)
V-A											L
V-B											

FIGURE 22. — Contact-criteria matrix for engineering geological zonation map, Zvolen Basin, Czechoslovakia (Matula, 1969). Contacts between map units in rows and columns require changes in attributes of geomorphology, G, thickness of deluvia, T, and (or) lithology of material under deluvia, L. Parentheses indicate change across contact is permitted but not always required; blank squares indicate units are not in contact on map. *, in contact at essentially a single point.

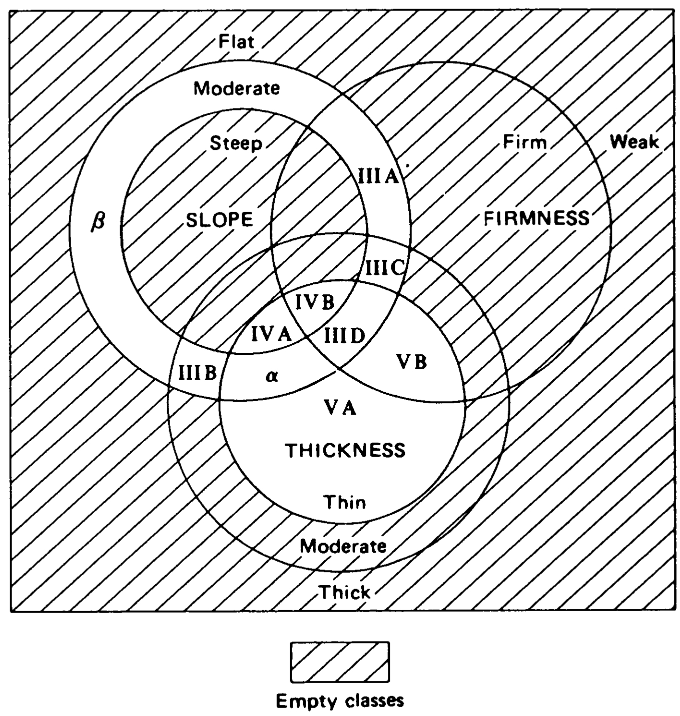


FIGURE 23. — Venn diagram showing classification of map units III through V, engineering geological zonation map of the Zvolen Basin, Czechoslovakia (Matula, 1969). Units are defined by three criteria: steepness of slope, thickness of deluvium, and firmness of underlying material.

planes, or points of contact if the boxes of the matrix were to be shoved together.

The geomorphological classification by slope or form is based actually on two different concepts: steepness of slope and narrowness of ridge. There are three categories of slope — steep (more than 15°), moderate (up to 15°), and flat — and two categories of width of ridge — narrow and wide. This minor cross-classification has led in some places to unit IVB being in contact with unit VA, without intervention of a band of Unit III, because the contact may have been drawn on the basis of width of ridge rather than steepness of slope or because the areas involved would be too small to show on the map. This "logical tunneling" is indicated in figure 24.

A three-dimensional matrix is useful also in checking to see whether all possibilities of the classification system are either discussed or specifically stated to be absent. For example, areas of moderate slope underlain by compressible bedrock and covered by deluvium either less than 2.5 m (meters) thick (indicated by α) or more than 5 m thick (indicated by β) do not seem to have been mapped separately as units; yet the map of engineering geologic conditions (not shown here) indicates that these criteria are fulfilled in some places. Such areas appear to have been incorporated into unit IIIB, and accordingly, connections or "bridges" are shown in figure 24 extending horizontally from IIIB to the α and β boxes. The single area of IIIA shown on the map is under-

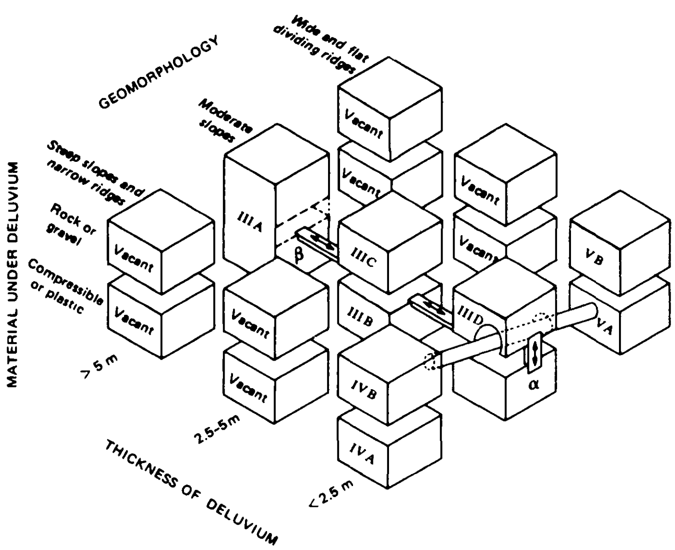


FIGURE 24. — Three-dimensional matrix of map units III through V, engineering geological zonation map of the Zvolen Basin, Czechoslovakia (Matula, 1969). Units are defined by three criteria: steepness of slope, thickness of deluvium, and firmness of underlying material.

lain predominantly by firm rock, but the definition of IIIA intends no commitment as to underlying material because of the practical difficulty of specifying lithology beneath more than 5 m of cover (Milan Matula, oral commun., 1972). On the other hand, some areas shown as IIID appear to be underlain by clayey material, so a connection is shown in figure 24 extending vertically from unit IIID to box α. The areas represented by the α box therefore may be shown either as IIIB or IIID on the map.

These remarks about a fine map are presented not in a spirit of criticism but rather to illustrate the inevitable difficulties that arise if map units are defined by ranges in attributes and if these attributes do not covary precisely in space.

In logical division, after the first division into, say, parts I, II, and III, the criterion for partitioning IA from IB may be, and usually is, inappropriate for partitioning IIA from IIB, and so on. Therefore, a map showing units derived by division cannot generally be analyzed by a criterion matrix of the type shown in figure 24. If, however, the map units are formed by grouping, as I believe the Zvolen Basin map units were, then theoretically the resulting groups can be arranged into an N-dimensional matrix where N is the number of categories of essential defining attributes. Actual complete graphic representation is possible, of course, only if N is 3 or less.

Problems that arise from the particular structure of a classification system are illustrated by a map of geological-engineering conditions and regionalization by Lozinska-Stepien and Stochlak (1970, fig. 2). The explanation and part of the map are here reproduced as plate 2*B*.

In the text discussion of regionalization for foundation of structures, item 6 in the explanation, the authors stated (p. 112):

> A detailed analysis was next carried out of all the factors that contribute to the full description of the geological-engineering environment. The following are regarded as of paramount importance in this evaluation:
> a — ground relief (gradients),
> b — permissible soil pressure of building soils encountered 1 m below the surface of the area under investigation,
> c — depth of occurrence of the first underground water level,
> d — presence of geodynamic processes.
> Therefore, potential sites for the direct foundations of structures have been differentiated on the 1:5000 urban area map of the geological-engineering conditions (Fig. 2).
> All these conditions (a, b, c, d, Fig. 2) must be fulfilled to qualify a given area for admittance into one of the differentiated categories. If so, the area will be indicated by a Roman figure only. Should even one of the required conditions not come up to the level of the given category that particular

area will be referred to a correspondingly lower category. For example: when three of the above requirements are complied with entitling an area to be included into the category for good geological-engineering conditions it will, nevertheless, be placed in the category of very bad conditions should the 4th requirement fit into that level. Say, if the gradients exceed 12 percent the given area will accordingly be classed lowest and will be indicated by the symbol Ia.

An area that lacks only one attribute for being classed at III will be downgraded into a subgroup of class II if IIa *or* IIb *or* IIc *or* IId is true. The designation of a particular area as IIb does not mean that the area has the attributes generally of II but rather that only one of its attributes is of rank II, namely b. This attribute thus becomes dominant in classification because the essential definition of II depends not on the whole suite of attributes listed under it but rather on the overall suitability rating "unfavorable." The other attributes of such an area, after it is classed as IIb, are then left in doubt, for downgrading could have occurred from either III or IV.

The structure of the classification system is brought out by figure 25, in which three of the cri-

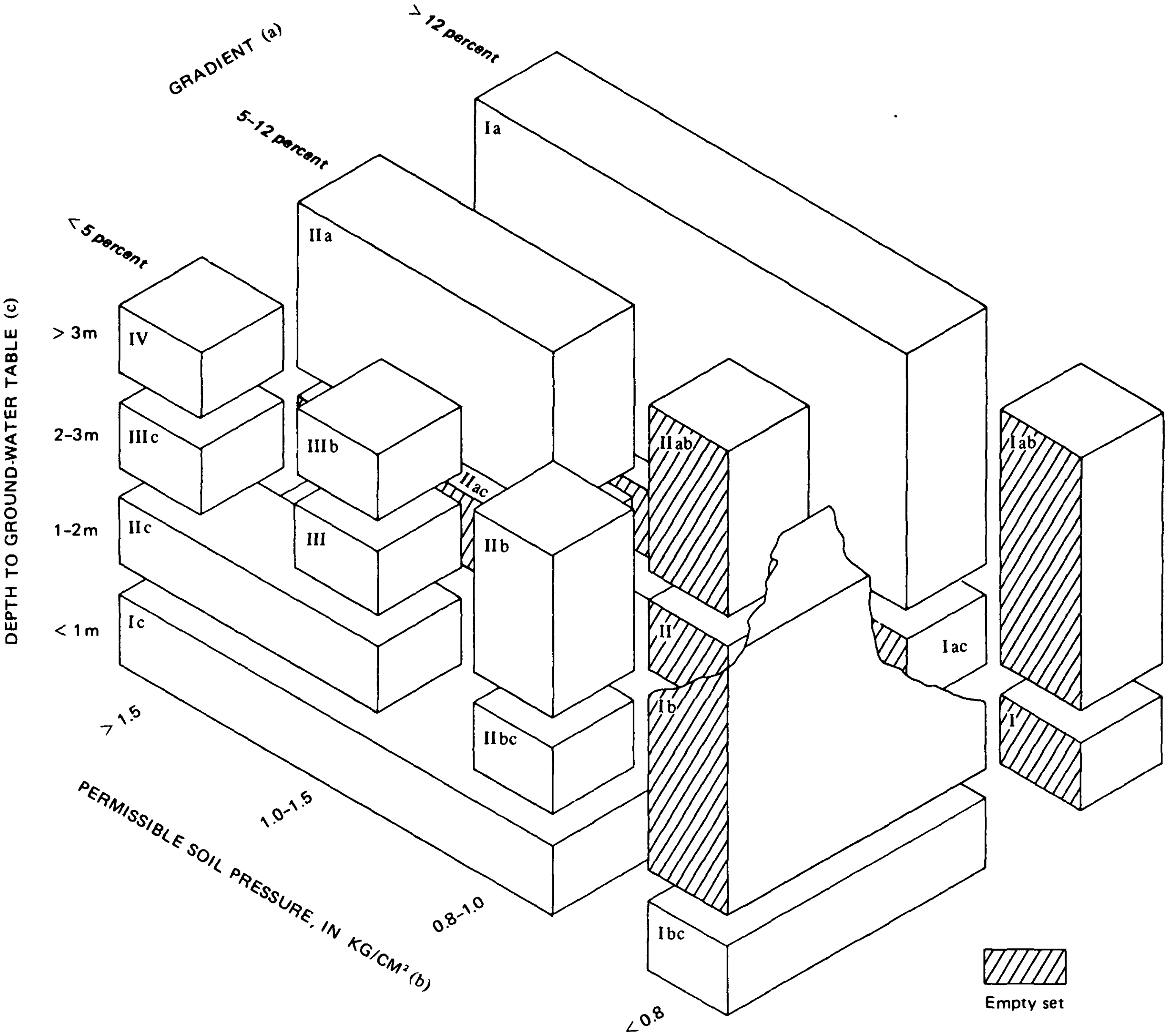


FIGURE 25. — Three-dimensional matrix of map units I through IV, map of geological-engineering conditions by Lozinska-Stepien and Stochlak (1970, fig. 2). Units are actually defined by four criteria, but only three were used to construct this example of a matrix. Units not actually present on the map reproduced herein are indicated by one ruled face.

teria for evaluation were used to form a three-dimensional matrix in which the prisms represent actual map units. A fourth major criterion, the presence of geodynamic processes, was omitted, together with some details. The matrix shows how the presence of a single unfavorable criterion results in downgrading into a large panel or block of low rank. Thus, specific information has been lost, while focus on judgment regarding suitability has been sharpened. If one tries, for example, to reconstruct depth-to-ground-water contours from the information given on the map, the results are equivocal, and alternative interpretations are possible. Because the boundaries of engineering geological regions coincide with either the color boundaries (depth to compact soil) or the pattern boundaries (material at depth of 1 m), then the depth-to-ground-water boundaries also must coincide with either depth-to-compact-soil boundaries or material-at-1-m-depth boundaries. These coincidences can be questioned.

TYPOLOGICAL DEGENERALIZATION

In the operation of typological generalization a map unit becomes defined by the "general" concurrence of a number of attributes, not all of which need to be present at any random point. A geologic formation typically is a generalized unit defined by the general concurrence or spatial covariance of a number of attributes such as lithology, environment of deposition, or genesis and relations with other units.

In the operation of typological degeneralization we ascribe to the whole of the generalized unit one of the specific attributes that was used during the original delineation of the unit. If that attribute was invariably essential to the generalized unit, then degeneralization is possible. If it was not, then degeneralization is successful only when the heterogeneity of the generalized unit with respect to that attribute is acceptable.

Suppose that a geologic map unit I has been defined on the basis of a characteristic suite of attributes A, B, and C. The attributes are fairly closely linked spatially, but not every area of I exhibits all attributes. Some areas showing each attribute have been mapped in the field as members, but their boundaries are gradational, interpenetrating, and poorly exposed. The boundaries between unit I and adjacent units that exhibit very different suites of attributes are sharp. So in the office, information regarding A, B, and C is not transferred to the master sheet; unit I is generalized typologically and defined as having attribute D that comprises A, B, and C. Now comes a user who is intensely interested in attribute B; he learns that D includes A, B, and C and that unit I exhibits D. In the absence of further information, he selects unit I as having attribute B and must assume that all parts of I are alike. An accompanying text may alert him to inhomogeneity within I, but it can never supply the specific spatial information that was lost when the lines demarking A, B, and C were erased.

For example, the Pierre Shale does not everywhere, laterally and in section, consist of shale. If, for interpretation regarding general engineering use, we ascribe the attribute "consists of shale" to all materials lying between established boundaries of Pierre Shale, we have then degeneralized that attribute. Such degeneralization may be acceptable for definition of a stratigraphic unit. It is easy to see, though, that degeneralization for certain purposes may not be acceptable, even regarding a lithologic attribute that forms part of a rock-unit name.

Consider now map units defined by "Natural landscapes with a characteristic pattern of rock, land form, soil, and vegetation, which is mappable from aerial photographs at the map scale used" (Haantjens, 1970, p. 7). Such "integrated" units are the object of applied geographical and geological mapping going on in many parts of the world. The particular example reported on by Haantjens concerns an area in New Guinea in which 39 land systems were recognized and described in terms of their relief, form, lithology, soils, vegetation, and agricultural capability, and a map of these land systems was prepared at 1:250,000. The point of interest is that from the land-system classification four small-scale maps were derived, which show lithology, ruggedness and maximum relief, associations of major soil groups, and agricultural land-use capability. The lithologic map, published at 1:500,000, has 10 units formed by grouping land systems. Some boundaries were removed, of course, but no new ones were added, and the ones that remain appear to have been reduced photographically. The resulting lithologic units appear now to be more heterogeneous, with respect to variety of rock types, than the original land systems. Perhaps the lithologic map serves some particular purpose, but this is not clear. In any event, the procedure is interesting in that a lithologic map is derived from a more general map, rather than the other way around.

Cartographical degeneralization — the restoration of cartographic detail that has been removed — is, of course, an impossible procedure without reference to original data.

MAP UNITS BASED ON RELATIONS

The units in many maps are defined not only by their inherent characteristics but also by their relations with other map units or components of map units. The relations expressed may, for example, be genetic, spatial, logical, ordinal with respect to some measure, geometric, temporal, sequential, or combinations of such relations. Most geologic map units are defined by essential attributes that are spatial, usually also sequential, and commonly genetic. Examples in the following sections show map units that are in part determined by the structure of the classification system, which, in turn, is designed primarily to display relations between map units or their components.

NESTED CATEGORIES

A nested classification structure is illustrated in maps by Pokorny and Tyczynska (1963). Figure 1 of the Pokorny-Tyczynska paper (geomorphological map) and figure 2 (geomorphological evaluation map) are here reproduced as figure 26. Note that the geomorphological evaluation map was constructed using a classification system having a nested structure; that is, map category IV is necessarily a subset of III, and III, a subset of II. The logical structure can be shown by a Venn diagram (fig. 27*A*) or, perhaps more clearly, by an Euler diagram (fig. 27*B*). Such a system would appear valid if only one criterion, say slope, were involved, and the successively smaller circles represented areas of steeper and steeper slope; but tables in the text that describe the units in more detail show that slope is not the only criterion. A nested map-logic diagram requires actual spatial coincidence between the areas of attributes causing unsuitability: areas of IV must everywhere have the unfavorable attributes of III plus others, and areas of III, the unfavorable attributes of II plus others. Perhaps this coincidence does in fact occur, but these implications are not discussed in the paper. Similar remarks are applicable to a map prepared by E. Jońca (Klimaszewski, 1960, map V).

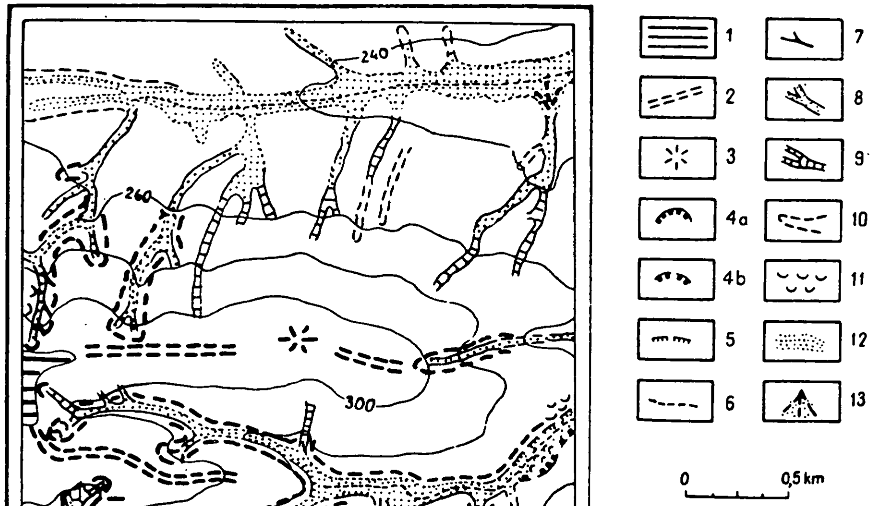
Plate 2*C*, from the explanation of a map published in 1971 by the Comisión de Estudios del Territorio Nacional (CETENAL) of Mexico, illustrates nested categories of potential use of soils. The colored matrix clearly indicates that lands in class I are suitable for all categories of use from wildlife to very intense agriculture. Similarly, lands in the other Roman numeral classes can be used for all purposes to and including the farthest right colored column in each row. Perhaps this nested classification works logically in many or most areas; but it would require that, in an as-yet-undeveloped area, class I land would be potentially suitable for wildlife and forestry and grazing and intense agriculture. Might not some lands be suitable for intense agriculture but not suitable for forestry or for wildlife? Are lands in classes I through VII always good for forestry or wildlife no matter what the character of the soil? In other words, are the attributes that determine the suitability for diverse uses spatially covariant?

VERTICAL RELATIONS

One of the most difficult problems of engineering geologic cartography is to show, on a plan map, the spatial relationships among a succession of near-surface stratigraphic or lithologic units. Commonly these units thin and thicken within short distances, interfinger, or are cut out by erosion surfaces. Such relations can easily be shown by sections, block diagrams, or fence diagrams. But to show in an areal plan the presence of several geologic units in proper sequence and also to indicate their lithology and some of their engineering characteristics requires not only detailed investigation but also thoughtful map construction.

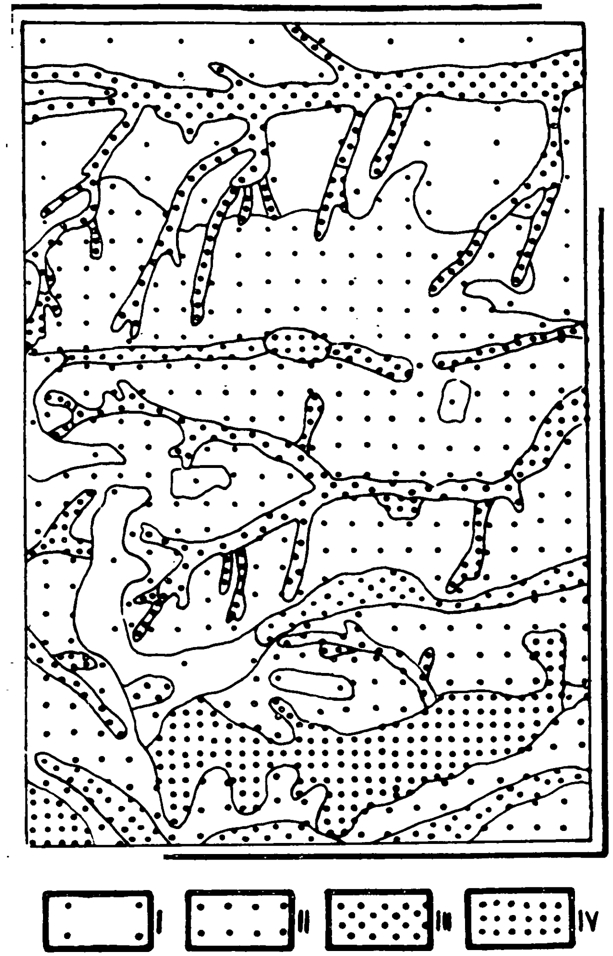
A simple method for showing that one unit rests on another is to print a pattern or halftone color representing the upper unit over the pattern or color for the lower unit. When done carefully, this way of adding maps works well for showing one unit over a variety of underlying materials, but only if the user can tell which pattern goes with the top unit.

More complicated sequences can be represented by uncovered, striped, or unitized maps. Uncovered maps are constructed to show the traces of contacts as they would appear on surfaces other than ground surface of the earth. These maps are of three types, depending on whether the surface of portrayal is (1) at a constant altitude relative to a base station ("level" map), (2) at a constant depth below the ground surface (specific-depth map), or (3) at a geologic horizon. Striped maps indicate underlying material by thin stripes of color or pattern that interrupt the color or pattern of the overlying material. Unitized maps use a specific color or pattern to indicate a particular succession of layers; thus, the pattern or color shown on the map is not determined solely by the outcropping formation. Vertical relations are also shown or can be inferred from contour maps that show, in plan, points at a constant depth below ground surface (or constant altitude above or below a datum) which lie on one or more surfaces of geologic interest, such as the tops of oil-bearing zones. Each method has advantages for certain purposes, and each also has its problems; some of these



A The geomorphological map:

1 — surface of planation; 2 — broad, rounded ridges; 3 — dome-like summits; 4 — young niches and scars; 4 b — old niches and scars; 5 — erosional edges; 6 — river beds; 7 — ravines; 8 — „Tielke"; 9 — „wądoły"; 10 — trough-like valleys; 11 landslide tongues; 12 — the lowest river terraces; 13 — Alluvial fans. For technical reasons the inclination of slopes has not been marked on this map.



B The geomorphological evaluation map:

I — forms generally suitable for house building, road construction and cultivation; II — forms making house building difficult; III — forms making house building and road construction in the direction of the maximum inclination of slopes difficult; IV — forms making house building, road construction and cultivation difficult.

FIGURE 26. — *A*, Geomorphological map, and *B*, geomorphological evaluation map, Kraków region, Poland. From Pokorny and Tyczynska (1963, figs. 1, 2). The derived evaluation map has a classification system with a nested structure.

problems are mentioned in the following discussion of uncovered, striped, and unitized maps.

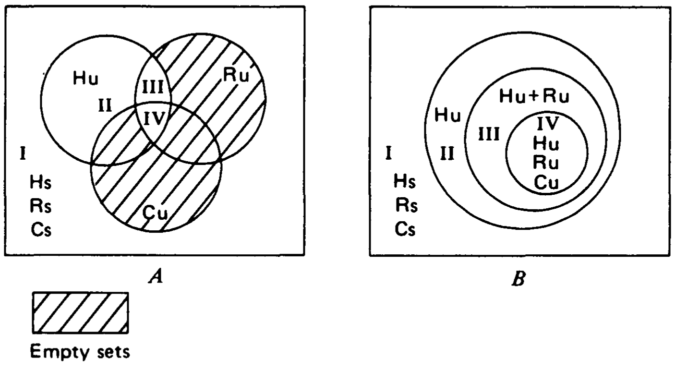


FIGURE 27. — *A*, Venn diagram, and *B*, Euler diagram showing classification of geomorphological evaluation map units I through IV in Pokorny and Tyczynska (1963, fig. 2). H, R, and C represent house building, road construction, and cultivation, respectively; s and u denote suitable and unsuitable, respectively, for the three purposes. Nested structure requires that all areas unsuitable for cultivation be also unsuitable for road and house construction.

UNCOVERED

Constant-altitude maps probably are most commonly prepared at large scales as a part of investigations of sites for major engineering works.

Specific-depth maps are exemplified by parts of the geologic map of Warsaw, Poland (Stamatello, 1965) ; one part is reproduced here as figure 28. Such maps show very well the particular lithology or other attributes at a place and at a certain depth, or the areal distribution of several lithologies or attributes at this certain depth. If the depth is one commonly of interest for foundations, say 2 m, such a map can be useful in land-use planning. Specific-depth maps are not easily used, however, for determining the sequence of materials at a point, unless each in a series of maps for various depths is on a transparent base and can be superposed in proper order; nor can specific-depth maps be easily used to gain a mental picture of the three-dimensional geometry of a unit whose borders cut at a low angle across the surfaces portrayed by the maps.

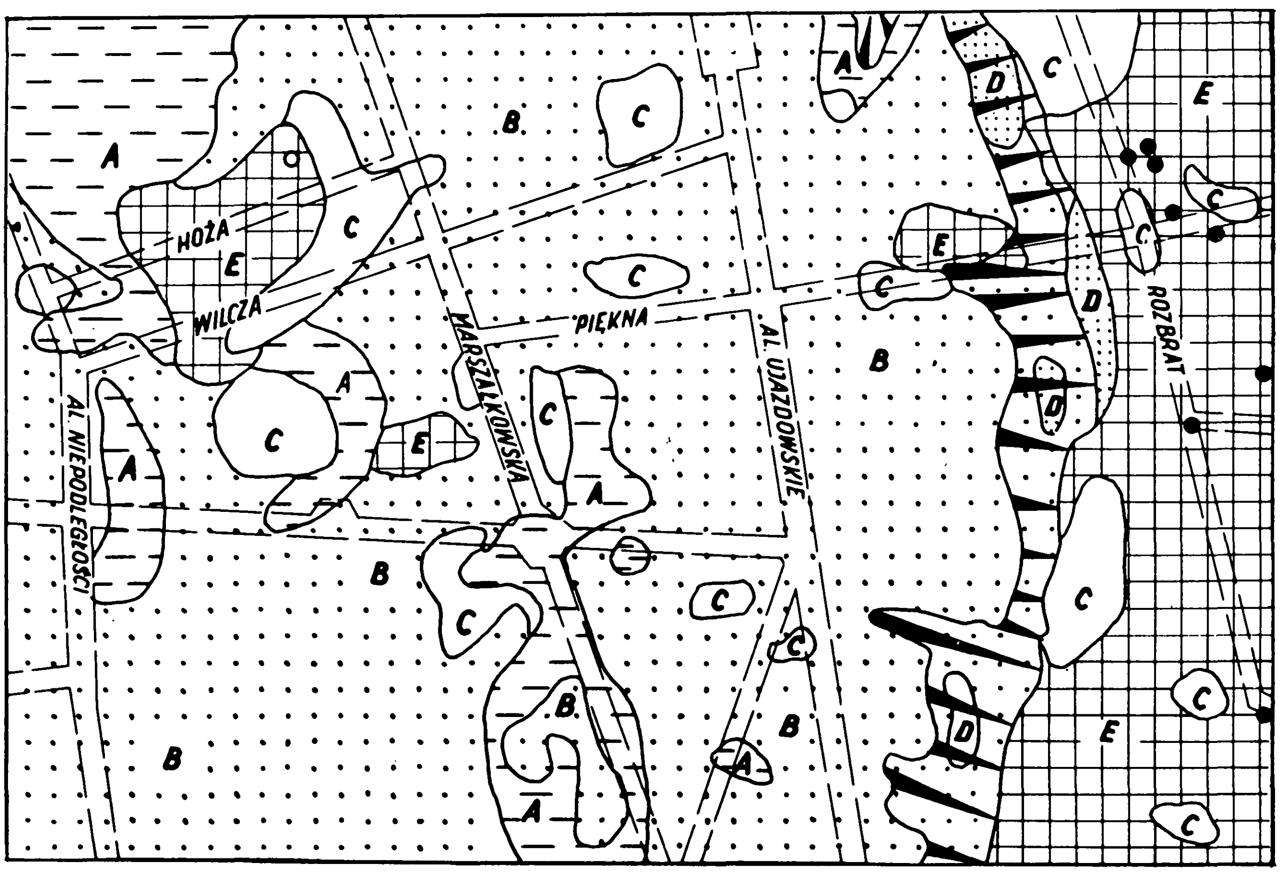


FIGURE 28. — Part of the geologic map of Warsaw, Poland, showing geologic units at a depth of 2 m. *A*, varved clay; *B*, morainic loam; *C*, fill; *D*, gravel; *E*, sand; *F*, clay, Pliocene. From Stamatello (1965, fig. 1).

Of the maps depicting contacts at a geologic horizon, perhaps the most common is the type of geologic map that shows bedrock contacts as they would appear if the surficial deposits and weathering products were removed.

STRIPED

The stripe method appears to have been first used in Czechoslovakia by Zebera in 1947 (Pašek, 1968), and it has come into increasingly wide use in Europe (Bachmann and others, 1967; Reuter, 1968; Bur. Rech. Geol. Min., 1969; Matula, 1969, map of Zvolen; Sanejouand, 1972). Patterns, stripes, and shades of color can be used to show lithology, thickness, and sequence of several bedrock and surficial geologic units (pls. 2*D*, *E*, and *F*). The method is well suited for showing the attributes at a point and the variation of attributes with depth; it can also show with some success the extent of both subsurface and surface units and thus exhibit the area of an attribute. It is well suited to showing intricate relationships or multiple attributes of small areas.

UNITIZED

Unitized maps use a particular color or pattern to represent a succession of two or more units rather than just the surface unit. This method has been rather commonly employed, particularly for the mapping of agronomic soil series in which the units are defined by a particular succession of materials, a soil profile. The terrain units in the Australian evaluation system for engineering (Grant, 1968a, b) generally involve, in addition to slope, vegetation, and other factors, a particular succession of surficial materials over bedrock. Some map units in the engineering geological zonation map of the Zvolen Basin (Matula, 1969) contain as essential parts of their definitions the stipulation that particular materials lie on others. On the engineering geologic map of the Creve Coeur quadrangle, Missouri (Rockaway and Lutzen, 1970), several map units are defined as a particular sequence of loess over a particular kind of bedrock (pl. 3).

A matrix that shows in somewhat simplified manner the definition of the units on the Creve Coeur map is shown in figure 29. Most of the units are relational, for they are defined as being alluvium or loess over cyclic deposits or over limestone. The type of display in figure 29 makes it possible to examine the classification structure and to raise some questions that are discussed below by numbers keyed to entries in the matrix.

UNITS DEFINED BY RELATIONS

COVER / BEDROCK		None	ALLUVIUM					LOESS		
			Silt, clay, high organic Missouri River flood plain	Thick Missouri River flood plain	Thin	Terrace	Lacustrine	Thin		Thick
								Ie(3)	Swelling	
CYCLIC					Ic	Id	Ie	Xb	Xc	Xa
LIMESTONE	Steep	IId						IId		
	Karstic				(1) Ic?			IIc		(4) IIa?
	Other				Ic	Id		IIb	(2)	IIa

UNITS NOT DEFINED BY RELATIONS

UNEXPRESSED			Ia	Ib						

FIGURE 29. — Matrix showing definition of units on the engineering geologic map of the Creve Coeur quadrangle, Missouri (Rockaway and Lutzen, 1970). The parenthetically numbered positions are discussed in the present text.

1. Areas of thin loess are divided into several units, depending on the underlying material, but areas of thin alluvium (and terrace alluvium) are not divided according to underlying material. Also, unit Ic is in contact locally with IIc; that is, areas of thin loess covering karstic bedrock are adjacent to areas covered by thin alluvium where there is no indication of possible solution activity in the bedrock. Does alluviation obscure karst topography or does it fill in karst and remove some of the possible hazard?
2. Swelling clay is shown as occurring only in loess that lies on cyclic deposits, not in loess of the same age on carbonate rocks. Is this coincidence, or is there a geologic-genetic reason?
3. Unit Ie (lake deposit) is overlain by loess, according to table 1 of their report. Here the matrix does not work.
4. Unit IIa is in some places in contact with unit IIc. Are there no karstic areas under thick loess, are they unobservable, or do they present no engineering geologic problem?

Because some of the Creve Coeur map units are two story (or three story), the tabular text description of their engineering behavior and limitations encounters some difficulty; that part of a complex unit to which a statement refers must be identified, or the statement must be qualified in some way. This raises the question of how one can describe both the engineering properties and the spatial distribution of a buried material that has been generalized into a more inclusive map unit.

Showing vertical relations in plan view has, in geological mapping, attained its most complex development in the profile-legend map. This type of map was developed by the Netherlands Geological Survey (Hageman, 1963; Thiadens, 1970) to serve the particular need in Holland for showing the great variety of relationships among the Holocene and Pleistocene deposits. Because each color, supplemented where necessary with patterns, represents a particular succession of as many as five deposits, as well as the interfingering and erosional relations between them, such a map carries a tremendous load of information. The examples I have seen (Hageman, 1962; Rummelen, 1965) show impressively detailed cartography of buried surficial units. Profile-legend maps raise questions, however, in spatial logic that are shortly to be discussed herein.

Deposits related to the Holocene marine transgression in Holland have three main components, which are, from top down:

Dunkirk deposits (marine),
Holland deposits (peat), and
Calais deposits (marine).

Holland deposits can interfinger with Dunkirk or Calais deposits, or both, but Dunkirk and Calais are separated by an unconformity and cannot interfinger. Thus, allowing omission of a deposit and assuming no interfingering, there are seven basic ways the deposits can occur in sequence; interfingering produces additional combinations (fig. 30). The possible combinations in a real map area are shown below the plan map by a schematic profile (pl. 2*G*), which shows the succession signified by each map unit. Details of the profile-legend method, including examples in color with the full suite of patterns and symbols, are given in a leaflet (in Dutch) that accompanies this map and text by Rummelen (1965).

The profile-legend method is apparently still being experimented with and improved, so any critical remarks at this stage may be inappropriate. Nevertheless, the method is clearly an important innovation that deserves study and analysis; hence, the following comments are offered, more or less within the subject of spatial logic.

First, the map by Rummelen (1965) illustrates very concretely a common difficulty in the handling of complex spatial information, namely, that the designation used for a sum or combination of attributes often cannot be formed by the sum or combination of the individual designations for those attributes. For example, if attributes A, B, C, and D are indicated on a map by colors, patterns, or symbols of respective types a, b, c, and d, then it would seem "logical" to indicate A+B by a+b and so forth (Golledge and Amadeo, 1966). Obviously, such summation can lead to intolerable clutter where more than a few combinations are possible. Moreover, if certain colors or patterns are added, the resulting visual impression may not be at all to the effect that a+b represents A+B. The Dutch maps are a deliberate effort to increase the information capacity of a map system by setting a single designation (color plus symbol) to indicate the combined presence of three or more units in a particular geometric relationship.

Second, in the profile-legend system the attributes concerning identity become subordinate to those concerning geometric relationships. Thus, where Dunkirk II deposits are at the surface, the map color may be dark tan (unit 33, DPo.2), light green (unit 4, Do.2), or olive brown (unit 11, Fo.2), depending on the subjacent materials. Also, minor variations in units at depth may result in a change in classification that produces strong visual contrast on the map. For example, a minor variation in the thickness of Calais, from slightly less than 1 m to slightly more than 1 m, as it occurs between peat lenses at considerable depth, results in major reclassification and striking changes in colors, patterns, and symbols, as for example from unit 16 to unit 23 or from unit 17 to unit 22.

Whether these properties of the Dutch maps are detrimental depends on the use to which the maps are put. In general, the maps appear to show well the attributes at any selected point or small area, but they may show poorly the area of an attribute or the areal extent of units exposed at the surface.

VALUE RELATIONS

A type of map that has come into increasing use comprises units whose only essential attribute is the ordinal position each occupies in a scale that measures value, limitations, or difficulty. Typical among such maps are "stoplight" maps, which use red, yellow, and green to show various degrees of suitability of the land for a particular purpose. Some of the McHenry County maps (Hackett and McComas, 1969) illustrated previously are examples of the type. The essential attribute of the unit — in effect its name — is the value judgment expressed by the colors and by the symbols R, Y, G; but this nomination is supplemented by much other information about accessory physical attributes pertinent to the use involved.

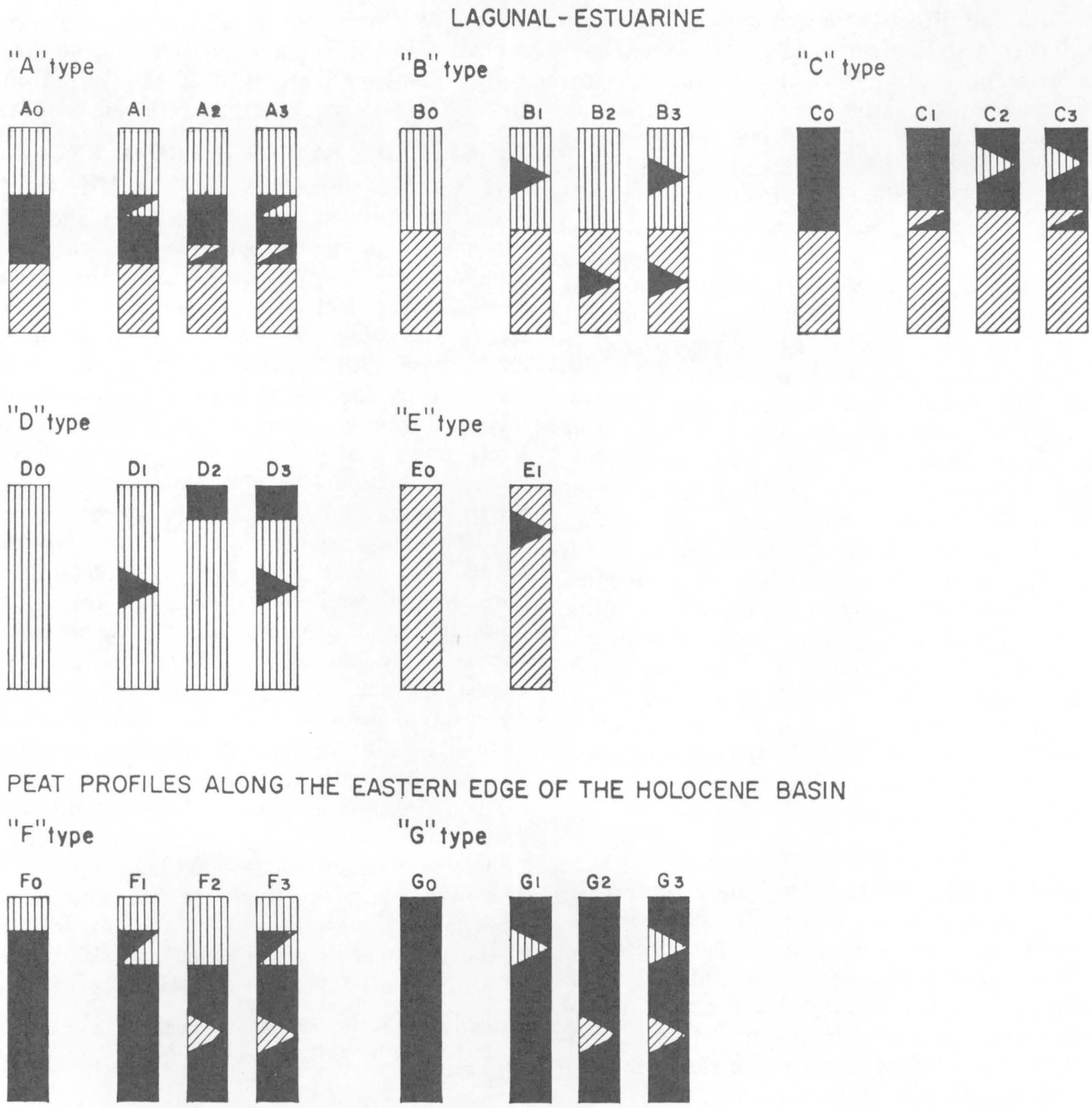


FIGURE 30. — Types of sedimentary units in the profile-legend type of map developed by the Netherlands Geological Survey. From Hageman (1963, fig. 7). The fundamental type, A_0, consists of Calais deposits overlain by Holland deposits overlain by Dunkirk deposits. Other types show various combinations of the deposits, and subtypes depict interfingering.

COMMENTS ON CARTOGRAPHY

The act of mapping is always basically the same, drawing lines around homogeneous areal units; but the role of a map in transmitting information from maker to user has many aspects, of which only a few are mentioned here. As Bowman (1968) has so clearly shown, graphic language has vocabulary, grammar, phrasing, structure, emphasis, meaning, and many of the other qualities of written language. And, in common with written or spoken language, the effectiveness of a map to transmit a concept from mind to mind depends not only on what it says but, equally, on how it says it.

VISUAL EMPHASIS

Visual emphasis logically should be placed on those elements of a map that are most important to the concept being presented. This may not be feasible for some purpose if colors, patterns, symbols, or other identifications of geologic units are based on a standard code derived from other real needs and logical justifications. But maps derived from basic geologic data and directed toward one or a few specific engineering geological needs more often have freedom to emphasize any selected feature. As the intent of the map to satisfy more needs broadens, however, so may the visual emphasis become either diffuse or even misdirected. From this point of view, the visual emphasis of the Creve Coeur map (pl. 3), which is an engineering geological map of intended broad usefulness, seems placed on the underlying bedrock rather than on the ubiquitous and thick blanket of loess. This emphasis seems intentional, yet the engineering characteristics, properties, and problems associated with loess units such as IIb and Xb where bedrock is not encountered are (and are stated to be) very similar; the visual emphasis produced by contrasting colors of the map might, however, lead one to expect considerable difference.

Similar difficulties appear on the soil map of Jefferson County, Wis. (Milfred and Hole, 1970), if one wishes to use it for a synoptic view of land capability or engineering characteristics of the units. Two units comprising soils with very different use limitations are of nearly the same color; some soils with similar properties, at least in the upper 3 or 4 feet, are shown in contrasting colors. The latter circumstance arises because units were differentiated, as at Creve Coeur, on the basis of the material lying beneath a blanket of loess.

RANK OF CONTACT

Classifications of geologic or soil units for practical purposes commonly make use of specified ranges of continuous variables such as depth, thickness, or slope. Where abrupt changes occur, the values of such continuous variables may differ across a contact by more than one step in the classification system; that is, one or more steps in the range may be skipped. Figures 31 and 32, from Haans and Westerveld (1970), illustrate such contacts.

It seems reasonable to suppose that a contact across which continuous variables change by more than one step may be more significant for a given purpose, or significant to more purposes, than a contact which simply marks a change of only one step in the range of a particular variable. Where continuous variables do not vary continuously something geologically important may be indicated; contacts marking abrupt breaks in variation of a characteristic carry more information, perhaps evidence of unconformity or faulting. This suggests possible usefulness of a concept of rank among contacts, depending upon how many classification-range steps or categories a contact represents, as shown in figure 33. Thus, the area 1Cv in the center of figure 31 is bounded by a contact of rank 3, as it represents a change in thickness of peat from <40 cm to >40 cm (1 step) and in depth of sand from 40–80 cm to >120 cm (2 steps, skipping the class 80–120 cm).

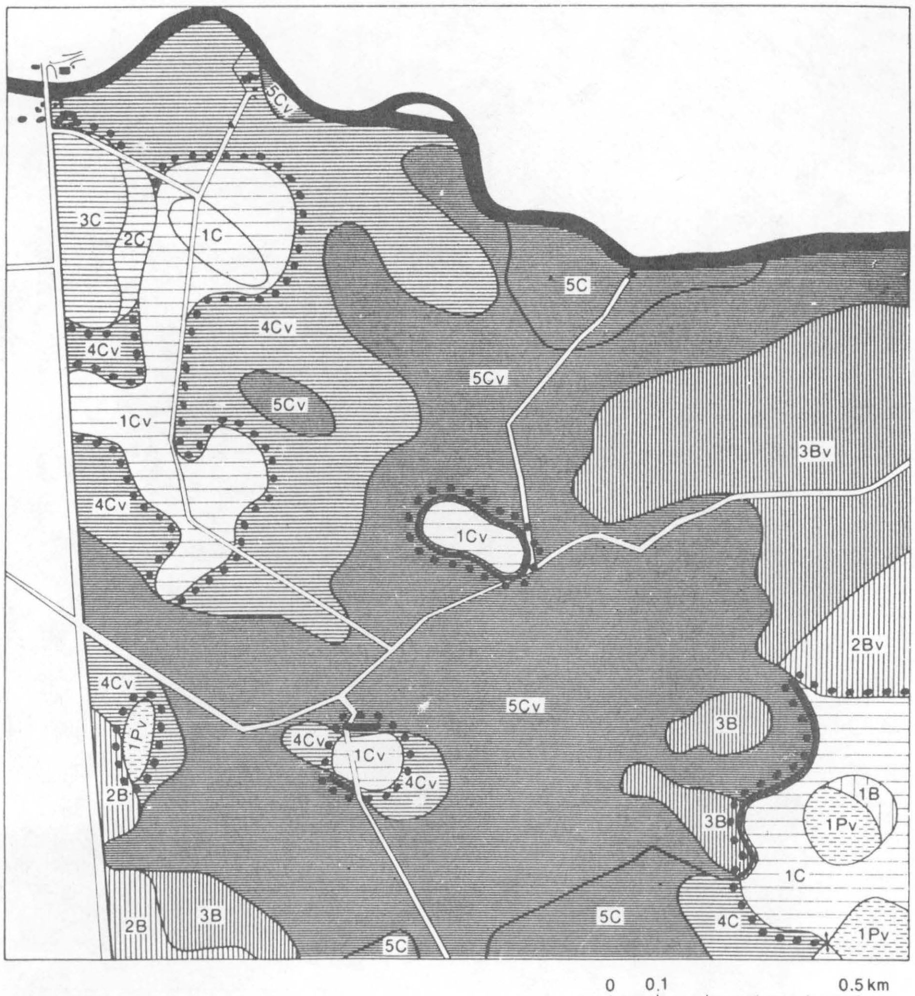
SUGGESTED WAYS TO IMPROVE ENGINEERING GEOLOGICAL MAPPING

Geologists must carry their facts and inferences far enough along the road toward satisfaction of human needs that (1) problems of the user and his necessity for decision are recognized and (2) elements of geologic knowledge required for decision among alternative courses of action are presented in forms ready for use. Generally, however, when geologic information is essential to decision, the decision itself must rest with others, with individuals or groups, who must weigh other criteria as well in seeking a solution to human problems.

Engineering geology is one of the principal fields of geologic science that directly affects large numbers of people and what they do. Therefore, it should inevitably and properly become rather deeply involved in the legislative, judicial, and executive processes by which people govern and are governed. What we need to remember is that these processes may have little similarity with the processes by which we, as geologists supposedly using the "scientific method," obtain, evaluate, interpret, and present information. In particular, as Cowan (1963) put it, "The scientist generalizes; the lawyer individuates." The engineering-geologist scientist is concerned with what general statements are tolerably valid relating to the engineering significance of geologic features. According to lawyer Cowan (1963),

> Litigation aims to individuate, and the judicial process is most at home when it disposes of a unique conflict situation uniquely. * * *
>
> The law is primarily interested in feelings — for example, feelings of justice: the *right* disposition of the dispute; the best ordering of human relations so as to attain a minimum amount of pain, suffering, loss; and the *optimal* procedures for attaining these results. And I believe that the law will warp and twist the facts, sometimes in an apparently shameless manner, if necessary, to obtain what it thinks of as the *just* result.

One can see immediately the potential for a communications gap between our science and the law and between us as individuals and the people who make, interpret, and enforce that law. There are several means by which engineering geological mapping can be improved to help close that gap — for example, change the possible products and their contents, use new techniques for investigation, or create organizational frameworks within which people can



Mapping units		Thickness of peat above 120 cm below surface	Depth of sand below surface	Mapping units		Thickness of peat above 120 cm below surface	Depth of sand below surface
Bog soils		cm	cm	Clay soils		cm	cm
	1B	> 40	< 80		1C, 1Cv	< 40	40 - 80
	2B, 2Bv	> 40	80 - 120		2C	< 40	80 - 120
	3B, 3Bv	> 40	> 120		3C	< 40	> 120
Half Bog soils (sand soils with peaty topsoil)					4C, 4Cv	> 40	80 - 120
	1P, 1Pv	40	< 80		5C, 5Cv	> 40	> 120

FIGURE 31. — Soil map of an area with peat and sand at various depths. From Haans and Westerveld (1970, fig. 10*A*). Some of the contacts on the map in the original paper represent concurrent changes in both defining criteria (thickness of peat above 120-cm depth, and depth of sand); these contacts are indicated here by heavy dots. Contacts at which a single criterion has changed by more than one step are here indicated by a heavy solid line.

do the job better. But I prefer to focus on mental processes and to consider just a few of the means under four modes of thought. These are: be *concerned* in a manner that guides effective action; be *clear* in transmitting both facts and inferences so that the user receives the true impression of reality that he requires; be *critical* in evaluating in an analytic rather than a fault-finding sense so that we, and our audience, can judge what is being done and what it means; be *creative* in a constructive manner

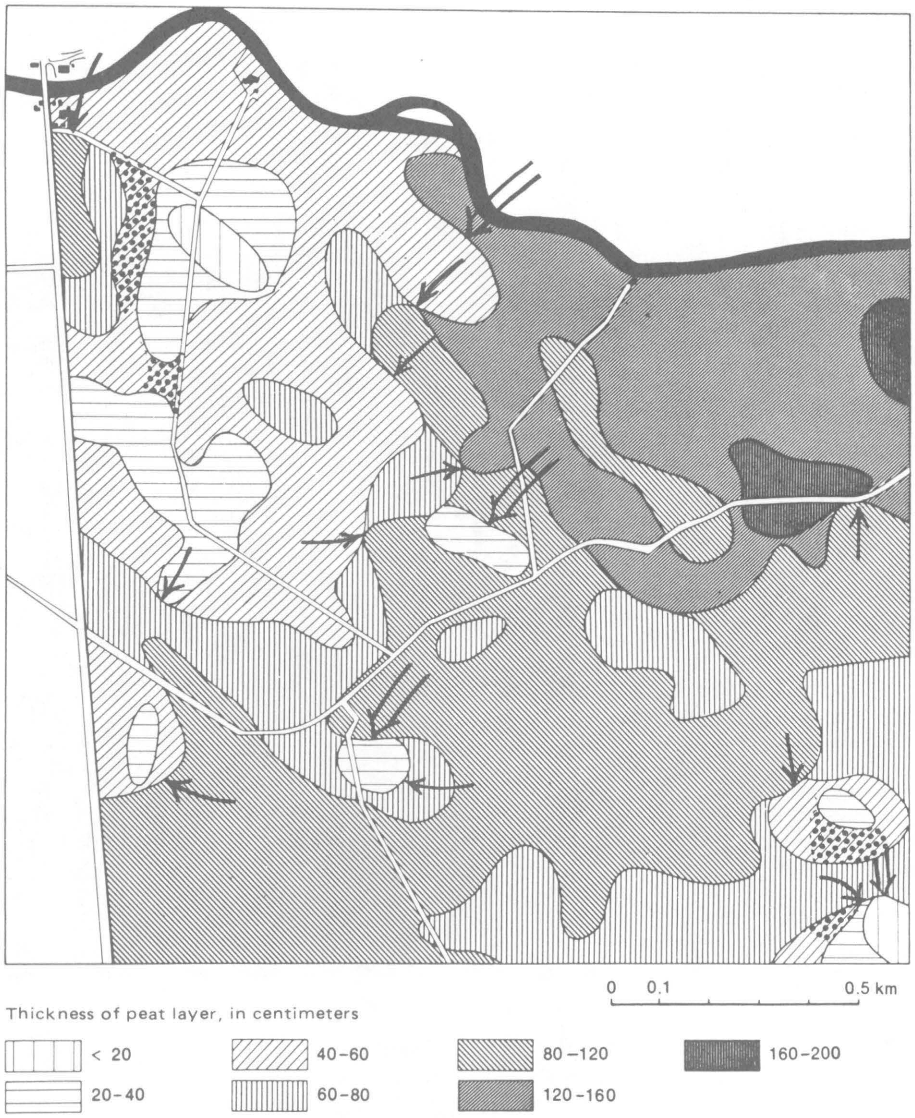


FIGURE 32. — Peat map of the area shown in figure 31, showing thickness of peat layers in 7 classes. Boundaries were partly derived from the soil map; in addition, results of deeper augerings were used. From Haans and Westerveld (1970, fig. 10*B*), Arrows indicate line contacts or points at which one class (single arrow) or two classes (double arrow) of thickness have been skipped; such places may indicate buried channel walls. Four areas within the 40- to 60-cm class appear to conflict logically with the definitions given for the classes in figure 31; these are marked by a dot overprint.

and look for new ways to acquire and portray information of value.

CONCERN

Continued development of our society will inevitably require more environmental geological surveys, on more areas, over a wider range of materials, with greater variety of subjects, and to a higher degree of reliability, accuracy, and detail. The location of such surveys, their scale, and their content must change as swiftly as do the spatial patterns of people, their needs from the environment, and their effects upon it. Hence, programs for making intermediate and small-scale engineering geological surveys, within the larger system of environmental studies, must incorporate the following:

1. Ability to identify, sense, measure, and map attributes that relate to real human needs.
2. Promptness of response.
3. Ability to change direction and focus.
4. Ability, in both knowledge and techniques, to determine the directions and rates of significant changes in:

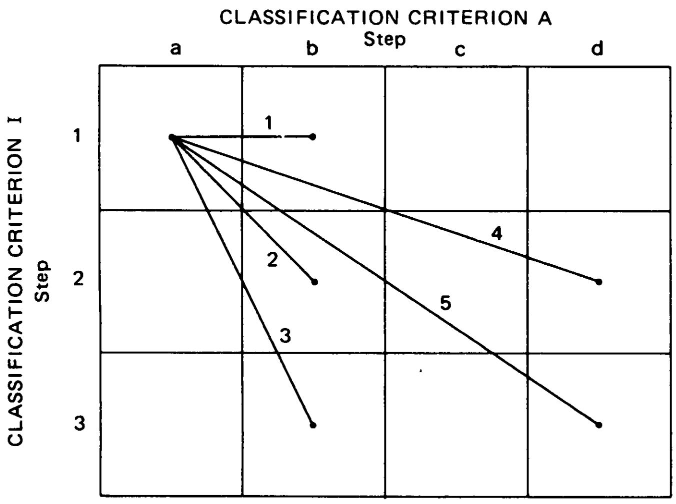


FIGURE 33. — Rank of contacts between map units defined by two criteria, each of which has a continuous range that has been divided into steps. Contact between unit 1a and 1b has a rank of 1, between 1a and 2b a rank of 2, and so on.

A. human population and its requirements,
B. effect of geologic conditions and processes on people, and
C. effect of people on geologic environment and processes.

The need for varied engineering geological studies is greater now than can be met by available competent people. Furthermore, the patterns of need shift faster, and the requirements increase more rapidly, than our capability — private and public, individual and corporate — can handle. Every new highway, bridge, or tunnel that significantly alters the traveltime contours around an urban center leads to progressive need for engineering geologic information that arises and becomes acute faster than the needs can be recognized and satisfied. Accordingly, we should be deeply concerned with devising ways and means to order priorities, to do the most important tasks promptly, if not wholly to our satisfaction, and to improve all elements of our communication system, from the training of people that use and operate it to the identification of our user and his problems.

To a considerable degree our concern must be on the future, so we must direct our course to become equal to the "present" needs of a distant day. This will require increased awareness of the changes likely to occur in our stack of data matrices (fig. 4) as we proceed along the longitudinal or time, axis. Our studies must show not only how things now are but increasingly what they will become and how fast. This is possible only as we understand the states of dynamic equilibria and hair-trigger relations that obtain not only among natural physical processes but also among social and economic processes affecting those who can make use of our work.

CLARITY

If one speaks or writes clearly he is unlikely to be misinterpreted; vagueness, ambiguity, illogic, bias, ignorance, and many other impediments to understanding cannot bear the light that shines through clear language.

We engineering geologists are admonished nowadays to speak the engineer's language, to put maps in a form that planners or even the layman can understand, and to quantify our statements. This is very good, very necessary. But let us also realize that users of our maps may understand us too well; they may see that we extrapolate without giving the odds, that we sometimes map one thing and say it is another without presenting evidence for covariance; and they may be more aware than we that statistical analyses of test results cannot alone serve as reliable measures of in-place heterogeneity. In preparing maps, particularly those derived from other maps, we need to spend much more effort on our words if we expect them to match the accuracy of our lines. The presentation of quantitative information often is helpful in our effort to gain and hold the attention of engineers, planners, legislative bodies, and other users. But even more important is the need to think and write straightforwardly, logically, and honestly — in a word, clearly. This is more than helpful: it is absolutely essential.

Although most of our serious problems are with words, we also have problems with graphics. We have, for example, not progressed as far as we might in developing cartographic means for expressing uncertainty, in both kind and degree. The problems of accuracy, reproducibility, and reliability of geologic maps have been discussed from time to time (Kupfer, 1966; Harrison, 1963; Hageman, 1968), but these problems have not been given nearly the attention they deserve. Because dashing a line can be a very time consuming and expensive operation in mapmaking, we have reasoned that the purpose of such graphic aids can be attained less expensively by remarks, in words only, concerning the accuracy, precision, and meaning of solid lines.

Perhaps conveyance of uncertainty by words alone is adequate for some purposes in general geology. But for four reasons I believe continued consideration should be given, in engineering geologic mapping, to expressing by graphics as well as words more, rather than fewer, types and degrees of uncertainty. These reasons are:

1. Well-designed graphics yield more efficient transmittal of spatial information than do words.
2. Users of engineering geologic maps are generally more interested than other users of geologic data in the accuracy of both attribute-at-a-point and area-of-an-attribute information and in the homogeneity of map units.
3. Being usually outside the science of the mapmaker, the user of engineering geological maps has no way to assess the qualifications and doubts that attend the lines around the map units unless he is shown and told. Matters of probability that we geologists believe we comprehend almost instinctively need explication in both written and graphic language. Otherwise, the user may receive a false impression either of unwarranted security or of unwarranted doubt.
4. Adherence to a philosophy of "conservatism," such as that advocated by Wentworth, Ziony, and Buchanan (1970), in practice requires having a variety of means for showing uncertainty. They very properly suggested that

> For engineering purposes, it is desirable to be alerted to possible geologic problems so that their presence or absence can be investigated and satisfactorily established, and so that appropriate modifications of plans can be made in advance of detailed design and construction.
>
> [This] map has been prepared with the conservative philosophy that portrayal of questionable geologic features which could adversely affect an engineering structure will lead to their investigation, whereas omission of such features might lead to the inference that no problems exist. To this end, information has been included on the map even if it seemed questionable or could not be verified, as long as it had some basis and was reasonable. Individual faults, and connections between faults, have been shown where reasonable, even though conclusive evidence for their existence may be lacking. * * *
>
> The inclusion of questionable geologic information, in part resulting from a standard of conservatism different from that normally used in preparation of geologic maps, requires that the map user consult the reliability diagram and that he be aware of the fault symbology used, in order to distinguish the more certain from the less certain information on the map.

Clarity in maps requires unimpeded transmission of unequivocal meaning through use of all the tools of language, symbols, and graphic portrayal. To a considerable degree clarity can be improved through standardization — by having the meaning of a word, a map symbol, or a common pattern fixed, at least as used within the context of engineering geological or related maps. Thus, one of the first acts of newly formed organizations in all disciplines, including engineering geology, is to appoint a committee or group to work on nomenclature and unification of aims and products. This need for standardization is fundamental and, I believe, now urgent. As computer technology becomes increasingly employed in geologic science and operated by specialized personnel, we may find that if the practicing field professional fails to define both his words and the concepts they represent, then they may, through necessity, be defined by people whose principal business is the processing of data. The words that need definition are not limited, of course, to those peculiar to our technical field; we must use common words, such as firm, weak, well, poorly, good, and closely, for special purposes and attach to them meanings that are generally more restricted but rarely standard in our employ. One notes with delight the way Briggs (1971) defined just such common words for the purpose of his map and engineering geological classification.

Standardization is welcome when it helps to make communication easy within a system whose basic elements, arrangements, and operations are well along toward being established. Standardization is, however, not desirable when it prevents, hinders, or delays the creation and critical evaluation of new systems that may have distinct advantage over those in use.

A kind of standardization that is desirable, and that seems certain to increase, is the use of symbols as tools of communication. As Betz (1963, p. 196) pointed out, symbols have the obvious advantages of precise and unequivocal meaning, ease of handling, independence from words, economy of space, and potential to express not only the description and classification of objects but also the relationships between them. Hubaux (1972), though urging standardization, very rightly indicated that standardization must be preceded by disentanglement of complex geologic concepts, particularly genesis, from the descriptions of the essential characteristics of geologic objects.

CRITICAL EVALUATION

A map has great power to persuade, a power that was discussed by Boggs (1947) under the apt term "cartohypnosis." Certainly many users have a strong tendency to accept a map simply because they cannot question it very deeply without direct knowledge of the area and because they naturally tend to believe that some information is better than none. The only way a user can appraise the reliability of some maps is to test internal consistency. So we mapmakers need to be self-critical and to devise means to evaluate not only the land but also our portrayals of the land. Nobody else can do this.

We should not evaluate a map without carefully considering its purpose. We tend to make value judgments without a clear understanding that evaluations cannot be made by examination of the properties of the object alone, be the object a parcel of land or an engineering geological map. As emphasized by Lopatina and others (1971), evaluation consists of an operation performed on a relationship. This relationship exists between a specific object and a specific subject and is examined according to criteria determined by an expressed purpose.

In evaluating land, the object might be a spatial unit with relatively homogeneous properties, and the subject, a particular person, group of people, or sector of society. For example, the evaluation of a geologic unit for septic sewage disposal — using such terms as good, favorable, questionable, or unfavorable — has to be made with a subject, or user, in mind, whether this user is actually named or not. The evaluation performed on a medium- to small-scale map will have considerably different accuracy, significance, and reliability if the subject is an individual lot owner, who either can or cannot use his small parcel of ground for this purpose (which involves attributes of a small area), than if the subject is a county planner or a developer of a large tract, who may be able to tolerate considerable inhomogeneity of the land in deciding on general courses of action (which involves areas of an attribute). This facet of evaluation is recognized in the warning statements, common in texts accompanying small-scale value-judgment maps, that these maps should be used only for general planning purposes, not for evaluation of the properties of a small site. Nevertheless, such disclaimers may be found close to statements that the map should be useful to individual homeowners and that it should help to "pinpoint" types of problems.

The area represented by a geologic map may contain many potential objects. One of the principal purposes of preparing a series of interpretive maps from basic geologic data is to reduce the number of potential objects by having each map depict selected data pertinent to a specific purpose in order that evaluation within an object-subject pair can occur without extraneous interferences. But unless the map is prepared by a consultant for a specific client, identification of the eventual subject, or user, remains in doubt, and the words used to express evaluation will always have different meanings to different potential users. Consequently, mapmakers, such as governmental agencies, who prepare maps for the general public have a particular obligation to use care in the wording on their maps.

Criteria for evaluating a map must closely relate to the power of the map to transmit information, to alter the subject's prior assessment of probabilities concerning possible states of the object. If, before studying a map, the user regards all possible states at all locations as being equally probable, then he is highly uncertain about decisions that require choice. His mental entropy is very high. The truly useful map is one that provides him with the information necessary to guide his choices.

A map user seldom applies a single criterion when he evaluates a map in terms of his problems. For instance, the suitability of a gravel terrace for exploitation as a source of construction materials depends ultimately not only on a number of basic geologic attributes but also on spatial and economic factors. Moreover, the basic geologic attributes may need to be used for other kinds of evaluations of the same area. Thus, grain size and grain-size distribution will be factors in many potential performance-use-behavior evaluations. But the weight that should be assigned to such properties almost always depends on the use to be made of the map. Slope, for example, is less critical in the choice of road alinements than in the siting of canals. Here again, the maker of derivative maps for public use may not have applied all the criteria for evaluation that would have been applied by a specific user. Consequently, clear statements on exactly how the map was derived are essential to aid the potential user and to avoid misleading him.

CREATIVITY

The stress placed on logical analysis in this discussion has perhaps obscured a parallel need for creative, constructive, innovative thought. Such thought does not in itself conflict with logic, but it can be impaired by standardization of methods no matter how logical the standardization appears to be. Innovative thought seeks to break from prior experience and gain insight, as often by forming new associations among familiar materials in nonstandard ways as by acquiring new data.

We must prize the ability to recognize and use new relations among elements of knowledge, to form classifications that in the words of Wadell (1938) are not only broad and close but also so flexible and elastic that they can serve effectively to organize the novel or strange. This human attribute is essential to cope with a future whose only certain character is accelerating change.

The scope of constructive creativity, that is, the number of possible associations among elements of knowledge, grows very rapidly both with increase in the number of such elements and with their capacity to enter into a variety of associations, that is, with their fundamentality. Hence, if generalized data are perceptively dissected into their fundamental components or attributes and if the spatial distribution of these attributes can be shown, then the possible number of useful synthetic regroupings into derivative maps is greatly enlarged. The qualifier "perceptively" must be emphasized because as the number of possible groupings increases, so also does the mental effort needed to examine, compare, and evaluate them; therefore, perceptive focus on potential value is needed.

Maps that present judgments as to whether a unit is good or poor for a particular use certainly are subject to possible rapid obsolescence as patterns of land use change and as technology advances. Such maps are useful; but because they may be short lived, we need to find ways to remake or alter them with relatively little effort. This requires having data on fundamental attributes in a form that can be processed rapidly and cheaply by such operations as generalization, selection, addition, superposition, and transformation to create new kinds of map units as needed.

The appropriate means for perceiving, acquiring data on, or measuring attributes can be shown in an array such as figure 34. Photographic and other remote-sensing devices give present means and future promise for acquiring some types of useful engineering geologic information. Computers increasingly can be used for processing, storage, retrieval, filtering, regrouping, and cartographic display of many kinds of data (Tanguay, 1969; Smedes and others, 1970). It seems inevitable that much spatial-typological information ultimately will be stored in its most flexible form — in mechanical, electronic, or optical memory — and that grouping and printing out maps of desired options can be performed at will. The making of an optional map may involve superposition to show every recorded attribute of a small area, or it may involve selection to show those areas that exhibit a combination of attributes newly required but never before imagined.

If individual fundamental attributes rather than generalized regions of grouped attributes are mapped, an inexperienced user may require a weighted attribute-use matrix to evaluate such maps for his needs. This matrix could most simply consist of an array (fig. 35) that shows what attributes are involved for each use and how important they are. For example, weights, or "coefficients of significance," were assigned by Nazarevskiy (1971) to various components of the environment for evaluation of areas for particular aspects of human living.

Only if the spatial distribution of each fundamental attribute is shown separately can the user assign weights to each attribute, outline the areal distribution of the most favorable combinations, or form regions or new units as determined by the maximum sum of weighted values for the particular use.

We need to construct use-attribute matrices for a variety of purposes, seeking always to identify those attributes that are widely applicable. The attributes

METHOD FOR PERCEPTION, AQUISITION, OR MEASUREMENT / ATTRIBUTE	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
m_1	X							X
m_2		X		X				
m_3			X			X		
m_4	X						X	
m_5		X		X				
m_6					X			

FIGURE 34. — Matrix indicating appropriate methods to perceive, acquire data on, or measure attributes.

PERFORMANCE, USE, OR BEHAVIOR / ATTRIBUTES	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
P_1	w_{11}	w_{12}	w_{13}	. . .	. . .			
P_2	w_{21}	w_{22}	w_{23}	. . .	. . .			
P_3	. . .	. . .	. . .	. . .				
P_4								
P_5								
P_6								

FIGURE 35. — Matrix indicating what attributes affect performance, use, or behavior, and to what degree. The weights (w_{11}, w_{12}, and so on) can be expressed by the various forms of measurement shown in figure 3.

most important for a desired use may not, however, be individually directly measurable, so the measurements must be inferred from the measure of other attributes. If inference must be made, the attribute-attribute correlation matrix (fig. 7) can start the logical chain that extends from measurement of observable attribute, to inference regarding areal distribution of desired attribute, to judgment of suitability of areas for proposed use.

Analytic fragmentation of geologic information, including map information, into more basic components is necessary before integrations, syntheses, or regionalizations can be tailored to each need. This will become apparent not only in engineering geologic work itself but increasingly as engineering geologic investigations are incorporated into or coordinated with interdisciplinary studies of the whole environment. With Mabbutt (1968, p. 27), I agree that in the long run the parametric, or factor, approach will dominate over the now popular integrated approach in environmental surveys, although both will always be needed.

In particular, several species of integrated maps will remain of basic importance. These are bedrock and surficial geologic maps and genetic soil maps. They will remain important because we will always require information on properties that have not been or cannot be measured, and the cheapest if not the surest method to extrapolate point information into three dimensions is to use knowledge of geologic- and pedologic-genetic structure, composition, and process. Standard geologic-genetic maps, even though they are special-purpose maps of prime interest to a rather small segment of our population, will always form an indispensable bank of spatial-typological information.

CONCLUSIONS

A geologic map is a synthesis; it is not information in its most fundamental and versatile form. It is a generalization that lies somewhere within the bounds in figure 2, a geologist's interpretation of the geology for a particular purpose. Its lines, units, and descriptions may not be sufficiently defined for another synthesis intended for another purpose. To an increasing degree, the concept of a "general-purpose" geologic map, which needs only to be "interpreted" to be of wide, varied, and accurate use, is being questioned. If a geologic map does not contain the proper information to the required accuracy, it logically cannot, and therefore should not, be interpreted for special purposes; if it does, it can. Facts cannot be generated by inference.

A performance-use-behavior map, which is derivable only with difficulty or not at all from a geologic-genetic map, is more surely derivable from an attribute-place map that shows those attributes directly relevant to the use in mind and that shows the areal distribution of each attribute, which may overlap others. The problem here, of course, is that the lines, contours, or other means of showing fundamental properties are, in general, more difficult to draw than the boundaries of conventional geologic formations. For any area to be mapped, the factors of appropriate scale, time, money, competence of investigator, and the numbers and knowledge level of potential users must all be evaluated and the mapping products decided upon *before* rather than after the field investigations are performed.

Such ideal planning is not always or, perhaps, even frequently possible. We are often called upon to aid in decisions that cannot await collection of all data known to have a bearing on the problem. Then, as geologists, our responsibility is to see that our maps convey clearly the differences between the well-documented and the inferred data, between observation or measurement and interpretation, and that they show nothing where we are truly ignorant. And we must do this with such honesty and clarity that those we wish to inform cannot possibly misunderstand either our spirit or our intent.

This perhaps returns us close enough to the starting point to call a halt.

Willatts (1970) favors outward attractiveness in maps but suggests that it can be deceiving. Certainly, maps should not be esthetically repulsive, for then they lose their power to inform and persuade; but pleasing appearance should rank much below honest usefulness. True value, of maps as of maidens, is more than skin deep: it involves outer form far less than inner content, and it resides more in the observer's response than in nature of the object observed.

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