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Landscape geochemistry: retrospect and prospect—1990

JOHN A. C. FORTESCUE
Ontario Geological Survey, Ministry of Northern Development and Mines, 77 Grenville Street, Toronto, Ontario M7A 1W4, Canada

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Abstract—At present, the terms *Environmental Geochemistry* and *Applied Geochemistry* are poorly defined in English. In fact they usually mean just what a particular geochemist, or geochemist(s), wishes them to mean.

There is a less common term, *Landscape Geochemistry*, which describes a holistic scientific discipline aimed at the geochemistry of the environment. Although little known outside the U.S.S.R., the basics of landscape geochemistry were first described more than 60 a ago. Since then, landscape geochemistry has had a history pertinent to all scientists who participate in environmental geochemistry today.

This review traces the evolution of landscape geochemistry, and related disciplines, over the past 90 a and shows how they all relate to the development of modern environmental geochemistry worldwide.

In landscape geochemistry, the term "landscape" refers to both the horizontal stratification of land (e.g. into terrestial, bog and aquatic ecosystems which co-exist in an area of country) and to the vertical stratification within these units (e.g. into vegetation, soils etc.). In these respects landscape geochemistry resembles *Landscape Ecology*, which is currently a discipline of growing importance in environmental science.

Landscape geochemistry differs from landscape ecology because it focuses attention on all aspects of the behaviour of chemical entities (e.g. isotopes, elements and ions), in both living and dead matter in landscapes of all kinds.

From the viewpoint of general geochemistry, landscape geochemistry focuses on the interaction of the lithosphere with the hydrosphere, atmosphere and biosphere. This holistic approach provides a common theoretical background for both "pure" and "applied" environmental geochemistry worldwide.

An important aspect of landscape geochemistry, particularly pertinent to environmental geochemistry in the non-Soviet world today, is that the subject provides a link between modern exploration geochemistry and modern environmental science, including geochemistry.

Historically, landscape geochemistry stems from the Russian school of "Landscape Science". This developed from the ideas of V. V. Dokuchaev (1846–1903) around the turn of the century. Concepts unique to landscape geochemistry were first described in the 1920s by one of Dokuchaev's students, B. B. Polynov (1867–1952). A. I. Perel'man (1909–), a student of Polynov, began to teach landscape geochemistry at Moscow University in 1952. Since then, the subject has become firmly established as the focus for fundamental and applied environmental geochemistry in the U.S.S.R.

This review traces the development of landscape geochemistry from its origins around 1920 until 1990. The volume of literature pertinent to the review is voluminous. For this reason, attention is usually focused on the basic concepts and principles of landscape geochemistry and related scientific disciplines. Readers who require more detailed information on subjects covered in this review should consult the references cited.

The review is organized in four parts. The first three trace the historical development of landscape geochemistry, and related disciplines, in three time periods. These are: (1) pre-1950; (2) between 1950 and 1980; and (3) 1980–1990. Part 4 uses paradigms to summarize the historical evolution of landscape geochemistry and indicates how a *Global Landscape Geochemistry* might develop in the future.

CONTENTS

GENERAL INTRODUCTION

> One of the problems facing landscape geochemistry* today is the overabundance of detailed information amassed by all sorts of specialists. This makes it very difficult for the student to visualize the whole. There is no lack of symposia at which geochemists* address themselves to some particular, sometimes very limited aspect of a narrowly defined problem; nor is there any shortage of well documented reviews reporting the latest investigations into various special questions; almost no attempt has been made at a synthesis; that is the presentation of relationships on the grand scale, with the whole as a starting point (Walter and Breckle, 1985, p. vi).

The above, edited, quotation sets the scene for this review which was written with four aims. The first is to trace the historical evolution of landscape geochemistry. This is achieved by tracing the evolution of approaches to (1) landscape description and (2) landscape geochemistry in the Soviet and non-Soviet world prior to 1990. The second aim is to describe the principles of landscape geochemistry as a basis for modern environmental geochemistry worldwide. This is achieved by describing details of the landscape geochemistry approach to environmental geochemistry as they were developed in the U.S.S.R. between 1950 and 1980. The third aim is to update the informatioin in my book *Environmental Geochemistry: A Holistic Approach* (Fortescue, 1980) to include development of the subject during the 1980s; and the fourth is to provide an introduction to a "global" landscape geochemistry of the future.

The first three parts of the review are a historical account of the evolution of landscape geochemistry between 1900 and 1990 with breaks at 1950 and 1980

* The terms "landscape geochemistry" and "geochemists" have been substituted by the present writer for "ecology" and "ecologists" in the original quotation.

when noticeable changes in the development of the subject took place. Part IV is in two sections, the first summarizes the historical development of landscape geochemistry (and its related disciplines) during the past 90 a using a series in paradigms. The second section provides guidelines for the future development of a *Global Landscape Geochemistry* (GLG) followed by some general conclusions.

The volume of published literature pertinent to this review is very large. For this reason, this review samples only some of the writings available on each of the subjects described. The review is written mainly for scientists in the non-Soviet world and for this reason almost all the references cited are in English, or are available in English translation.

PART I. PIONEER CONCEPTS OF GEOCHEMISTRY AND LANDSCAPE

Geochemistry pre-1950

The era of modern geochemistry commenced in the 1880s with researches of the pioneer American geochemist F. W. Clarke (1837–1934). Clarke's classic book *The Data of Geochemistry* (CLARKE, 1924) led to worldwide interest in geochemistry among geologists and other scientists. This book also stimulated many creative scientists to make major contributions to geochemistry as described by RANKAMA and SAHAMA (1950). This pioneer era in geochemistry ended around 1950 with: (1) the publication of a general textbook on geochemistry in English by RANKAMA and SAHAMA (1950); (2) the posthumous publication of V. M. Goldschmidt's incomplete summary of geochemistry (edited by Alex Muir) (GOLDSCHMIDT, 1954); and (3) the founding of the journal *Geochimica et Cosmochimica Acta*, in 1950.

In addition to F. W. Clarke, three other thinkers made substantial contributions to modern geochemistry prior to 1950. These were two Soviet scientists [V. I. Vernadski (1863–1945) and his pupil A. E. Fersman (1883–1945)] and a Norwegian [V. M. Goldschmidt (1888–1947)]. All four were concerned with the geochemical behavior of *all* elements in the Periodic Table in all four geospheres (i.e. the lithosphere, hydrosphere, atmosphere and biosphere).

The pioneer geochemists were particularly interested in describing the role of chemical entities (i.e. isotopes, elements, ions) in the synthesis and decomposition of materials of all kinds in natural environments. In order to illustrate aspects of this holistic approach, some of the elementary concepts of modern geochemistry which the pioneers described will now be briefly discussed.

Relations between the chemical composition of living and dead organic matter, the lithosphere, soils, waters and the atmosphere were all included in geochemistry as described by V. M. Goldschmidt and reported by his pupil Brian Mason (MASON, 1952).

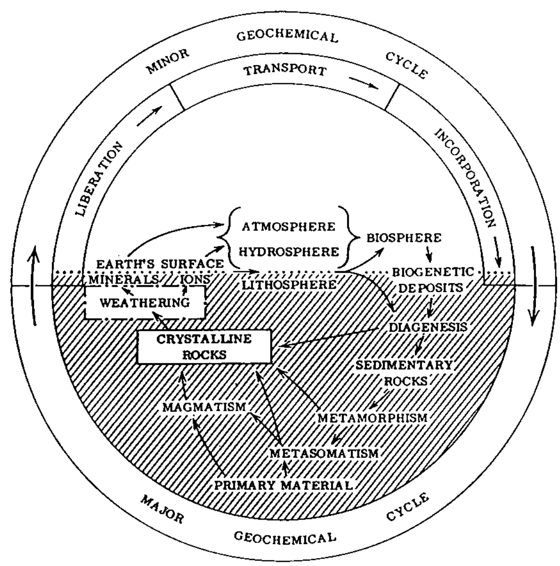


FIG. 1. The geochemical cycle redrawn after MASON, 1957 (from FORTESCUE, 1967).

As an example, let us consider Goldschmidt's concept of the "geochemical cycle". The geochemical cycle (Fig. 1) is in two parts, the first is the major geochemical cycle which is largely geological in nature and occurs deep in the Earth. The second is the minor geochemical cycle which occurs at, or near, the Earth's surface and results in the formation of landscapes.

In theory, the minor cycle begins when crystalline rocks, derived from the major cycle, are exposed to the atmosphere and subjected to mechanical, chemical and biological weathering. The minor cycle continues as the products of weathering are transported by water and the atmosphere through landscapes, and it ends when weathering products participate in the formation of new sedimentary rocks. Later, after deep burial, these sedimentary rocks may re-enter the major geochemical cycle (MASON, 1952).

Goldschmidt pointed out that the minor geochemical cycle is analogous to a quantitative chemical analysis. The cycle begins when metastable crystalline rocks are broken down by weathering. The cycle continues when weathering products are transported through landscapes and ends when they are incorporated into one, or more, of six types of sedimentary rocks (Fig. 2).

The concepts of the "geochemical cycle" and the "Goldschmidt classification of sediments" demon-

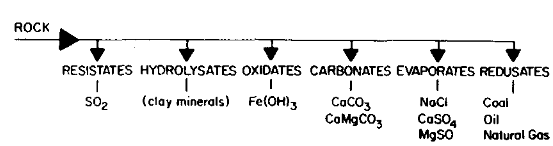


FIG. 2. Goldschmidt's classification of sediments (from MASON, 1952).

strate that, prior to 1950, geochemistry was considered by its founders to include the simultaneous study of all elements in landscapes everywhere. Thus general geochemistry was not to be restricted to special groups of elements such as "major rock-forming elements", "trace elements", "elements related to ore deposits", "nutrient elements", or "radioactive elements".

It is unfortunate that Goldschmidt did not live to describe details of the geochemistry of the minor geochemical cycle in more detail. This would have probably provided a solid foundation for non-Soviet environmental geochemistry after 1970.

The Soviet geochemists Vernadski and Fersman shared Goldschmidt's vision of geochemistry. In fact, it was Vernadski who, in 1924, had defined the terms "lithogeochemistry", "hydrogeochemistry", "atmogeochemistry" and "biogeochemistry" as major branches of geochemistry (RANKAMA and SAHAMA, 1950).

Vernadski was particularly interested in the geochemistry of the biosphere (VERNADSKI, 1945). He stressed the importance of the "biogeochemical cycle" to describe the circulation of elements in the surficial environment brought about by organisms. Later, the Swedish geochemist MATTSON (1938) added a fifth geosphere, the "pedosphere" (or "soil sphere") to describe where the lithosphere interacts chemically with the other three geospheres in terrestial landscapes.

Fersman was particularly concerned with the development of geochemical mapping. In the 1930s, he defined as "Geochemical Provinces" areas "which are geochemically homogeneous and contain a certain association of chemical elements" (BEUS, 1976). BEUS (1976, p. 23) continues:

> The concept of geochemical province is fairly wide and includes concepts of metallogenic and petrogenic provinces. Moreover it should be regarded as more rational because it characterizes a natural relationship between the distribution of rock-forming, ore-forming and trace elements in the Earth's crust.

In 1938, another noted Soviet geochemist, A. P. Vinogradov (VINOGRADOV, 1938), defined a parallel concept of "biogeochemical provinces" (PEYVE, 1963, p. 731) to describe:

> . . . areas of insufficient, or excessive, amounts of various elements which often result in biogeochemical epidemics among plants, animals and human beings.

Today, biogeochemical provinces are of considerable importance in geochemical mapping especially in relation to human health. Relations between many kinds of biogeochemical provinces and Fersman's geochemical provinces are still poorly understood.

Another aspect of Fersman's ideas was the priorizing of elements for inclusion in the mapping of geochemical provinces. For this purpose FERSMAN (1934, 1939) divided elements into four groups (GINZBURG, 1960, p. 21) as follows:

1. Elements to be mapped as a rule: Be, B, Bi, W, Ti, U, Au, Sr, V, Co, Ni, Cu, Mo, As, Nb, Os, Pt, Pd, Ag, Hg, Pb, Sb, Ta, Ti, F, Cl, Zn and Zr.
2. Elements to be mapped only after special investigation: Cd, Ge, Rb, Ru, Se, Te, Cs, Re and Sc.
3. Elements to be mapped only if they occur in significant accumulations: Al, Fe, K, Na, Ca, Mg, Si, Mn and C.
4. Gasses which are not normally mapped except in special cases: H, He.

According to GINZBURG (1960, p. 21), Fersman qualified what he had proposed as follows:

> the foregoing suggestions have a somewhat theoretical character (i.e. in 1934) and resemble an outline of future work rather than a well developed and tested methodology.

This statement underlines a major issue which plagued geochemical mapping until the 1990s. This is to find practical, reliable, rapid, sensitive and cheap methods of multi-element chemical analysis applicable to the large numbers (i.e. thousands, or tens of thousands) of geochemical samples required during mapping. Even today, this problem has not yet been fully solved, although in 1990, databases including more than 65 elements have been proposed for geochemical mapping on a global scale by DEMIETRIADES *et al.* (1990).

A companion problem of the 1930s was how to process and manipulate large sets of multi-element geochemical data. Fortunately, this problem was solved by the introduction of the modern personal computer into geochemistry during the mid-1980s.

In 1923 Fersman suggested a *geochemical* unit—the "Clarke"—for use in legends of geochemical maps (BEUS, 1976, p. 21). Fersman defined a Clarke :

> to characterize the average percentage of an element in a given astronomical body or its part (for example in the lithosphere).

The general idea was the Clarke value would be fixed as a "global datum" for each element, analogous to sea level in topography. If this were done, the legends for all geochemical maps could then be standardized and comparisons among the element patterns upon them would be facilitated.

As we shall see later, Fersman's concepts of "geochemical provinces" and "Clarkes" are fundamental to Soviet landscape geochemistry. One more aspect of Fersman's approach to geochemical mapping must also be mentioned. According to GRUZA (1983), Fersman stressed the need for the use of mathematics during the interpretation of geochemical map data. As GRUZA (1983, p. 19) put it, Fersman considered:

> Mathematics made it possible to (a) reduce multidimensional compositions to unidimensional ones, (b) to validate isolated associations of chemical elements on the basis of correlational, factorial, and cluster analysis, and (c) to strictly describe the dependence of the characteristics being studied on spatial coordinates of the basis of regression analysis.

In summary, many concepts from modern geo-

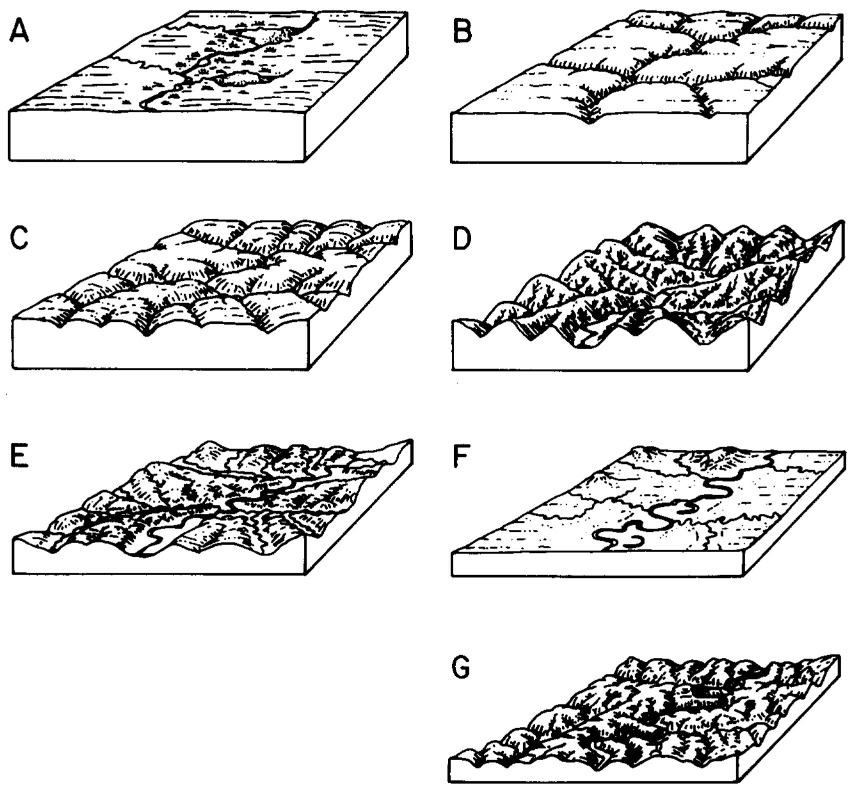


FIG. 3. The geographic cycle proposed by W. M. Davis (from STRAHLER, 1965; drawn by E. Raisz).
A. In the initial stage, relief is slight, drainage poor.
B. In early youth, stream valleys are narrow, uplands are broad and flat.
C. In late youth, valley slopes predominate but some interstream uplands remain.
D. In maturity, the region consists of valley slopes and narrow divides.
E. In late maturity, relief is subdued, valley floors broad.
F. In old age, a peneplain with monadnocks is formed.
G. Uplift of the region brings rejuvination, or a second cycle of denudation, shown here to have reached early maturity.

chemistry as described by MASON (1952), RANKAMA and SAHAMA (1950), BEUS (1976), and GINZBURG (1960) are common to geochemistry and to landscape geochemistry.

Today, Vernadsky's concepts of the "geosphere", "biogeochemistry" and "biogeochemical cycles" are universally accepted as a part of environmental science. This is surprising when other concepts equally useful in environmental geochemistry such as "geochemical provinces", "biogeochemical provinces" and "Clarke" units have only been seriously considered by most non-Soviet geochemists during the past 10 a.

*Landscape description pre-*1950

Before 1950, geographers and other scientists usually described landscapes using the methodologies of what was called "Landscape Science" in the Soviet Union and "Physical Geography" (or "Geomorphology") in Europe and North America.

In North America and Europe, thinking concerning those parts of geomorphology and physical geography involving the study of the origin and evolution of landscapes was dominated for decades by theories of physical weathering. The most important of these was a theory of orderly landform development described by an American, W. M. Davis (1850–1934). Davis was a geologist, meteorologist, and physical geographer who served as professor of physical geography and geology at Harvard University. He called his theory of landscape evolution "The Geochemical Cycle" (DAVIS, 1899, 1902), and was one of the first geographers to attempt an overall landscape analysis. In order to do this he postulated a staged evolution of landforms as indicated in Fig. 3. The salient points of the Davis theory were summarized by GARNER (1974, p. 4) as follows:

> An uplifted land remains structurally stable while it passes through a series of time significant erosional stages during its progressive lowering and levelling. These stages, by analogy to man's growth, were designated YOUTH, MATURITY, and OLD AGE, a time framework that was readily grasped and has been immensely popular down to the present. The presumed long term landform culmination was the low relief, low elevation erosional surface Davis called a *peneplain*. The assumed landscape and landform changes

depended upon a series of secondarily postulated interrelationships. These were largely included in Davis's original synthesis but most were elaborated upon in many subsequent papers up to the time of his death.

A modern discussion of the considerable impact of the ideas of Davis in non-Soviet geography is found in MELHORN and FLEMAL (1980).

Another pioneer theorist concerned with the physical evolution of landscapes was Walter Penck (1867–1926), who was a Swiss national, writing in Germany. Penck stressed that the formation of landscapes should be interpreted by means of ratios between erosional and diastrophic processes. Penck's approach to the evolution of landscapes was originally described in 1924 in German and later translated into English (PENCK, 1953). Penck's contribution was summarized by CHORLEY *et al.* (1984, p. 19) as follows:

> Penck believed that landforms should be interpreted by means of the ratios which might be expected to occur between erosional (exogenetic) processes and diastrophic (endogenetic) processes. Erosional processes were held to operate according to the following world wide laws, differing only in rate between different climates:
> (1) Local intensity of erosion is directly related to steepness of the slope segment.
> (2) The inclination of each segment of an erosional slope is determined by the sizes of the mobile debris.
> (3) The largest debris size which is mobile on a slope segment varies with the inclination of the latter; the greater the inclination the greater the largest size which is mobile.
> (4) If the production of debris by weathering is uniform on a slope segment, erosion will cause the segment to retreat parallel to itself.
> (5) If some eroded material is allowed to collect at the base of a retreating slope segment, a new slope segment of lower inclination will develop.
> Most important, Penck believed (as a result of his studies of sedimentary facies flanking Alpine ranges) that most tectonic movements began and ended slowly, and that the common pattern of such movements involved a slow initial uplift, an accelerated uplift, a deceleration in uplift and finally, quiescence.

Relatively long descriptions of these two systems of landscape evolution are included here to emphasize the stress they place on physical weathering to the exclusion of chemical weathering. As long as these two physical theories dominated geographic and geomorphological thinking in North America and Europe, the Soviet approach to soil formation and landscape geochemistry was not seriously considered by non-Soviet geographers.

Meanwhile during the first decades of this century in the Soviet Union, sophisticated methods for soil formation and landscape description were developed by the Soviet school of geographers. This activity stemmed from the seminal thinking of the pioneer soil scientist and geographer V.V. Dokuchaev (FANNING and FANNING, 1989). Three of the Dokuchaev school geography students [L. S. Berg (1876–1950), G. F. Morozov (1867–1920) and B. B. Polynov (1867–1952)] are of particular importance to the development of Soviet landscape geochemistry. Polynov, after considerable field experience as a soil scientist, gradually rejected the teachings of his master Dokuchaev on the formation of landscapes. In the 1920s, Polynov then began to describe basic concepts of what would later become landscape geochemistry.

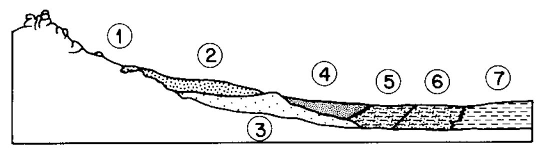


FIG. 4. Soils of an East African catena (after MILNE, 1936; from GERRARD, 1981). For explanation of numbers see text.

The development of soil science in Europe and North America prior to 1950 is also pertinent to the history of landscape geochemistry. The review by FINKL (1982) suggests that, prior to 1950, most non-Soviet soil scientists were not seriously concerned with the relation between soils and the geochemistry of landscapes. This opinion is supported by a recent book on soil morphology, genesis and classification by FANNING and FANNING (1989). There are two notable exceptions to this opinion of pre-1950, non-Soviet, soil science. One is the "catena" concept as described by MILNE (1935, 1936) and the other is an interesting book *The Factors of Soil Formation* by Hans Jenny (JENNY, 1941).

Milne, working in East Africa, used the catena concept to link descriptive soil science with a description of landscapes in which soils occur. MILNE (1935, p. 197) defined a catena as:

> a unit of mapping convenience . . . a group of soils which while they fall wide apart in a natural system of classification on account of fundamental and morphological differences, are yet linked in their occurrence by conditions of topography and are repeated in the same relationships to each other wherever the same conditions are met with.

GERRARD (1981) noted that Milne was one of the first researchers to include the processes of erosion as a major factor leading to the differentiation (under constant climatic conditions) of different, but related, soils derived from a common soil parent material. Milne's example of this situation was a residual granite hill and associated slopes in East Africa (Fig. 4) This area was described by GERRARD (1981, p. 62) as:

> A shallow dark grey loam (1) formed by weathering of the granite surfaces has worked downhill by creep and slow erosion to act, on the footslope, as a parent material on which a deeper soil (2) of the red earth group has developed. At the base of the red earth profile, where a temporary accumulation of seepage occurs in the wet season, a horizon of coarse granite grit (3) in a black rusty ferruginous cement has formed. Occasional storm water running over the surface has gradually pared off the topsoil and the material has travelled differentially according to particle size, so that by a cumulative effect a zone of washed sand (4) has covered the footslope, with silty or clayey sand (5)

(6) beyond it, and clay has accumulated on the level bottomlands (7). At all stages the erosion has been slow and non-catastropic and the soils have borne their appropriate vegetation and have been developing towards maturity.

GERRARD's (1981, p. 62) conclusions regarding Milne's catena concept are also interesting:

(the catena) . . . is extremely important in the way it relates soil to the processes operating and to the past history of the landscape. It is therefore very difficult to make any useful distinction between "slope genesis" and "pedogenesis" and this means that a better understanding of the soil should be sought in a geomorphological evaluation of the soil landscape. But, equally, a better understanding of the geomorphology of a region should be sought in a study of the soil.

The *Factors of Soil Formation* by Hans Jenny (JENNY, 1941), is of considerable importance as a link between soil science, geomorphology and landscape description. Jenny's main contribution was to use simple descriptive equations to describe the genesis of soils due to the interaction of the five "factors of soil formation". Jenny postulated that, in normal soils, all five factors interact during the development of the soil. He also showed that in certain areas, the effect of a single factor may dominate the soil formation process to form a "soil sequence" (JENNY, 1941). Recently, FANNING and FANNING (1989) summarized important Jenny soil sequence types as follows:

1. Lithosequences—soils related by differences in parent material;
2. Chronosequences—soils related by differences in soil age;
3. Rainfall sequences—soils related by differences in rainfall;
4. Temperature sequences—soils related by differences in air and/or soil temperature;
5. Biosequences—soils related by differences in organisms;
6. Toposequences—commonly these are drainage catenas, or hydrosequences.

In summary, since 1941, JENNY's (1941) approach to soil formation, which has its roots in the ideas of Dokuchaev, has been available to non-Soviet geochemists for use in the systematic description of the genesis of soils and landscapes.

During the early decades of this century the description of landscapes by Soviet geographers followed a very different course from that just outlined for Europe and North America. By 1910, in the U.S.S.R., "Landscape Science", based on the Dokuchaevian school of soil science and geography, was well established.

A detailed account of the early development of this school of "landscape science" was provided by A. G. Isachenco (ISACHENCO, 1973). In summary, ISACHENCO (1973, p. 26) noted that:

Dokuchaev first treated zonality as a natural law: every natural, or natural history zone constitutes a regular natural complex in which the living and non-living aspects of nature are closely associated with one another.

AFANASIEV (1927, p. 5) attributed to Dokuchaev himself an even more succinct statement that:

Soil is an independent natural body which must not be mistaken for surface rocks.

This statement lies at the heart of the Soviet approach to landscape description and study, and is clearly in marked contrast to the ideas of Davis and Penck described previously.

After the turn of the century the Dokuchaevian school of geography trained many scientists who shared the master's outlook on landscape description and development. For example, according to ISACHENCO (1973), G. F. Morozov was probably the first scientist to define forests as "geographic phenomena" and to differentiate forests into geocomplexes. Morozov also considered that the ultimate result of the study of natural history of a territory is its subdivision into a set of "landscapes", or "geographic individuals" (ISACHENCO, 1973).

L. S. Berg, another student from the Dokuchaevian school, is remembered today for his monumental work *The Geographic Zones of the U.S.S.R.* (BERG, 1930, 1937). As ISACHENCO (1973, pp. 33–34) put it:

In his book Berg takes a very broad view of landscape. Among the examples, he includes both the typological aggregates of elementary geocomplexes appearing regularly in a given zone, e.g. swamps, spruce stands and sand dunes etc. and intricate, unique geocomplexes, e.g. the central-Siberian Plateau and the Valdai Hills.

Berg's book was used for many years as a model for a geographic theory of landscape, and this duality in his concept of landscape is reflected in the works of many later Soviet writers (ISACHENCO, 1973).

To summarize, it is evident that, prior to 1950, Soviet geographic study of landscapes followed a very different course compared with North America, Europe and East Africa. In the U.S.S.R. this approach led, by way of Polynov's ideas, to the development of the discipline of landscape geochemistry in the 1950s.

*Soviet landscape geochemistry pre-*1950

Soviet landscape geochemistry would not have developed without the original ideas of another graduate of the Dokuchavian school of geography, B. B. Polynov. Between 1920 and 1950 Polynov described several concepts which linked the Soviet approach to landscape study with geochemical concepts of Fersman and the other pioneer geochemists.

PARFENOVA (1963, p. 111) provided a detailed account of the evolution of Polynov's thinking from which the following quotes are taken. She first described how Polynov's thinking diverged from that of his master Dokuchaev:

Polynov did not reach immediately the conclusion that one of the principal links connecting living and dead nature is the migration of chemical elements. His earlier works on soil science were mostly of a physiographic nature. He tried to uncover relationships among vegetation, soils, underlying rocks, water geomorphology and geology of a locality by using complex investigations according to Dokuchaev's program. These studies led to new ideas concerning the landscape as a dynamic system which changes constantly as a result of the struggle between opposite directions of natural processes concerning the relict and newly arising features of the landscape, which make it possible to judge the direction in which it develops, and the paleography of landscapes and the necessity for a historical approach to their study. The concept of elementary landscapes (see below) is found for the first time in these studies.

The new methodology became more definite in the Mongolian studies of Polynov, when his attention was drawn to correct the geochemical relationship between regions of removal and accumulation of the weathering products. He came to the conclusion that salts in enclosed basins are derived from mountain ridges surrounding them and, in a more general form, that the primary source of all salts are igneous and metamorphic rocks. He established that there is a definite pattern in the migration of elements between the residual eluvium of watersheds and the unconsolidated material of slopes and depressions.

Some of Polynov's ideas are described in his classic work *The Cycle of Weathering*, which was translated into English by Alex Muir (Polynov, 1937). In his book, Polynov describes the geochemical evolution of the "weathering crust". He envisaged that each element in this crust participates repeatedly in large and small cycles of transformations of its compounds which are accompanied by the transformation of energy. In this respect Polynov's geochemical model was more detailed than Goldschmidt's general description of the "minor geochemical cycle". Polynov also noted that his chemical weathering cycles are not reversible. The net result of the process is that elements are redistributed among the lithosphere, hydrosphere and atmosphere. In all landscapes some elements tend to accumulate, and others to dissipate.

Polynov also advanced ideas of the role of geochemistry in soil formation. According to Basinski (1959, p. 20)

> Polynov (1933) considered that soil evolution proceeds along two lines, one governed by eluviation and one by salinization or desalinization. In the eluvial evolution, Polynov recognized two basic processes, acid and alkaline weathering, and considered that soil types merely reflect evolution's many stages due to progressive dealkalization.
>
> Thus alkaline weathering produces alkaline, prechernozemic, and cherzonomic phases, while acid weathering results in pre-podzolic, podzolic and swampy phases. With increased humidity, alkaline weathering may give place to acid weathering and thus the two series may be regarded as continuous. Halogenic evolution consists of phases corresponding to transition from solonchak group through the carbonic group to the swamp group.

This thinking led Polynov (Parfenova, 1963, p. 112) to introduce the concept of the *migration capacity of elements* to describe the:

> true relative speed of their movement from the land to the ocean, ordinarily associated with the repeated form changes of their compounds.

Parfenova continues the description of the evolution of Polynov's thinking in 1934 when, as a result of detailed investigations in Adzhariya, he defined the three elementary landscapes (i.e. eluvial, superaqual and aqual) (Fig. 5) on the basis of relations between the daylight surface and the water table. The important point here is that all three may coexist in the same *area* of country where they can be mapped.

Polynov showed that the intensity of chemical weathering may vary from place to place in the same landscape. He described how the three elementary landscape types (e.g. land, bogs and lakes) are always *geochemically* connected to form a "geochemical landscape" (Parfenova, 1963).

Polynov described in detail element migrational relationships and patterns in several important kinds of geochemical landscapes including: (1) semi-desert areas; (2) chernozem steppes; and (3) the taiga zone. As a result of these studies Polynov concluded (Parfenova, 1963, p. 114) that the:

> composition of natural waters is not determined by simple abiotic reactions between water and the minerals of magmatic rocks i.e. by hydrolysis and dissolution as taught in the textbooks, but by a more complex and rapid process of the removal of elements from minerals by organisms and the dissolution in water of the ash of organisms during their mineralization.

In summary, Polynov's ideas of landscape geochemistry form a bridge between the concepts of modern geochemistry on the one hand and the Soviet concepts of landscape science (e.g. as described by Berg and his co-workers) on the other. Once identified, this bridge led to other new ideas and concepts which evolved into the scientific discipline of landscape geochemistry. This evolution was finalized by Polynov's students A. I. Perel'man, M. A. Glazovskaya, V. A. Kovda and many others after the master's death in 1952.

Summary of the development of landscape geochemistry 1900–1950

The development of landscape geochemistry during the first half of this century may be summarized in the following five points:

1. The pioneer thinkers of geochemistry (i.e. F. W. Clarke, V. I. Vernadski, A. E. Fersman and V. M. Goldschmidt) were all holists with respect to the study of geochemistry and included reference to all elements in the Periodic Table in modern geochemistry.

2. The pioneer thinkers of geochemistry described

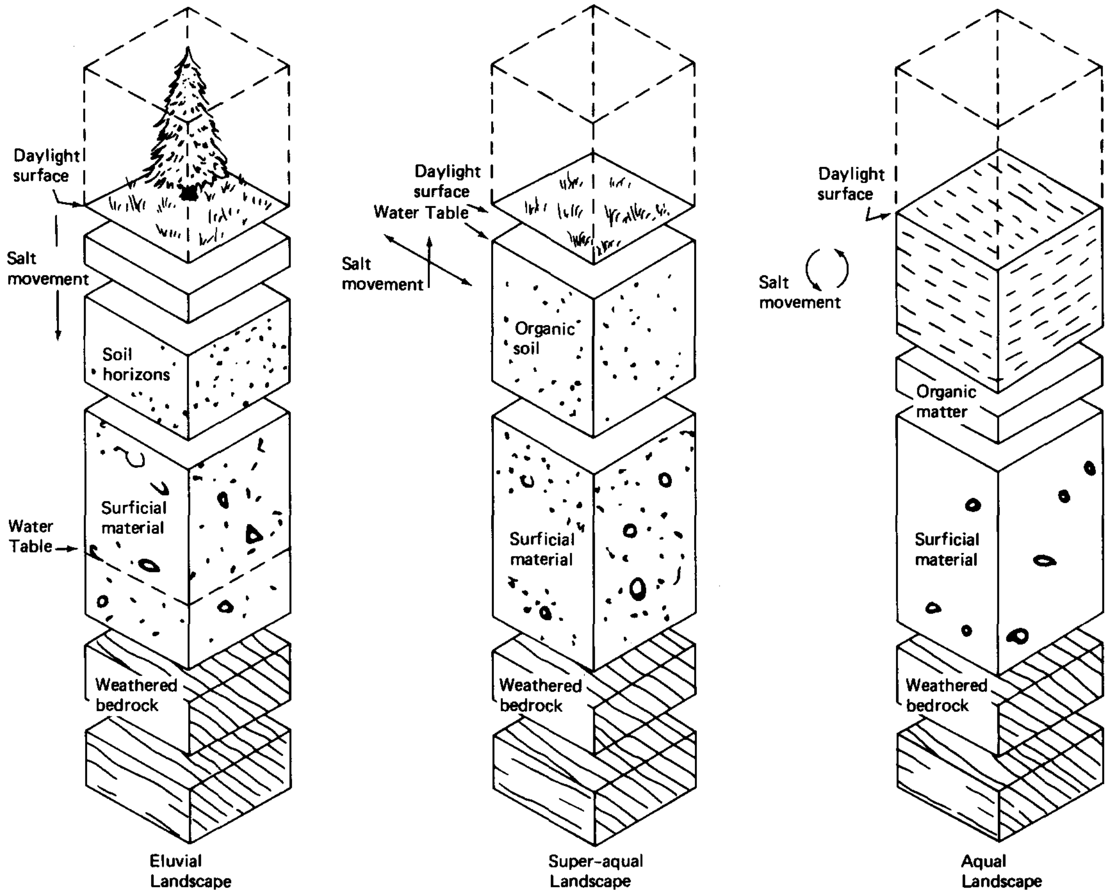


FIG. 5. Landscape prism diagrams for each of Polynov's three elementary landscapes (from FORTESCUE, 1980).

general geochemical concepts and principles which apply in all landscapes. They did *not* focus on details of geochemistry of elements in particular landscapes, or on the role of geochemistry in landscape evolution.

3. The worldwide revolution in soil science and geography which stemmed from the ideas of Dokuchaev 90 a ago had two major consequences for the later development of landscape geochemistry: (1) it led to the development of a school of "landscape science", and (2) it trained B. B. Polynov *before* he broke away from its teachings to develop his own ideas of landscape evolution in the 1920s.

4. Owing to the domination of non-Soviet geography (and geomorphology) by the ideas of Davis and Penck, it was almost impossible for Soviet ideas of landscape geochemistry to penetrate into the non-Soviet world prior to 1950.

5. Geochemical ideas of A. E. Fersman and V. M. Goldschmidt are particularly important in relation to Polynov's development of landscape geochemistry. These ideas were also essential for the rapid development of landscape geochemistry by Perel'man and Glazovskaya after Polynov's death.

PART II. THE DEVELOPMENT OF LANDSCAPE GEOCHEMISTRY 1950–1980

Introduction

In Part II the development of Soviet and non-Soviet approaches to landscape geochemistry between 1950 and 1980 are described. During this period Polynov's ideas of landscape geochemistry were developed into an important sub-discipline within geochemistry in the U.S.S.R. by A. I. Perel'man, M. A. Glazovskaya and their many co-workers. In the non-Soviet world exploration geochemistry grew rapidly in importance followed by geochemistry in medicine, nutrition and health studies. Environmental geochemistry also began to be studied by both geochemists and non-geochemists.

Soviet landscape geochemistry 1950–1980

Polynov soon attracted co-workers and students who helped develop his ideas of landscape geochemistry. During the 1950s and 1960s the principal architects of the new discipline were A. I. Perel'man, assisted by M. A. Glazovskaya and V. A. Kovda.

A. I. Perel'man began to lecture on landscape geochemistry at Moscow University in 1952 and he published a series of essays on the subject three years later (PEREL'MAN, 1955). Prior to the publication of a classic book in 1966 titled *Landscape Geochemistry* (PEREL'MAN, 1972a) Perel'man wrote a series of important papers on different aspects of the subject. One of these articles (PEREL'MAN, 1961a) discussed "geochemical landscape classification" and another described the "geochemistry of ancient landscapes" (PEREL'MAN, 1961b); in a third article PEREL'MAN (1965) described a "general geochemical classification of elements". These early papers indicate Perel'man's dedication to landscape geochemistry for some years prior to the publication of his definitive book *Landscape Geochemistry* in 1966 (PEREL'MAN, 1972a). This book is a comprehensive account of all aspects of landscape geochemistry in the mid-1960s.

PEREL'MAN (1972a, p. 23) comes straight to the point in the introductory chapter as follows :

> landscape geochemistry in not the simple sum of our chemical knowledge on landscape; it is not a new term concealing an old and familiar content (the chemical characterization of weathering crusts, soils, plants and water), nor is it merely a collection of the chemical information accumulated by geologists, geobotanists, soil scientists, hydrogeologists and so on. . . .
>
> From the geochemical viewpoint, *a landscape is a part of the Earth's surface in which the solar energy causes elements to migrate in the atmosphere, hydrosphere and lithosphere*. These parts of the crust alter during this migration and penetrate one into the other to produce special natural bodies: living organisms, soils, weathering crusts, and natural waters. . . . We can therefore say that landscape geochemistry is *the history of atoms in the landscape*.

Then follow twenty one chapters organized as follows:

Part I. *General landscape geochemistry*, which describes general characteristics of landscapes.

Part II. *The classification of geochemical landscapes*, which describes the geochemical classification of landscapes and provides information on the geochemical features of important types of geochemical landscapes.

Part III. *The geography of geochemical landscapes*, which describes laws of spatial location of geochemical landscapes, including principles of landscape zoning and mapping.

Part IV. *Historical landscape geochemistry*, which describes geochemical features of landscapes in past geological epochs.

Part V. *The geochemistry of elements in landscapes*, which deals with the history of elements in landscapes and explains the laws of their migration via the properties of their atoms.

Each of the five parts will now be reviewed in order to provide an overview of the principles of landscape geochemistry. Part I begins by describing the Polynov concept of elementary landscapes. It continues with information on the general morphology of landscapes and describes landscape types in relation to element migration. Examples are provided of the modes of migration of elements in landscapes and element behaviour in landscapes is described using general rules. For example, Perel'man distinguishes between the behaviour of "major" and "minor" elements in landscapes and between "active" and "inactive" elements in landscape evolution. The role played by the biosphere, hydrosphere and atmosphere in the migration of elements during the evolution of landscapes is also stressed.

After a brief, but informative, description of the methodology of landscape geochemistry in the early 1960s Perel'man described practical applications of the subject as being:

1. Landscape geochemistry in relation to man's activities in landscape (i.e. environmental geochemistry).

Perel'man noted in 1966 that new element migration routes may result from man's activity and that such migrations may produce "artificial" element associations foreign to the biosphere. He stressed that some of these may be unstable.

2. Landscape geochemistry in relation to prospecting for minerals and hydrocarbons.

Perel'man stressed that only geochemical prospecting methods appropriate to the geochemical landscapes in which prospecting occurs must be used during exploration.

3. Landscape geochemistry in relation to the nutrition and health of plants, animals and man.

PEREL'MAN (1972a, p. 187) pointed out that "the Earth has no natural landscapes whose local foods and water contain all the elements in optimal amounts" and considered nutrition and health as some of the most important applications of landscape geochemistry.

In summary, by 1966, Perel'man had demonstrated that landscape geochemistry was a unique scientific discipline with major practical applications in environmental geochemistry, exploration geochemistry, and nutrition and health.

In part II of his book, PEREL'MAN (1972a) described a "global" geochemical classification of landscapes. Perel'man's classification included four principal groups of landscapes:

1. woodland landscapes
2. steppe and desert landscapes
3. tundra landscapes
4. primitive desert landscapes.

Perel'man devoted a separate chapter to the description of the geochemical features of each of these four important landscape groups. The Soviet holistic approach to landscape description is exemplified by the idealized conceptual model (Fig. 6). This diagram includes information on: (1) precipitation; (2) evaporation; (3) temperature; and (4) accumulation of

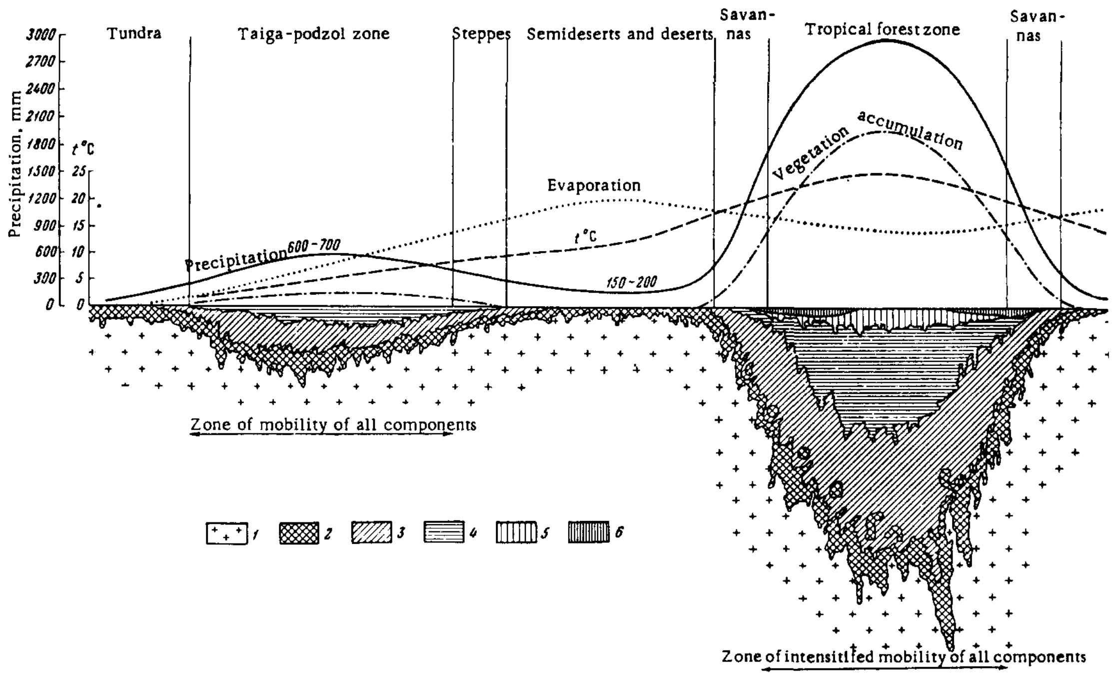


FIG. 6. Idealized conceptual model for the weathered crust in tectonically inactive areas. (1) new crust; (2) grus zone, chemically little modified; (3) hydromica–montmorillonite–beidellite zone; (4) kaolinite zone; (5) ochers Al_2O_3; (6) hard layer Fe_2O_3 (after STRAKHOV, 1960; from MALYUGA, 1964).

organic matter within major climatic zones (tundra, taiga-podzol, etc.). On the diagram, this information is combined with a description of general geochemical properties of the weathered crust and the soils developed in each of the regions.

Perel'man carried this type of thinking a stage further and defined the two *geochemical gradients* that are of fundamental importance in landscape geochemistry. One is a "*water series*" and the other is a "*thermal series*". These gradients help to define the four landscape groups mentioned above.

PEREL'MAN (1972a) also described a hierarchy of taxonomic units for a global landscape geochemical classification system (Table 1). For example, *landscape groups* were distinguished largely on the basis of biological circulation of the air migrants (especially C, H and O) and in relation to the amount and type of the primary productivity of the biosphere. These criteria are usually considered a part of ecology, or biogeography, by non-Soviet geochemists.

Until recently, broad hierarchical systems of landscape description, such as that described by Perel'man in 1966, were as often considered somewhat outdated and impractical. This was partly because they usually require a very complex legend to describe the landscapes mapped. However, the recent development of image processing and geographic information system (GIS) techniques may solve this problem and, eventually, lead to a revival of interest in Perel'man's taxonomic units of a geochemical landscape classification (PEREL'MAN, 1972a, p. 203) scheme for the mapping of geochemical landscapes

Table 1. Taxonomic units of a geochemical landscape classification (from PEREL'MAN, 1972a)

No.	Name	Criteria for distinction
I	Series	Form of motion of matter (physical, chemical, biological) related to element migration in landscape
II	Group	Biological circulation of air migrants, relation of total mass of living matter to annual production, organism types involved in biological circulation
III	Type	Biological circulation of air migrants, annual production of living matter, decomposition rate of remains of organisms
IV	Family	Living matter production within the type
V	Class	Typical elements and ions in water migration
VI	Genus	Rates of water circulation and mechanical migration
VII	Species	Local landscapes (see Table 2)

(Table 1). This aspect of a future landscape geochemistry is discussed in Part IV of this review.

Part III of Perel'man's book deals with techniques for the mapping of both areal and linear geochemical features of landscapes. In order to do this, Perel'man stressed the importance of two critical geochemical concepts: *geochemical gradients* which describe gradual changes of a geochemical feature of a landscape; and *geochemical barriers* which describe abrupt changes.

According to Perel'man, at the regional scale, the geochemical evolution of landscapes is largely deter-

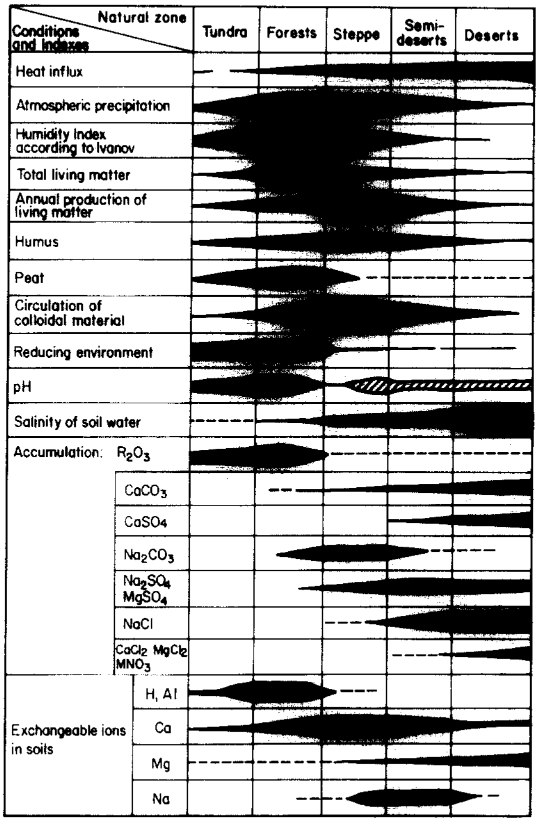


FIG. 7. Geochemical features of landscapes along a thermal series according to Kovda and Perel'man (from LUKASHEV, 1970).

mined by three factors: (1) climate; (2) geological structure; and (3) relief. This is in contrast to the local scale, where many other factors are usually involved, some of them of major importance. Glazovskaya's classification of geochemical landscapes (described below) covers this aspect of the subject in more detail.

The role of geochemical gradients in the global classification of geochemical landscapes is indicated in Figs 6 and 7. These figures provide an overview of important chemical and geochemical parameters involved in the mapping of Perel'man's five principal natural landscape geochemical zones found on the Earth.

Perel'man described how mapping of geochemical landscapes on a broad scale begins with the existing general maps (e.g. geology, tectonics, soil cover, geobotany and topography) on a scale of 1:5,000,000. The mapping procedure then continues with a stepwise description of geochemical landscapes at the more detailed scales of the hierarchy described on Table 2. Perel'man also mentioned that the 1:5,000,000 landscape geochemical maps formed a basis for geochemical maps of the entire U.S.S.R. on a scale of 1:20,000,000.

In part IV of his book Perel'man discussed geochemical mapping in relation to the geological time scale. He does this by describing landscape development in relation to the biological circulation of water migrants in several tectonic and climatic epochs. PEREL'MAN's (1980) recent paper on geochemical landscapes in the U.S.S.R. during the Miocene (discussed below) is a modern example of this aspect of landscape geochemistry.

Perel'man, in part V of his book, described the geochemical behaviour of selected elements during landscape evolution. He stressed the importance of a small number of air and water migrants in the formation of landscapes. Part V also included a geochemical classification of elements based on their behavior in landscapes. This classification scheme is then related to the general processes and concepts of landscape geochemistry discussed above.

As might be expected, Clarke units are used extensively throughout Perel'man's book. Figure 8 illustrates the use of the Clarke unit to provide general information on the abundance of two elements with similar geochemical behavior, but differing Clarke values. The Clarke of Cl is 137 ppm and of Br 2.6 ppm. Perel'man then shows that, because of its relatively high Clarke value, Cl may dominate the entire geochemistry of certain arid and semi-arid landscapes. In contrast Br, with a low Clarke value, *never* dominates the geochemistry of a landscape.

Perel'man diagrams (similar to Fig. 8) are of interest to all geochemists today especially because databases of 50–60 elements are often used for geochemical maps. Perel'man diagrams for all elements and important isotopes (e.g. ^{137}Cs) are of interest to scientists interested in environmental geochemistry.

In summary, Perel'man's emphasis on the geochemical classification and formal mapping of landscapes were logical extensions of Polynov's ideas. More important, Perel'man's book brought landscape geochemistry into the forefront of environmental geochemistry by showing that:

1. Landscape geochemistry links geography and geochemistry by describing, systematically, patterns of behaviour of all elements in processes occurring at, or near, the daylight surface which lead to the development and evolution of landscapes.

2. Landscape geochemistry provides a holistic conceptual framework for the structuring of most geochemical research in the environment. In particular, Perel'man's geochemical classification of elements is orientated to the systematic study of the behavior of all elements *concurrently* in any particular landscape, or landscapes.

3. Landscape geochemistry provides a common theoretical background for multi-element geochemistry as applied to the solution of practical problems in:

a. Baseline geochemistry, land management and pollution;

b. Prospecting for mineral deposits and hydrocarbons; and

c. The use of geochemistry in the study of the health and nutrition of plants, animals and man.

Table 2. Classification pattern for elementary landscapes by type of migration of chemical elements (from GLAZOVSKAYA, 1963a)

Landscape groups, after B. B. Polynov	According to type of geochemical integration	According to migration cycles of elements in original rocks: Primary (ortho)	Secondary (para)	Superimposed secondary (neo)
Eluvial	Eluvial (flat tops, well drained ancient plains)	Orth-el (ortho-eluvial on massive igneous rocks)	Par-el (para-eluvial on dense sedimentary rocks)	N-el (neo-eluvial on loose sediments)
	Trans-eluvial (upper parts of slopes)	Trans-orth-el (trans-orthoeluvial)	Trans-par-el (trans-paraeluvial)	Trans-n-el (trans-neoeluvial)
	Eluvial-accumulative (parts of slopes and dry gulleys)	Orth-el-ac (trans-orthoeluvial-accumulative)	Par-el-ac (trans-paraeluvial-accumulative)	N-el-ac (neoeluvial-accumulative)
	Accumulative-eluvial (local confined lower ground with deep groundwater table)	Orth-ac-el (ortho-accumulative-eluvial)	Par-ac-el (para-accumulative-eluvial)	N-ac-el (neo-accumulative-eluvial)
Superaqual	Trans-superaqual (trans-hydromorphic)	Trans-hydr-oth (trans-ortho-hydromorphic)	Trans-hydro-p (para-trans-hydromorphic)	Trans-hydro-n (neo-trans-hydromorphic)
	Superaqual (confined lower ground with weak water exchange)	Hydr-orth (ortho-superaqual)	Hydro-p (para-superaqual)	Hydro-n (neo-superaqual)
Subaqual	Trans-aqual (streams, flowing lakes)		Trans-aqual	
	Aqual (stagnant lakes)		Aqual	

4. Perel'man also stressed the practical applications of landscape study and provided a hierarchical classification of geochemical landscapes which could be used for mapping at the local, regional, or global levels of detail.

Since 1966 Perel'man has written several more books describing and clarifying his approach to the study of geochemistry in landscapes and related subjects. These include *The Geochemistry of Epigenesis* (PEREL'MAN, 1967); *The Geochemistry of Elements in the Zone of Supergenesis* (PEREL'MAN, 1972b); *Biological Systems of the Earth* (PEREL'MAN, 1979a); and *Geochemistry* (PEREL'MAN, 1979b). All these books contain valuable information concerning geochemistry in landscapes, unfortunately they are too long to be included in this review.

M. A. Glazovskaya is another pioneer thinker in landscape geochemistry. Like Perel'man, she is a professor at Moscow University. In general, her emphasis has been on the classification of geochemical landscapes and the formulation of general concepts which are now used throughout the discipline of landscape geochemistry. Glazovskaya's first classic paper was published in 1962 (GLAZOVSKAYA, 1963a). It describes a classification system for geochemical landscapes based directly upon Polynov's elementary landscape types. In the classification, Glazovskaya defined a whole series of new terms for use in the systematic description and mapping of landscapes. She illustrated the use of the terms by examples describing geochemical landscapes in the U.S.S.R.

For example, GLAZOVSKAYA (1963a) described geochemical landscapes of the same "landscape type" as having:

1. The same character and amplitude for biological circulation;

2. The same sequence of stages in the vertical profile (which is governed by the leaching depth, the depth reached by roots and the groundwater level); and

3. The same element mobility due to weathering rate, rate of accumulation of organic matter and mineralization of organic remains.

GLAZOVSKAYA (1963a) also distinguished numerous "sub-types" of geochemical landscapes and provided a logical, but complex, terminology to describe them (Table 2). Figure 9 is an example of the application of this terminology to a typical humid landscape. To some extent this aspect of her landscape classification scheme is based on the generalized conceptual model for water flow patterns within in a hypothetical landscape (Fig. 10).

Glazovskaya also described two distinct "genera" of landscapes. These are *homogeneous landscapes* and *heterogeneous landscapes*. The former are the result of a single weathering cycle and the latter have relict features derived from one, or more, previous weathering cycles prior to the current one. Canadian glaciated landscapes would be assigned to the former group and most Australian landscapes clearly belong to the latter group.

Between 1963 and 1980 Glazovskaya wrote numerous articles on the development of different aspects of landscape geochemistry. She also edited a collec-

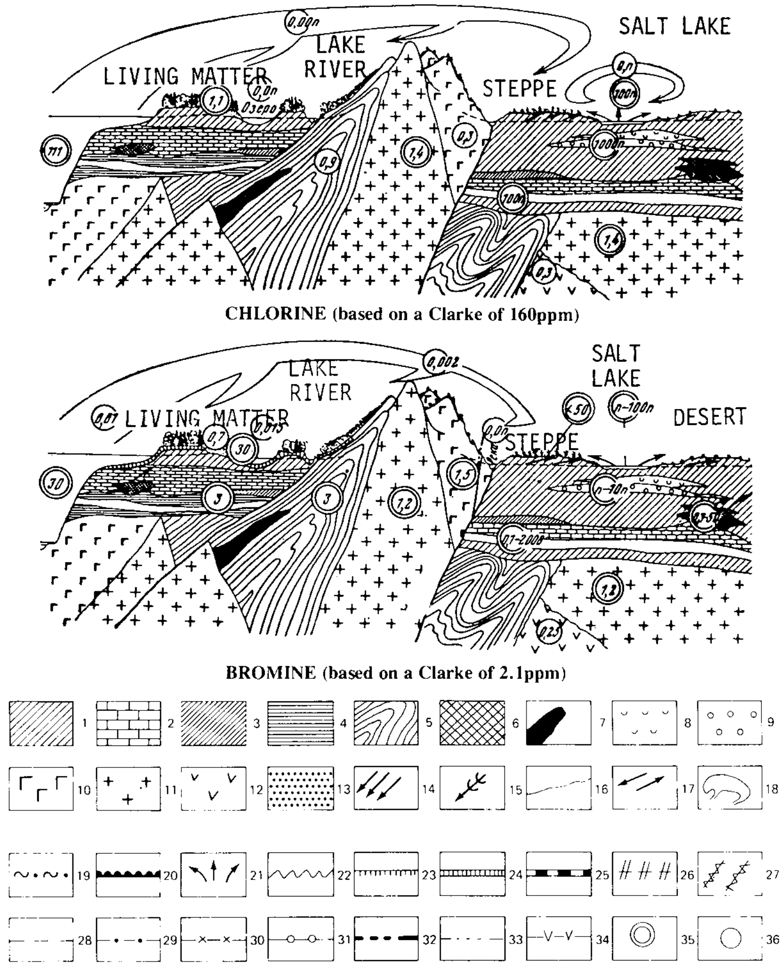


FIG. 8. Diagrams showing the relative abundance of Cl and Br in the environment (from PEREL'MAN, 1972a).

Landscape Components: (1) Buried sedimentary rocks; (2) Limestones; (3) Brown coal; (4) Clays; (5) Clays and schists; (6) Petroleum; (7) Anthracite; (8) Gypsoliths; (9) Halloliths; (10) Basic igneous rocks; (11) Acid igneous rocks; (12) Ultrabasic rocks; (13) Sapropel and peat; (14) Acid leaching; (15) Sulphuric acid leaching; (16) Oxygen boundary; (17) Direction of water flow; (18) Air migration.
Geochemical Barriers: (19) Sorptive; (20) Thermodynamic; (21) Evaporative; (22) Reducing; (23) Reducing and sorptive; (24) Biogeochemical; (25) Biogeochemical and sorptive; (26) Carbonatic; (27) Sulphatic; (28) Alkaline; (29) Acid; (30) Hydrogenic; (31) Oxygenic; (32) Calcic; (33) Arenaceous; (34) Sulphidic.
Abundance Ratios: (35) Equal to or >1.0; (36) <1.0. This is a general legend provided by PEREL'MAN (1972) for a series of 15 diagrams each of which involves the relative abundance of a different element. This list is provided in full in order to indicate the potential of such diagrams as guides to comparative abundance geochemistry.

tion of 11 papers on the subject which were published in the U.S.S.R. in 1964 and later translated into English (GLAZOVSKAYA, 1976a). This collection includes one by GLAZOVSKAYA (1976b) in which she describes how the principles of landscape geochemistry can be applied to Scandinavian landscapes. She concluded that the geochemistry of sub-arctic landscapes is particularly important from the theoretical and practical viewpoints. She suggested that, because of their importance, their geochemistry should be thoroughly investigated in the future.

Companion papers in the volume discuss: soil–geographic concepts (LIVEROVSKII and LIVEROVSKIY, 1976), the application of the landscape geochemistry approach to general landscape research (DOLGOVA, 1976; PANKOVA, 1976; GOLOVENKO, 1976; DOBRODEEV, 1976), the relation between landscape geochemistry and agricultural problems (ESCHENKO, 1976; GEDYMIN and PROBEDINTSEVA 1976), landscape geochemistry and geochemical prospecting for minerals (MIKHAILOVA, 1976; PAVLENKO, 1976) and landscape geochemistry in the search for hydrocarbons (IVANOV, 1976).

In GLAZOVSKAYA (1967) she related principles of landscape geochemistry to the description of soils of the entire Earth, and concluded that the largest

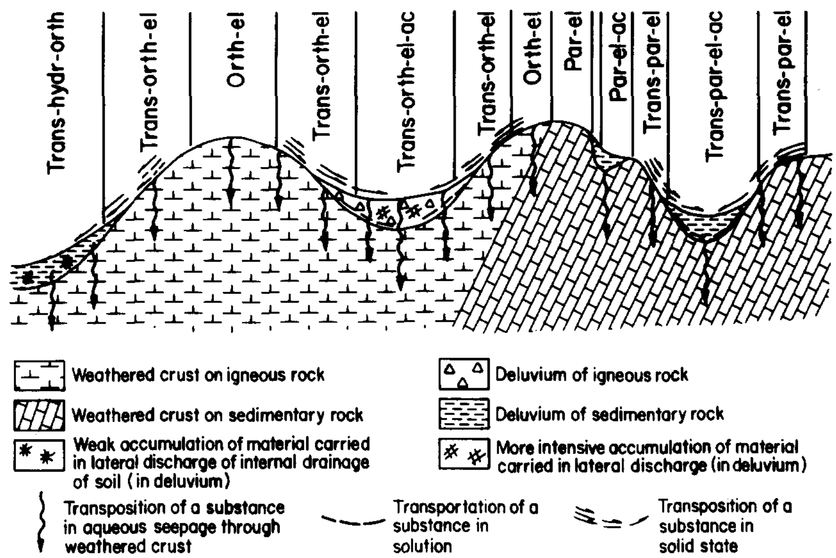


FIG. 9. Relations among topography, landscape type, hydrology and geology illustrated by means of a conceptual model (from GLAZOVSKAYA, 1963a).

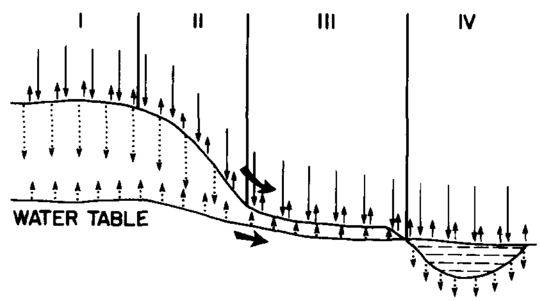


FIG. 10. Summary of flow patterns for waters for four elementary landscapes: (I) eluvial; (II) trans-eluvial; (III) super-aqual; and (IV) aqual [redrawn after GLAZOVSKAYA (1961) with additions].

global units of soil cover are "geochemical soil fields" which correspond to moisture, rather than to the thermic belts of continents. She considered that, globally, the geochemical soil fields coincide with basic types of vegetation cover. This information is clearly pertinent to the proposed geochemical atlas of the world (IGCP Project 259; see DARNLEY, 1990a,b).

In a later paper, GLAZOVSKAYA (1970) explored the relation between landscape geochemistry and the soil catena concept of MILNE (1935) mentioned previously (Fig. 4). GLAZOVSKAYA (1970, p. 245) concluded that:

> The study of the patterns of migration of chemical elements in these geochemical soil sequences, aside from being of theoretical interest, has also practical significance in ameliorative and agrochemical research, in geochemical mineral prospecting and in the generalization of soil maps.

In still another paper, GLAZOVSKAYA (1973) described "technobiogeomes". These are man-modified landscape systems endowed with the same level of geochemical stability as natural systems. She proposed that the following criteria be used for the grouping of technobiogeomes :

1. The probable intensity of decay of technogenic products in the soil and in the atmosphere;
2. The probability of the dissolution of these products, their evaporative concentration and their precipitation in reducing environments; and
3. The probable intensity of removal of these products by aqueous and aerial currents.

In her paper, GLAZOVSAKAYA (1973) included geochemical data from different areas of the U.S.S.R. to support her classification.

GLAZOVSKAYA (1977) discussed certain problems in the theory and practice of landscape geochemistry. She focused on the role of landscape geochemistry in environmental protection and suggested that the environmental threat posed by a particular element could be measured by an index of its destructive activity. She explained that the index is a ratio of an element's "technophilia" (i.e. its affinity for engineering uses) to its "biophilia" (i.e. its affinity for living matter). She suggested that the index would be highest for the toxic element Hg and lowest for the major nutrient elements Ca, Mg and K. The ability of natural geochemical environments for self purification is also discussed in this paper and a map showing the regionalization of the U.S.S.R. in terms of probable self-purification from solid, liquid and gaseous pollution is provided.

Finally, in 1979, GLAZOVSKAYA (1981a) discussed the interesting problem of quality and quantity in geographic classifications as they relate to landscape geochemistry.

In summary, between 1950 and 1980, landscape geochemistry became established as an important scientific discipline in the U.S.S.R. This was the result of the work of numerous Soviet writers led by A. I. Perel'man and M. A. Glazovskaya. The writings of these pioneers have been reviewed here in some detail because together they provide an introduction to the scope and depth of classical landscape geochemistry. All these writings are available in English translation. They are exceptional because the majority of information on Soviet landscape geochemistry between 1970 and 1980 is in Russian. The scope of this Soviet research was sketched by GLAZOVSKAYA (1985) in the foreword to the Russian edition of my book (FORTESCUE, 1985a) where she listed the following lines of research in landscape geochemistry then being actively pursued:

1. The classification and analysis of patterns of anthropogenic inputs in the various landscape zones and regions in the U.S.S.R.;
2. The study of the response of natural landscapes to anthropogenic inputs of different intensities in the U.S.S.R.;
3. The study of post-anthropogenic transformation and regeneration of landscapes using selected spatial and temporal models;
4. The selection of indicators of environmental pollution for the purpose of monitoring; and
5. The scientific substantiation of anthropogenic effects in the geochemistry of landscapes and the development of recommendations aimed at the elimination of undesirable consequences of man's activities in landscapes.

GLAZOVSKAYA (1985) pointed out that these new research thrusts led to a further development of the theory of landscape geochemistry and the development of new research methods. In particular, she mentions: (1) papers by PEREL'MAN (1972a, 1976) on the geochemical behaviour of pollutants and the detection of anthropogenic geochemical anomalies; (2) her research on geochemical systems and criteria for their stability and the destructive ability of polluting chemical entities (GLAZOVSKAYA, 1976c, 1981b); (3) the general nature of biogeochemical cycles and their destabilization by man's activities (KOVDA, 1976; BEUS *et al.*, 1976); and (4) the study of shifts in biogeochemical patterns in the European part of the U.S.S.R. during historic times (EVDOKIMOVA *et al.*, 1976).

Soviet landscape science 1950–1980

In his book *The Principles of Landscape Science and Physical-Geographic Regionalization* Professor A. G. Isachenco, of Leningrad State University, reviewed progress in landscape science in the U.S.S.R. from its conception until 1965. His book, which was translated into English in 1973 (ISACHENCO, 1973), should be consulted for details of Soviet progress in landscape science between 1950 and 1965.

This translation (ISACHENCO, 1973) is also important for another reason because in a foreword to the book MASSEY (1973) provided a brief and interesting perspective on the development of the landscape concept outside the U.S.S.R. prior to 1973.

Non-Soviet landscape geochemistry 1950–1980

A generally accepted, integrated, approach to the study of geochemistry of landscapes, such as that just described, did not exist in the non-Soviet world prior to 1990. As a consequence, in the non-Soviet world, the rise of: (1) exploration geochemistry; (2) environmental geochemistry; and (3) geochemistry in relation to health and nutrition, proceeded more or less independently. In this state of affairs geochemical advances were often made independently by scientists in any one of several disciplines.

Although they did not actually mention landscape geochemistry, the holistic vision of the four pioneers of modern geochemistry is reflected in the three major geochemistry textbooks of the 1950s (RANKAMA and SAHAMA, 1950; MASON, 1952; GOLDSCHMIDT, 1954). In general, over time, introductory textbooks in geochemistry written in English (e.g. WEDEPOHL, 1971; BROWNLOW, 1979; BOWEN, 1979; KRAUSKOPF, 1979; and the second (1958) and third (1966) editions of MASON, 1952) tended to play down the holistic vision of the pioneers of geochemistry. These textbooks usually omit all reference to landscape geochemistry and its three practical applications.

Between 1950 and 1980, several collections of papers on specific topics in "environmental geochemistry" did appear (e.g. KOTHY, 1973). These were usually organized by non-geochemists and did not refer to landscape geochemistry.

In summary, in the non-Soviet world between 1950 and 1980, several generations of students were trained as geochemists without being made aware of the existence of landscape geochemistry.

The interest of the writer of this review in a holistic approach to the geochemistry of landscapes was sparked during the 1950s while he was a student of Professor H. V. Warren at the University of British Columbia. At that time, the problem was to find a general conceptual model for comparisons of geochemical data obtained from rocks, with these obtained from overburden, soil and plant cover from one or more landscapes underlain by mineral deposits (WARREN *et al.*, 1955).

Some years later, during biogeochemical research at the Geological Survey of Canada the writer published (FORTESCUE, 1970) a "landscape prism" diagram (Fig. 11) to provide a link between the concept of "landscape" and various methods of mineral exploration then in use in areas of continuous overburden (FORTESCUE, 1967). It was while he was at the Geological Survey of Canada, that the writer first became aware of landscape geochemistry through

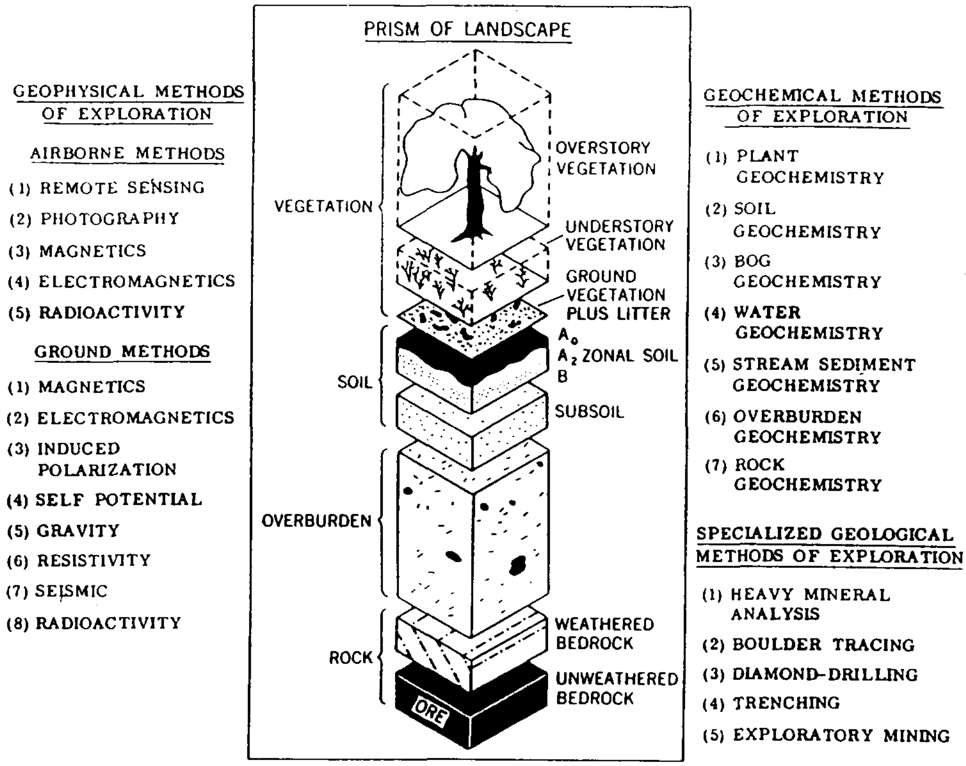


FIG. 11. A generalized "prospecting prism" showing the different landscape components which may become involved in prospecting methods research and the geochemical, geological and geophysical prospecting methods that are used for mineral exploration in Canada (from FORTESCUE, 1967).

the writings of PEREL'MAN (1972a) and GLAZOVSKAYA (1963b) (FORTESCUE, 1967).

By the time the writer moved to Brock University in 1970, he was convinced of the need in the non-Soviet world for a discipline of "landscape geochemistry". He described in a number of short papers how the fundamentals of Soviet "landscape geochemistry" might be applied to: (1) exploration geochemistry (FORTESCUE, 1974a,1975a); (2) environmental geochemistry (FORTESCUE, 1974b); (3) geochemistry applied to health and nutrition (FORTESCUE, 1973, 1974c); and (4) the study of organic terrain (FORTESCUE, 1975b). He also published a diagram designed to provide an overview of the basics of landscape geochemistry (FORTESCUE, 1974b) which is included here as Fig. 12. These papers were supported by field research in landscape geochemistry carried out by the writer and his students at Brock University (e.g. WOERNS, 1976; VESKA, 1976).

Non-Soviet geography and landscape study 1950–1980

By the mid-1960s non-Soviet geographers had come to seriously question the Davis and Penck approaches to landscape evolution. They then began to study, systematically, the role of chemical weathering and geochemistry in the formation of landforms. Also, following the thrust of ecological research in the early 1970s, geographers and geomorphologists began to apply the "systems approach" to landscape evolution. HUGGETT (1985) provided an excellent review of this development from a geographer's viewpoint. Huggett described how modern mathematical and statistical methodologies began to be included in the study of Earth surface systems by geographers and others after 1960. In chapter 3 of his book Huggett describes the history of theories of landscape development including reference to DAVIS (1899), PENCK (1953), JENNY (1941) and GLAZOVSKAYA (1968). HUGGETT (1985) also includes examples of local and global biogeochemical cycles. In his concluding chapter, HUGGETT (1985) provides a general discussion of the application of models to landscape evolution.

Another geographic approach to the study of landscapes in the 1960s and 1970s is discussed in the book by HOWARD and MITCHELL (1985) under the title of *Phytogeomorphology*. This book is important to non-Soviet students of landscape geochemistry because it includes an introduction to the hierarchical "land unit" approach to landscape description. Howard and Mitchell's book does not mention Soviet landscape geochemistry. This book is important because it provides an introduction to the relation between remote sensing and landscape description.

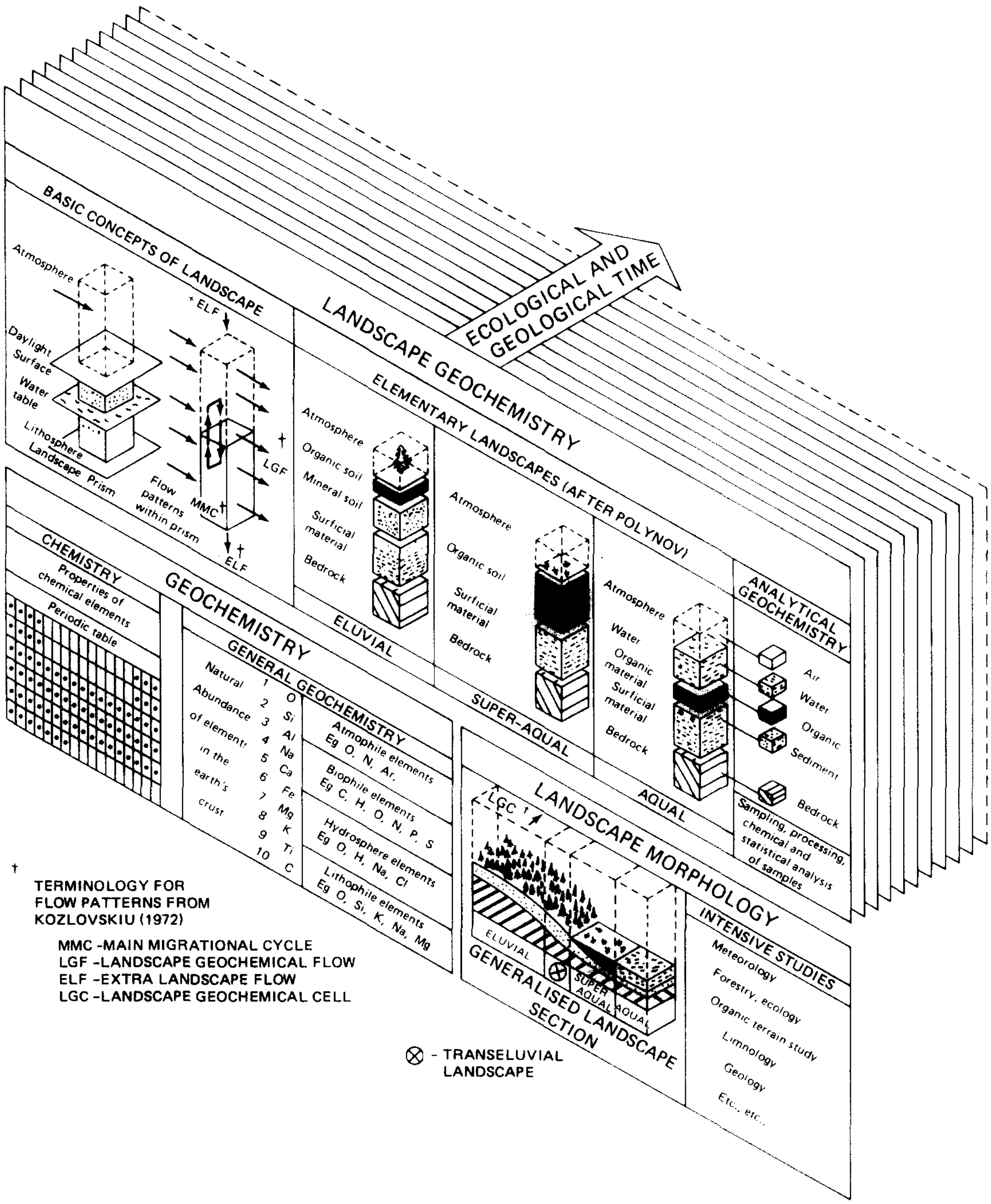


FIG. 12. Chart showing some basics of landscape geochemistry (from FORTESCUE, 1974b).

Non-Soviet soil science 1950–1980

In his book *The Soil Resource* H. Jenny (JENNY, 1980) provided an ecological perspective to soil science and landscape description during the 1960s and 1970s. This book stresses the importance of always considering both *the mineral and biological* evolutioin of soil cover. JENNY (1980) reviewed progress made with the development of his conceptual approach to soil genesis described in his previous book (JENNY, 1941). Both books should be consulted for more details on this important aspect of landscape study.

The interesting book by A. J. Gerrard entitled *Soils and Landsforms* (GERRARD, 1981) traces the history of links among soils, landforms and geomorphological processes. Gerrard first summarized the development of conceptual models for soil genesis and geomorphology prior to 1980 and, in doing so, referred briefly to a paper by GLAZOVSKAYA (1968). In this paper Glazovskaya contrasted geochemical gradients in landscapes developed in the Tien Shan of

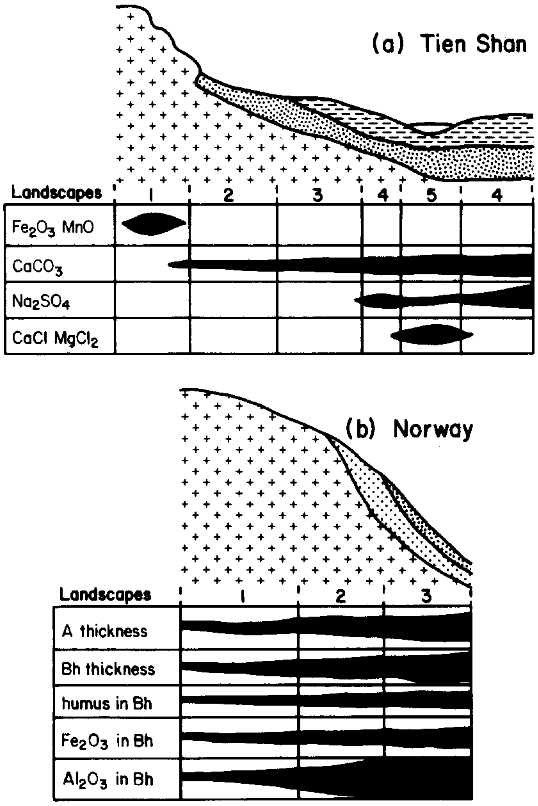


FIG. 13. Geochemical soil sequences in (a) Tien Shan; (b) Norway (from GLAZOVSKAYA, 1968).

central Asia with others developed in Norway (Fig. 13).

Gerrard's book also discusses a nine-unit landsurface model (Fig. 14), originally described by DALRYMPLE *et al.* (1968) and updated by CONACHER and

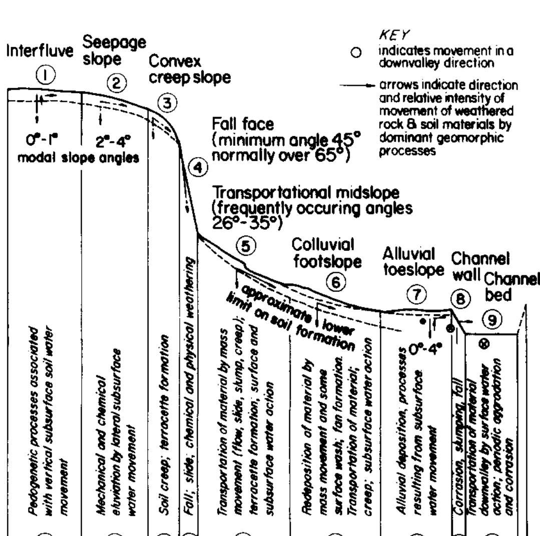


FIG. 14. Hypothetical nine-unit landsurface model (from DALRYMPLE *et al.*, 1968).

DALRYMPLE (1977). Gerrard notes that the process–response pedogeomorphic units included in the model can be mapped in detail over extensive landsurfaces. These ideas come close to the mapping of "geochemical landscapes" as described by Perel'man and Glazovskaya and discussed previously.

Components of the "traditional" approach to the geochemistry of soils were described in BEAR (1955). They include an interesting chapter on trace elements in soils by one of Goldschmidt's students—R. L. Mitchell (MITCHELL, 1955). Later, ANDRIANO (1986) provided an excellent update of "traditional" soil geochemical studies in the period under review. Andriano's book includes detailed reviews of literature on the geochemistry of As, B, Cd, Cr, Cu, Pb, Mn, Hg, Mo, Ni, Se and Zn in agricultural soils. Other books on the geochemistry of soils include BOHN *et al.* (1979) and LINDSAY (1979) who describe details of chemical equilibria in soils. STEILA (1976) in his small book *The Geography of Soils*, provides a useful introduction to the description of soils based on the United States Comprehensive Soil Classification System. None of these books are concerned with the study of soil based on the principles of landscape geochemistry.

Non-Soviet study of natural waters 1950–1980

Both POLYNOV (1937) and PEREL'MAN (1972a) stressed the important role played by ground and surface water in the formation of landscapes. A good introduction to non-Soviet studies of groundwater geochemistry is found in chapters 3 and 7 of FREEZE and CHERRY (1979). This book also includes a good introduction to the literature on non-Soviet groundwater studies prior to 1980.

POLYNOV (1937) described *aqual landscapes* (i.e. rivers and lakes) as major components of geochemical landscapes. The non-Soviet literature on the geochemistry and limnology of surface waters from 1950 to 1980 is immense. Some indication of non-Soviet surface water geochemistry during this period may be obtained from PAGENKOPF (1978) and STUMM and MORGAN (1981). WETZEL (1975) and LERMAN (1977) provided similar information on the non-Soviet study of the geochemistry of lakes.

Another aspect of water geochemistry is the study of pollution in the aquatic environment (TODD and MCNULTY, 1976). Progress in this area of environmental geochemistry in relation to pollution by metals was summarised by FORSTNER and WITTMANN (1979) and to pollution by agricultural wastes was reviewed by WILLRICH and SMITH (1970) and ELLIOTT and STEVENSON (1977). None of these references mention Soviet landscape geochemistry.

In summary, the textbooks mentioned above, and many others like them written between 1950 and 1980, were used in the training of environmental geochemists during the period under review. Unfortunately, references to landscape geochemistry in these books are very rare. Consequently, few non-Soviet environmental geochemists became aware of the ideas of Polynov, Perel'man and Glazovskaya between 1950 and 1980.

Non-Soviet ecology 1950–1980

A useful overview of the evolution of ecology as a science prior to 1980 is included in *The Background of Ecology: Concept and Theory* (McIntosh, 1986). This story, which is too complicated to be described here, is pertinent to the development on non-Soviet landscape geochemistry. Unfortunately, the book does not refer to landscape ecology, landscape science, or landscape geochemistry.

A holistic, ecological, approach to geochemistry in landscapes became popular in the 1960s and 1970s in North America. The classic study of this type was the multi-year project at Hubbard Brook in the White Mountains of New Hampshire. The findings of this study are described in two books and in many papers cited in them. The two books, which have since become classics of modern ecology, are by Likens *et al.* (1977) entitled *Biogeochemistry of a Forested Ecosystem* and by Bormann and Likens (1989) entitled *Pattern and Process in a Forested Ecosystem.*

Likens *et al.* (1977) described details of the biogeochemical flux and internal cycling of nutrients in the typical northern hardwood forest ecosystems at the Hubbard Brook site. The Hubbard Brook study involved simultaneous study of six adjacent forest ecosystems, each defined by the catchment areas of a small stream. All six ecosystems are underlain by impermeable crystalline bedrock which allowed for the calculation of nutrient budgets.

The second book uses the same geochemical data base as the first but puts emphasis on "the role of biological processes in controlling destabilizing forces to which every ecosystem is continually subjected" (Bormann and Likens, 1979, p. vii). Although these books describe detailed ecological investigations, much of the information on element cycling rates is also directly pertinent to landscape geochemistry. From the viewpoint of geochemistry the Hubbard Brook studies are somewhat circumscribed because they are restricted to plant nutrient and micro-nutrient elements plus a small number of other elements.

Non-Soviet landscape ecology 1950–1980

Perhaps the nearest non-Soviet approach to Soviet landscape science is found in the discipline of "Landscape Ecology". This subject was reviewed first by Naveh and Lieberman (1984) and later by Forman and Godron (1986). Landscape ecology was originally introduced by a German scientist (G. Troll) in 1939 as "the study of physico-biological relations which govern spatial units of a region in both the vertical and horizontal directions" (Troll, 1950, 1971). Naveh and Lieberman (1984), in their book *Landscape Ecology: Theory and Application*, described the scope of the subject as it developed during the time under review.

These writers note that Dansereau (1957), in his book *Biogeography: An Ecological Perspective*, also described the landscape ecological approach and stressed the importance of the study of natural landscapes (usually studied by plant and animal ecologists in the 1950s) *and* landscapes disturbed by man's activities. Dansereau later updated these ideas in an essay entitled *The Template and the Impact* (Dansereau, 1980).

There is an overlap of concepts among landscape ecology and descriptive landscape geochemistry. For example, Naveh and Lieberman (1984) described Zonneveld's (Zonneveld, 1972, p. 12) hierarchical definition of *land units* for use in landscape ecology as follows:

1. The *ecotope* (or site) is the smallest holistic land unit, characterized by homogeneity of at least one land attribute of the geosphere—namely, atmosphere, vegetation, soil, rock, water and so on—with nonexcessive variations in the other attributes;
2. The *land facet* (or microchore) is a combination of ecotopes, forming a pattern of spatial relations and being strongly related to properties of at least one land attribute (mainly landform);
3. The *land system* (or mesochore) is a combination of land facets that form one convenient mapping unit on the reconnaissance scale;
4. The *main landscape* (or macrochore) is a combination of land systems in one geographic region.

These ideas are broadly similar to those of Perel'man discussed above. It is important to note that both landscape ecology and landscape geochemistry emphasize:

1. The study of spatial units of country in the vertical and horizontal directions and the transitions between them; and
2. The study of natural landscapes and landscapes disturbed by man's activities.

To summarize, in the non-Soviet world between 1950 and 1980, several approaches to the study of landscape description and geochemistry of the environment flourished largely independently of each other. Collectively, these approaches had very little contact with the development of landscape geochemistry in the Soviet Union during the same time period.

Soviet exploration geochemistry 1950–1980

Ginzberg (1960) described how, within the U.S.S.R., the development of exploration geochemistry commenced in the 1930s. By 1966, Perel'man (1972a) was able to list four important ways in which his landscape geochemistry aided exploration geochemistry. These were :

1. Landscape geochemistry could be used to establish the geochemical background levels for elements in all kinds of landscapes;

2. Landscape geochemistry could be used to aid in the delineation of areas in the U.S.S.R. suitable for the application of particular methods of geochemical prospecting;

3. Landscape geochemistry experience could be applied to the interpretation of geochemical patterns in relation to the location of mineral deposits; and

4. Landscape geochemistry could be used for planning and performing geochemical prospecting on secondary haloes and dispersion flows as demonstrated by Glazovskaya in the Southern Urals.

Early examples of the use of landscape geochemistry as an aid in geochemical prospecting include papers by PEREL'MAN and SHARKOV (1957), GLAZOVSKAYA (1963b), MIKHAILOVA (1976), PAVLENKO (1976), and IVANOV (1976). Papers by PAULIUKEVICIUS and MASILIUNAS (1967) and PAULUIKEVICIUS (1981) review 20 a of progress in landscape geochemistry and exploration in Lithuania.

By 1974, in the Soviet world, landscape geochemistry was being taken for granted in the development of geochemical prospecting methodologies. For example, KOVALEVSKII (1979, p. 26) writing in 1974 noted:

> (the) use of data on geochemical landscapes and geomorphology of the territory studied is necessary for the correct selection of areas for which biogeochemical prospecting has advantages over pedogeochemical (metallometric) surveys.

Non-Soviet exploration geochemistry 1950–1980

Exploration geochemistry became generally popular in the non-Soviet world after 1945. Initially, this was due to: (1) the publications of HAWKES (1957) and CANNON (1952) and their co-workers in the United States Geological Survey; (2) the publications of J. S. Webb and his co-workers at the Royal School of Mines in London, England (WEBB and MILLMAN, 1950, 1951); and (3) the publications of H. V. Warren, R .E. Delavault and co-workers in Canada (WARREN and DELAVAULT, 1948, 1949; WARREN *et al.*, 1949).

The book by HAWKES and WEBB (1962) included a succinct summary of the development of geochemical prospecting in the non-Soviet world up to that time. HAWKES and WEBB (1962, p. 17) refer briefly to POLYNOV (1937) and his concept of "relative mobility of elements" in the zone of weathering. A little later, HAWKES and WEBB (1962, p. 22) included the following interesting paragraph:

> In any given area, the net effect of all the dynamic forces concerned in the movement of earth materials will be reflected in the over-all pattern of distribution of the elements. This pattern has been refered to as *geochemical landscape*, wherein the *geochemical relief* is determined by geographical variations in the levels of concentration of the elements. Geochemical relief is defined not only by the contrast between high and low values but also by the homogeneity of their distribution.

This passage shows that these writers were aware of "landscape geochemistry" but considered it only in relation to the "geochemical relief" with which it was associated.

Twelve years later, in the first edition of his book *Introduction to Exploration Geochemistry*, LEVINSON (1974) mentioned briefly the concept of a "geochemical landscape". He also included an exploded prism diagram (Fig. 11) as a convenient focus for the various types of geochemical prospecting which can occur in landscapes.

Outside the U.S.S.R., exploration geochemistry developed largely without reference to landscape geochemistry. Perhaps the nearest approach to the implementation of landscape geochemistry principles in non-Soviet geochemical exploration was the compilation of case histories edited by BRADSHAW (1975) which was based partly on ideas put forward two years earlier in a preliminary study (FORTESCUE and BRADSHAW, 1973).

BRADSHAW (1975) made an important attempt to generalize geochemical prospecting experience in Canada using conceptual models. Bradshaw mentioned landscape geochemistry briefly in the introduction to his book which also included a short prologue by the writer. The experience summarized by Bradshaw's models was derived mostly from two workshops organized to collect Canadian geochemical case history data. One workshop was focused on the Canadian Cordillera and the other on the Canadian Shield of Ontario. Bradshaw's landscape models were of three kinds :

1. *Idealized models* which are block diagrams that show the total surface area in a landform affected by a geochemical anomaly;

2. *Idealized cross sections* which display the geochemical characteristics along a continuous cross section across a landform of interest; and

3. *Idealized prisms* which show details of geochemical changes up and down a particular landscape profile (i.e landscape prism).

In each section of his book diagrams of these three types are used to summarize experiences derived from geochemical prospecting in different terrains. The models aimed to provide guides for the interpretation of geochemical patterns derived from areas with landscape conditions similar to those found in the models. Figure 15 is an example of one of BRADSHAW's (1975) diagrams.

Bradshaw's approach was a significant step toward the linking of concepts of landscape geochemistry with the data from non-Soviet exploration geochemistry. Unfortunately, his approach was limited, partly

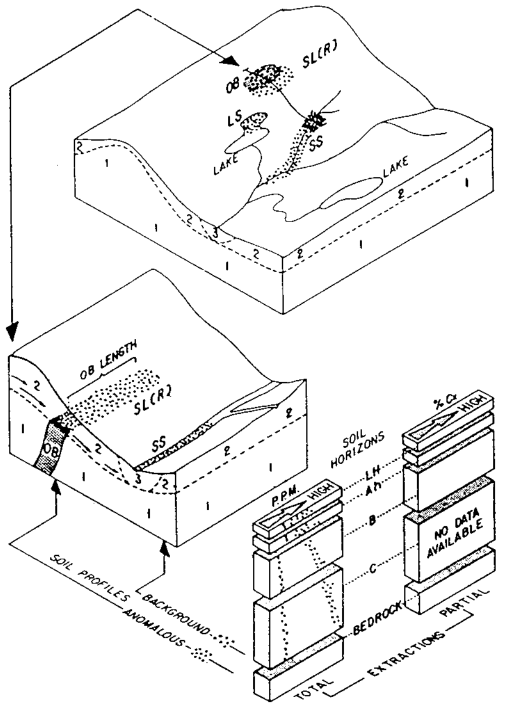


FIG. 15. Idealized conceptual models for geochemical dispersion of mobile elements in a well-drained residual soil in the Canadian Cordillera (from BRADSHAW, 1975).
Anomaly Types: SL(R) = residual soil anomaly; SL(M) = mechanically smeared soil anomaly (by glacial action); SS = stream sediment anomaly; LS = lake sediment anomaly; SP = seepage anomaly; BG = bog anomaly.
Overburden Types: 1 = bedrock; 2 = residual soil; 3 = recent alluvium; 4 =till; 5= overburden of remote origin.
Others: OB = orebody; ::: = density of dots indicates anomaly strength.

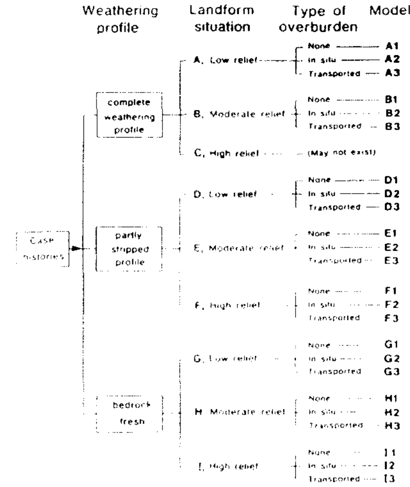


FIG. 16. Hierarchical classification of landform situations and models in Australia (from BUTT and SMITH, 1980).

by the lack of standardization of landscape and geochemical data collection by the participants in the workshops, and partly because his conceptual models are difficult to relate to multi-element geochemical data. Despite these limitations, Bradshaw's book introduced several generations of exploration geochemists to a "landscape approach" to the interpretation of the data from exploration geochemistry.

The publication of Bradshaw's book led to publication of several other collections of case histories in exploration geochemistry. One of these was from Scandinavia (KAURANNE, 1976); others are from the Basin and Range Province of the western U.S.A. and northern Mexico (LOVERING and MCCARTHY, 1978) and Australia (BUTT and SMITH, 1980).

BUTT and SMITH (1980) included a general hierarchical classification of landform situations (Fig. 16) and block diagram models for nine different landform situations in Australia. One of these models is reproduced here as Fig. 17.

To summarize, Bradshaw's synthesis of geochemical case history data was a first step toward the linking of landscape geochemistry with exploration geochemistry. In retrospect, it is a pity that Bradshaw did not take the second step of recommending that the terminology of landscape geochemistry (i.e the use of the Clarke) become an essential part of exploration geochemistry.

Another use of conceptual models in exploration geochemistry was demonstrated by COUSTAU (1977), who used them to demonstrate flow patterns of formation waters in oilfields.

In general, between 1950 and 1980, non-Soviet exploration geochemists were not aware of the potential of the landscape geochemistry approach as an aid to exploration (HAWKES, 1982).

Soviet health and nutrition geochemistry 1950–1980

In his book, PEREL'MAN (1972a) devoted a chapter to relations between landscape geochemistry and human health. After noting that there is abundant medical geographic evidence included in disease distribution maps, he suggested that such maps should always be examined from the viewpoint of landscape geochemistry. PEREL'MAN (1972a, p. 186) justified this reasoning as follows:

> In any case, we can say that natural landscapes differ in chemical compositions of the air, local foods, and water, and also that these differences are frequently such as to be important to the human body.

He then pointed out that no natural landscapes contain local foods and water with all elements in optimal amounts. Perel'man also described areas where human diseases were related to the chemical composition of soils and water as *biogeochemical provinces*, and the diseases themselves as *biogeochemical endemics*. PEREL'MAN (1972a) cited endemic goitre and dental caries as examples of diseases associated with deficiencies in the elements (I and F, respectively); and brittle bone disease (Sr), spotty tooth enamel (F), and gout (Mo) as examples of

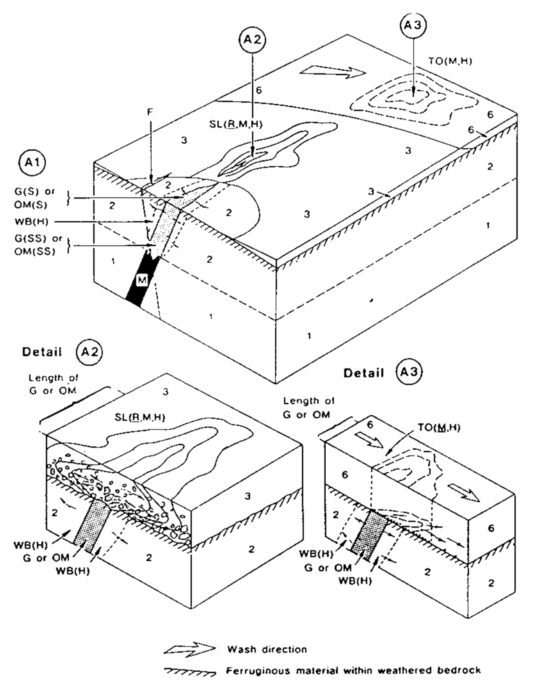


FIG. 17. Landform situation A (see Fig. 16). Complete deep weathered profile, low relief (from BUTT and SMITH, 1980).

Abbreviations:

Sample Media		*Nature of bedrock and overburden*
M,M(S)	Mineralization, mineralization at surface	*Transported*
		8 glacial
G(S)	Gossan, surface	7 aeolian
G(SS)	Gossan, subsurface	6 alluvium or colluvium
OM(S)	Oxidized mineralization, surface	5 pisolitic limestones
OM(SS)	Oxidised mineralization, subsurface	4 slumped and colluvium
PG soil	Pseudo-gossan	
F	Fault ironstone	*Residual*
WB	Weathered bedrock	3 soil
SL	Residual soil	2 weathered bedrock
TO	Transported overburden	1 fresh bedrock
SS	Stream sediments	

Anomaly Types: R = residual; M = mechanical; H = hydromorphic. Contours show general nature of anomaly; broken contours show subsurface anomaly.

human disease caused by excess of elements in the environment. PEREL'MAN (1972a) also suggested that Mg may be in some way related to stomach cancer. Perel'man described how man has made positive changes to the geochemical conditions in some areas (e.g. adding elements such as I to common salt) or by the application of fertilizers which improve the quality of plant products. He noted that a current scientific objective was to define the best norms for element consumption for various geographic conditions.

PEREL'MAN (1972a) then addressed the problem of providing optimum geochemical conditions for the healthy growth of humanity within each region of a country. It is important to note that in his book Perel'man was largely concerned with geochemistry in relation to human health and that the health of plants and animals was only mentioned incidentally. Further relations between geochemical landscapes and endemic diseases in the U.S.S.R. are discussed by MESCHENKO (1974).

Non-Soviet health and nutrition geochemistry and geomedicine 1950–1980

In North America and Europe the study of geochemistry in relation to nutrition and disease was also under active investigation between 1950 and 1980. This research was done by medical geographers, epidemiologists and other non-geochemists. However, by the late 1960s, the geochemists themselves began to organize scientific meetings to discuss relations between elements and health.

For example, in 1968, the American Association for the Advancement of Science held a symposium on Environmental Geochemistry in Health and Disease (CANNON and HOPPS, 1971). In the proceedings of this meeting a timely paper by Howard Hopps, emphasized the complex causality of disease (HOPPS, 1971). In another paper, Professor J. S. Webb (WEBB, 1971) described health implications of regional geochemical mapping in the British Isles. This paper included a geochemical map for the Southern Pennines in Derbyshire which showed high Mo values in stream sediments in one area, and another map of the same area showed an almost identical pattern for Mo-induced hypocuprosis in cattle. WEBB (1971, p. 40) concludes with these words:

> On present evidence it would be unwise to ignore the interdisciplinary potential of stream sediment reconnaissance in medical geography.

The Derbyshire research is important because it is one of the first well documented descriptions of a relation between regional (stream sediment) geochemistry and disease in animals.

At the same meeting the role of geochemists in pollution studies was discussed by CANNON and ANDERSON (1971). Like PEREL'MAN (1972a) before them (i.e. in 1966) they pointed out that geochemists could provide useful data on *baseline levels* of elements in rocks, soils, plants and water in areas subsequently contaminated by man's activities. In one of their examples they described a high Pb content of grasses collected near highways, which was derived from gasoline.

During the 1960s and 1970s a series of successful annual conferences on *Trace Substances in Environmental Health* were organized by Delbert D. Hemphill of the University of Missouri (HEMPHILL, 1966–1980). These multidisciplinary conferences involved health and geochemistry and attracted an international group of participants drawn from numerous scientific disciplines. Interdisciplinary communication was fostered at the meeting because all the papers were delivered in one session.

The informal nature of these conferences led to the generation of considerable enthusiasm for conducting research on many aspects of the relations between geochemistry and environmental health. Readers are referred to the published proceedings of the Missouri conferences for a detailed account of the development of the study of geochemistry in environmental health and related research from 1966 to 1980 (HEMPHILL, 1966–1980).

The writer presented several papers concerning geochemical mapping and landscape geochemistry at these conferences (FORTESCUE, 1971, 1973, 1974c; FORTESCUE *et al.*, 1976; SHAVER *et al.*, 1977).

Non-Soviet regional geochemical mapping 1950–1980

It is one thing to prepare a series of regional geochemical maps of a country; it is quite another to combine them with landscape geochemical maps of the same area.

In the non-Soviet world, the instant success of the stream sediment geochemical survey of New Brunswick in the early 1950s (HAWKES and BLOOM, 1956) led to a general application of "reconnaissance" geochemical mapping in Canada and elsewhere (FORTESCUE, 1986b). Geochemical mapping in the 1950s usually included less than 10 elements (HAWKES and BLOOM, 1956). This type of geochemical mapping was designed specifically for prospecting by mining companies and for mineral resource appraisal by government agencies. Mapping activities of this type became common during the late 1950s and 1960s in Canada (e.g. BOYLE *et al.*, 1966), in Norway (e.g. KVALHEIM, 1967) and elsewhere.

As mentioned above, these maps only tell half of the story from the viewpoint of landscape geochemistry. This is because they pay no attention to the geography of the geochemical landscapes mapped. Okko's paper in Kvalheim's book is an exception because the paper described the physiography of Finland (OKKO, 1967) prior to a discussion of geochemical mapping. From the practical viewpoint, the "anomaly patterns" on geochemical maps of the late 1950s and 1960s usually proved adequate for the recognition of indications of mineral deposits in the areas mapped.

In 1960, J. S. Webb and his co-workers at the Applied Geochemistry Research Centre at Imperial College, London, began to produce multi-element regional geochemical maps of various parts of the world. One of the first of these was a set of 15 coloured geochemical maps of a 6216 km^2 (2400 sq. mile) area in the Namwala Concession of Zambia (WEBB *et al.*, 1964). The Zambia maps were followed by publication of regional geochemical maps for Northern Ireland (WEBB *et al.*, 1973) and other areas. This research culminated in the production of *The Wolfson Geochemical Atlas of England and Wales* in 1978 (WEBB, 1978). There is no reference to landscape geochemical mapping in any of these maps.

PLANT (1971) described important research at the British Geological Survey. This led to an updating of the "traditional" methodology of stream sediment geochemical mapping used in the preparation of the Wolfson Atlas. Fruits of this research, which set a new standard for geochemical mapping, were described toward the end of the decade by PLANT and MOORE (1979).

In the 1970s, "reconnaissance" geochemical mapping by government agencies became popular in North America as a part of a general search for U and other mineral deposits (CARPENTER, 1980). These geochemical maps were not planned according to Fersman's rules for regional geochemical mapping described above. This is because the "reconnaissance" geochemical maps: (1) did not use standardized legends based on the Clarke; (2) did not include many of the elements recommenced by Fersman for use in mineral resource appraisal; and (3) did not have the identification of geochemical provinces within their data sets as one of their major objectives. One aspect of Fersman's plan which was applied extensively during U "reconnaissance" programs was the (computerized) statistical analysis of the data with particular stress on the use of factor analysis (CARPENTER, 1980).

Computerized methods for processing of multi-element geochemical data were introduced by Webb's research group in London around 1960. The approach involved the application of uni-, bi- and multivariate statistics to multi-element geochemical data, usually without reference to parallel topographic, geological, or geophysical data sets.

In summary, neither Fersman's approach to geochemical mapping, nor Perel'man and Glazovskaya's landscape geochemistry, played a significant part in the extensive North American U "reconnaissance" geochemical mapping of the 1970s.

Summary of the development of landscape geochemistry 1950–1980

The development of landscape geochemistry between 1950 and 1980 is conveniently summarized by the following six points:

1. In the U.S.S.R., landscape geochemistry became established as a scientific discipline with applications in exploration geochemistry, environmental geochemistry, and health geochemistry. During this time landscape geochemistry played a unique role in environmental geochemistry of the U.S.S.R. and included some information which was considered a part of ecology and other disciplines in the non-Soviet world.

2. In the non-Soviet world, the Soviet landscape geochemistry was almost unknown prior to 1980. By 1980 non-Soviet soil scientists were aware of Dokuchaev's ideas and non-Soviet geographers had access to Isachenco's book describing the evolution of the Soviet approach to landscape science in English.

3. Between 1950 and 1980, in the non-Soviet world, exploration geochemistry became established as an integral part of most mineral exploration programs worldwide. This was initiated by the writings of H. E. Hawkes, J. S. Webb, H. V. Warren and their co-workers in the 1940s and early 1950s. Later, books by HAWKES and WEBB (1962), KVALHEIM (1967), LEVINSON (1974) and BRADSHAW (1975) and others guided students of the subject. The *Journal of Geochemical Exploration*, which commenced publication in 1972, and the proceedings of numerous meetings organized by its sponsor (the Association of Exploration Geochemists) have also played a major role in the rapid development of exploration geochemistry in the non-Soviet world. General information on the development of the Soviet approach to exploration geochemistry became available to non-Soviet students with the translation of the book by GINZBERG (1960).

4. As a part of exploration geochemistry, non-Soviet regional geochemical mapping was developed in Canada and elsewhere during the 1950s and 1960s. The success of these early regional geochemical maps led to the development of government "reconnaissance" geochemical mapping programs in North America in the 1970s. "Reconnaissance" geochemical mapping was applied on a vast scale in North America, most notably in the search for U deposits.

The North American "reconnaissance" geochemical mapping technique was developed largely independently of Fersman's rules for geochemical mapping developed in the 1920s and 1930s. "Reconnaissance" geochemical mapping was also developed independently of Perel'man's principles of geochemical landscape mapping as described in his 1966 book (PEREL'MAN, 1972a) and summarized above.

5. Between 1950 and 1980 health geochemistry and environment geochemistry were actively researched in the non-Soviet world. Perhaps the greatest achievement in geochemistry in this period was the publication of *The Wolfson Geochemical Atlas of England and Wales* (WEBB, 1978). This provided a considerable stimulus for research in environmental geochemistry field worldwide.

The Wolfson atlas clearly demonstrated the feasibility and potential of reconnaissance mapping on a country-wide scale and included geochemical data that have since been applied successfully in mineral exploration, environmental geochemistry, and health geochemistry.

6. Between 1950 and 1980 landscape geochemistry became established as a scientific discipline upon which most aspects of applied geochemistry were based in the U.S.S.R. Elsewhere during this time exploration geochemistry, geochemistry in health and nutrition, and environmental geochemistry developed largely independently of each other without a unifying discipline based of the concept of landscape.

PART III. THE DEVELOPMENT OF LANDSCAPE GEOCHEMISTRY 1980–1990

Introduction

By 1980, landscape geochemistry occupied a position in the U.S.S.R. analogous to a combination of parts of ecology, environmental science, environmental geochemistry, geomorphology, exploration geochemistry and other disciplines in the non-Soviet world. In 1980, in the non-Soviet world, the applied aspects of landscape geochemistry were usually studied independently of one another and the holism of the landscape geochemistry approach to environmental geochemistry was almost unknown.

In the third part of this review, historical information on the development of landscape geochemistry prior to 1980, (reviewed in Parts I and II) is updated to 1990. Also in Part III, reference is made to major innovations and changes in emphasis in environmental geochemistry worldwide during the 1980s.

New methods for study of landscape and geochemistry 1980–1990: *Introduction*

In the 1980s three methodologies were developed in the non-Soviet world which revolutionized landscape geochemistry and landscape description. Consequently, before describing progress in the individual disciplines relating to landscape geochemistry it is necessary to provide an introduction to these methodologies and how they are applied in environmental science.

The first new methodology is in chemical analysis. During the latter half of the 1980s, sophisticated, low-cost, multi-element, techniques for the precise, accurate and simultaneous determination of almost all elements in the Periodic Table were developed. Many of these methods were sensitive and precise enough to determine elements at levels required for geochemical investigations of all kinds (VAN LOON and BAREFOOT, 1989; RIDDLE, 1987a,b). Consequently, it is now feasible for geochemists to include almost any element in a geochemical study. This advance in chemical analysis is reflected in the numbers of elements included in modern geochemical mapping programs. For example, in the IGCP Project 259 (International Geochemical Mapping Project; DARNLEY, 1988, 1990a,b), a total of 60 elements were recommended for inclusion in mapping programs and in the Western European Geological

Surveys (WEGS) geochemical mapping project (DEMETRIADES *et al.*, 1990) 65 elements were recommended for routine determination in 9,000 samples of overbank material.

The second methodological development of the 1980s was the introduction of the personal computer. This facilitated the routine application of uni-, bi- and multivariate statistics and other mathematical methods to landscape and geochemical data by geochemists. The personal computer has also enabled geographers (e.g. HUGGETT, 1985) and soil scientists (e.g. WEBSTER, 1985) to apply sophisticated mathematical models to solving problems of landscape evolution. GOUDIE (1990) provided a comprehensive introduction to modern geomorphological techniques of this type, most of which require the use of a computer.

A third major methodological development in the 1980s was the widespread application of image processing and geographic information systems (GIS) to landscape data. For example, in mineral resource appraisal, data from geochemistry, remote sensing, topography, geology and geophysics are often in the same GIS as described by DWYER *et al.* (1987).

In summary, it is essential to consider all three of these methodological developments of the 1980s in discussions of progress in non-Soviet landscape and environmental geochemistry during the 1980s. Taken together, these technological advances constitute a revolution in environmental science in general and, potentially, in landscape geochemistry as well.

The use of mathematical models in landscape description. As described previously, in the 1970s, non-Soviet geographers and geomorphologists gradually broke free from the ideas of Davis and Penck. In doing this they began to describe the development of landscapes by mathematical rather than conceptual models.

HUGGETT (1985) described the introduction of mathematical models into landscape description. He classified the mathematical models applied in geography and geomorphology during the early 1980s under the following six headings: (1) deductive stocastic models; (2) inductive stocastic models; (3) statistical models; (4) deterministic models (for water and solutes); (5) deterministic models of slopes and sediments; and (6) dynamic systems models. HUGGETT (1985) described many approaches to the study of landscape which are pertinent to today's problems of landscape geochemistry. This paper should be consulted for further information on this interesting aspect of landscape study.

Ever since the work of CLINE (1949), mathematical approaches have been applied to the classification of soils. With the advent of personal computers this activity developed rapidly in the 1980s. For example, WEBSTER (1985) described the application of sophisticated mathematical methods for spatial analysis of soils in the field. These included regionalized variable theory, semi-variogram models and fractal representations. The use of mathematical models in other natural sciences pertinent to landscape geochemistry was equally rapid. For example, MARSAL (1987) and DAVIS (1986) described their application in the earth sciences; THOMAS and HUGGETT (1980) and RAPOPORT (1986) described their application in geography; and GREIG-SMITH (1983) and DIGBY and KEMPTON (1987), described their application in ecology. More generally, BARNETT (1981) and BOX *et al.* (1983) discussed problems of the application of mathematical models to large data sets.

In summary, during the 1980s, mathematical models began to be commonly applied in all aspects of landscape study including geochemistry. By the end of the decade it was almost mandatory to include some form of mathematical model in all environmental studies.

The use of image processing and GIS in landscape study. Image processing and GIS are, together, another approach to landscape study which developed during the mid 1980s. BURROUGH (1987) described five important aspects of GIS pertinent to landscape study as follows:

1. Thematic maps;
2. Digital elevation models;
3. Methods of data analysis and spatial modelling;
4. Classification models; and
5. methods of spatial interpolation.

All these are pertinent to modern landscape study and landscape geochemistry. As described previously, a GIS methodology began to be used for the interpretation of multi-element regional geochemical mapping data in the late 1970s (GREEN, 1984). More recently RYGHAUG and GREEN (1988) described the application of GIS to geoscience including geochemical mapping, and BONHAM-CARTER *et al.* (1988) described an application of the same approach to regional mineral resource appraisal in Nova Scotia. Although image processing methodologies pre-date the wide use of GIS today there is considerable overlap between the two methodologies (ROGERS, 1986, 1988).

Air photography and remote sensing have long been used for landscape description (COLWELL, 1983). A breakthrough in the mid-1980s was the introduction of the personal computer for real-time processing of remotely sensed images. As a consequence, both geochemistry and remote sensing, and geobotany and remote sensing, were the subjects of combined active research during the late 1980s. This research has provided large amounts of important information pertinent to landscape geochemistry.

General references on the development and application of modern remote sensing of landscapes include books by LILLESTRAND and KIEFER (1979), AVERY and BERLIN (1985), and CAMPBELL (1987). A book by MULDERS (1987) provided an introduction to remote sensing designed specifically for soil scien-

Table 3. Thematic map types associated with photogeomorphic landscape features derived from remote sensing (from HOWARD and MITCHELL, 1985)

A. General	B. Applied	C. Integrated
Climatic	Agricultural	Land unit–land system
Single feature	Land use	
Synoptic weather	Land capability—potential land use (general)	Parametric
Climatic zones		
Hydrological	Land suitability—potential land use (particular crops)	
Water table depth		
Rain acceptance		
Hydrogeological	Hazards (e.g. erosion)	
Geohydrochemical	Agroclimatic	
	Agroecological	
Geological	Soil degradation	
Stratigraphic	Potential carrying capacity (e.g. human)	
Metamorphic		
Tectonic		
Structural		
	Pastoral	
Geomorphic	Rangeland types	
Morphological	Range values	
Morphometric		
Topomorphic	Forestry	
Morphogenetic	Forest types	
Morphochronological	Timber classes	
Physiographic diagrams	Logging route	
	Working circles, cutting series, etc.	
Pedological		
Soil survey	Site quality	
Vegetation	Applied geological	
Static	Mineral	
Succession	Metallogenic	
Type		
Dominant	Engineering	
Communities	Surface materials	
Nodal	Engineering geological	
	Engineering soils	
	Flood risk	
	Recreational	
	Regional planning	
	Communications	

tists. Detailed information on remote sensing in geoscience is included in proceedings of five conferences on "Remote Sensing for Exploration Geology" (organised by the Environmental Research Institute of Michigan) which were held between 1982 and 1988. A total of 521 papers were presented at these conferences (COOK, 1982, 1984, 1986) and (ROGERS, 1986, 1988).

HOWARD and MITCHELL (1985, p. 199) focus attention on the global importance of climate, landform, vegetation and soil in the development of natural landscapes as follows:

> The main value of applying phytomorphology to studies of the earth's surface is its contribution to studies of land potential and land use. This derives from two main factors: the practical homogeneity provided by phytogeomorphology, especially at the level of meso- and microunits and their ready recognition on remotely sensed imagery. This value of remote sensing is recognized in most environmental disciplines, and the wide usefulness of such imagery plays an important role in integrating the studies provided by the different disciplines.

This quotation focuses attention on the distinction between 1980s landscape description from that of earlier work; that is, the use of remote sensing to classify landscapes. In this regard HOWARD and MITCHELL (1985) provided a list of "thematic map types" which could be generated for particular areas on the basis of phytogeochemical information (Table 3).

In summary, image processing of remote sensing data for landscape description grew very rapidly in importance during the 1980s. This was due partly to the use of new sensors with higher resolution and partly to a rapid increase in the effectiveness of image processing techniques, particularly those based on the personal computer.

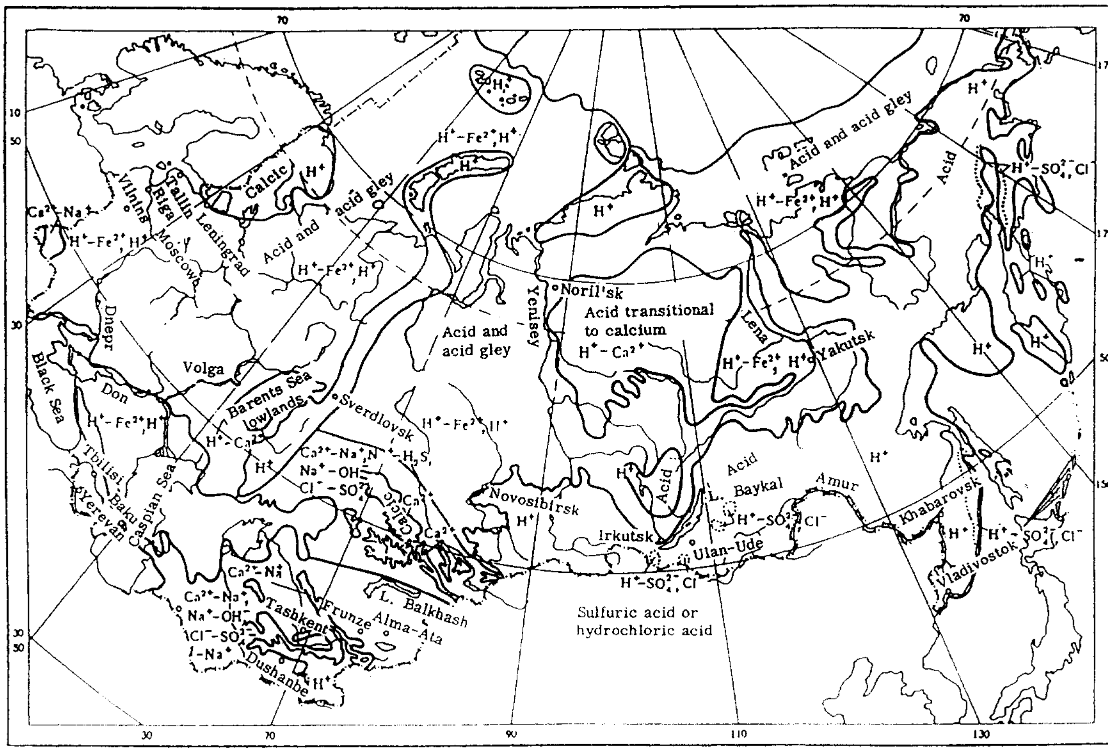


FIG. 18. Landscape geochemical map of the U.S.S.R. at the start of the Miocene showing classes of geochemical landscapes (from PEREL'MAN, 1980).

From the viewpoint of traditional landscape geochemistry, these developments are of considerable importance. For example, today the basic picture element unit (pixel) of a remotely sensed image from space, (or aircraft), can be considered as the daylight surface expression of a "prism of landscape" as previously described. The implications of this development for the mapping of geochemical landscapes are considerable as indicated by FORTESCUE and SINGHROY (1985b).

During the late 1980s, all aspects of GIS were being rapidly developed and improved. Some of these developments are of considerable potential for the landscape geochemistry of the future. The rapid rate of these developments is indicated by the following example. In 1986 one of the first workshops on GIS included 70 papers (CLERKE, 1986). Three years later, a meeting of the Canadian Institute of Surveying and Mapping included 146 papers on GIS (ANONYMOUS, 1989). The full implications of relations between remote sensing, GIS, landscape description and landscape geochemistry have yet to be explored.

In summary, during the 1980's the use of image processing and GIS for the solution of problems of landscape description and evolution became commonplace in the non-Soviet world. Although these methodologies have a great potential in landscape geochemistry little progress along these lines has been reported to date.

Soviet landscape geochemistry 1980–1990

During the 1980s a few important papers on landscape geochemistry by Soviet scientists appeared in English. For example, PEREL'MAN (1980) updated a tradition set in an earlier paper (PEREL'MAN, 1970) which described paleogeochemical maps. In the 1980 paper he described three paleogeochemical maps which cover the entire U.S.S.R. at the start of the Miocene. One map shows geochemical landscape *types* (i.e. climatic zones) which are quite different from those in the U.S.S.R. today because, in the early Miocene, there were no "tundra zones", "taiga", or "typical deserts" in the area now occupied by the U.S.S.R. Perel'man's second map shows the distribution of *classes* of geochemical landscapes in the early Miocene. This map shows areas with "humid-tropical", "sub-tropical" and "savanna" landscapes and indicates areas with geochemical landscapes which were predominantly "calcic", "calcic-sodic", "sodic", and "chloride-sulphate" (see Fig. 18). Perel'man's third map shows *Genera* of geochemical landscapes (i.e. landforms) developed in the U.S.S.R. at the start of the Miocene including "flat-plains", "dissected-plains", "areas of uplands", "areas of mountains" and "areas with highly dissected, hilly, terrain". PEREL'MAN (1980) concluded that these three general landscape paleogeochemical maps may aid in the evaluation of geochemical anomalies discovered in present-day landscapes.

This is because some of the element patterns discovered today were developed before, or during, the early Miocene.

More recently, PEREL'MAN (1986) described the concept of *geochemical barriers* for non-Soviet readers. He recognized four classes of barriers as follows:

1. Mechanical;
2. Physio-chemical;
3. Biochemical; and
4. Anthropogenic.

Perel'man then concentrated his attention on the description of the physio-chemical class of geochemical barriers. He did this because he considered them to be the most important group with respect to natural waters. Then, from the theoretical viewpoint, he classified physio-chemical barriers into eight series and assigned characteristic elements to 12 sets of pH–Eh combinations within each series. This procedure resulted in 96 theoretical element groupings. He noted that not all 96 theoretical groupings are populated by ions found in natural waters. PEREL'MAN (1986, p. 680) concluded:

> This grouping (i.e. of geochemical barriers) may be used as a predictive tool in the geochemical exploration of ore deposits, and can assist in explaining the origin and occurrence of many ore deposits.

At the end of the decade, PEREL'MAN *et al.* (1990) summarized some relations between landscape geochemistry and environmental geochemistry. These writers stressed: (1) the need to map geochemical landscapes as an essential preliminary to the study of environmental geochemistry; (2) the importance of a knowledge of different types natural geochemical barriers in environmental geochemistry; and (3) the *potential* importance of artificial geochemical barriers in the containment of pollution.

Soviet experience in the investigation of fundamental and applied problems in the geochemistry of the supergene zone (i.e. landscapes) was reviewed by LUKASHEV (1986). His paper described several successful methods for prospecting for deeply buried mineral deposits in areas of complex overburden. Lukashev noted that some of these methods have detected secondary dispersion haloes (derived from ore bodies) 100–600 m (or more) below the surface. For example, one successful program was conducted in an area with a complex overburden section. This included a surface layer of swampy, glaciofluvial sediments 17–30 m thick, underlain by a complex layer of Cretaceous chalk and Quaternary till 150–170 m thick. In this area geochemical survey methods discovered mineral deposits in Precambrian crystalline rocks of the Byelorussian Shield which underlie the overburden section just described.

After acknowledging his debt to Fersman, LUKASHEV (1986, p. 444) provided a modern definition of "the geochemistry of technogenesis" as a branch of geochemistry which deals:

1. With the role of mankind in those geochemical processes involving migration, dispersion and concentration of chemical elements and compounds in the hypersphere (specifically the biosphere);
2. In the alteration and transformation of this zone from a natural to a technologic state; and
3. In the formation of new natural–technologic areas with different geochemical properties and environmental parameters.

LUKASHEV (1986) also noted that the study of "technogenesis" is still in its infancy and, as a science, it draws on experience gained in both exploration and landscape geochemistry.

Like Perel'man, LUKASHEV (1986) mentions the importance of using the Clarke unit in almost all technogenetic studies. He also noted that the results of modern geochemical investigations can be used to predict geochemical changes in landscapes which will result from specific technological effects (e.g. pollution). LUKASHEV (1986, p. 449) ended his paper with a glance into the future:

> Future geochemical programs should be multipurpose and the geochemical information which is obtained must be in a form available to a wide range of researchers.
>
> It is predicted that by the end of this century, and certainly by the early 21st century, the role of environmental geochemistry will be substantially more significant and will require personnel specifically trained for that science.

More recently, at the 14th International Symposium on Geochemical Prospecting in Prague, LUKASHEV (1990) reiterated the importance of "technogenesis" in environmental geochemistry. He also stressed the importance of "geochemical inventory" (i.e. baseline studies) in environmental geochemistry, and pointed out that data on all elements in the Periodic Table should be included in urban geochemistry because man has often spread relatively large quantities of uncommon elements into the environment in unexpected places. In the oral presentation of his paper LUKASHEV (1990) showed examples of "urban geochemical maps" for Zn, Pb, Cu, Cd, Hg, Bi and W for cities in Byelorussia. Some of these maps included strong "geochemical anomalies" for one, or more, of these elements. In his lecture Lukashev also described urban geochemical maps based on soils, moss bags, human hair, or snow, as sample media. His presentation ended by stressing that the impact of the Chernobyl disaster on the geochemistry and ecology of landscapes in Byelorussia is very serious.

PARK (1989) provided a convenient general account of the Chernobyl disaster which may be used as a background to discussion by LUKASHEV (1990), who pointed out that radioactive fallout has complicated the previously existing geochemical and cancer-incidence patterns on maps of the area in unexpected ways.

At the Prague meeting another Soviet geochemist, SUDOV (1990), described a comprehensive urban geochemical survey of the city of Tbilisi in the Caucasus. His account included multi-element geochemical data derived from soil, water, and snow samples. Other information on environmental geochemistry presented at Prague described geochemistry in landscapes of China (TIANXIANG *et al.*, 1990). These writers described a number of interesting investigations at the interface between geochemical mapping, agriculture, pollution and medicine without recourse to the principles of landscape geochemistry.

In summary, during the 1980s in the U.S.S.R., China, and other parts of the world, "urban geochemistry" and "geochemistry/health" increased in importance as components of environmental science, usually without reference to landscape geochemistry. PEREL'MAN *et al.* (1990) made a very important point when they emphasized that systematic environmental geochemistry should always include landscape geochemical mapping and geochemical mapping of the areas studied.

Non-Soviet landscape geochemistry 1980–1990

In the late 1970s the writer published a book entitled *Environmental Geochemistry—A Holistic Approach* (FORTESCUE, 1980). The book was designed partly to introduce traditional Soviet landscape geochemistry to non-Soviet environmental scientists. The book described seven basics of landscape geochemistry as follows:

1. Element abundance in landscape components;
2. Element migration in landscapes;
3. Geochemical flows in landscapes;
4. Geochemical gradients in landscapes;
5. Geochemical barriers in landscapes;
6. Historical landscape geochemistry; and
7. Geochemical landscape classification.

Each of the basics was illustrated by examples taken from the world literature and/or the writer's experience. The book also showed how landscapes and their geochemistry may be described for comparative purposes with reference to four hierarchies: (I) space; (II) time; (III) scientific complexity; and (IV) scientific effort.

This descriptive approach facilitates the classification, synthesis and analysis of the data of environmental geochemistry which is otherwise difficult to integrate into the discipline of landscape geochemistry.

The book was favourably reviewed in non-Soviet journals [e.g. by ROSE (1981) in *Nature*; by GOODELL (1982) in *Economic Geology*; by WALI (1980) in *Ecology*; by DAVIES (1981) in *Chemical Geology*; and by JACKSON (1980) in the *Journal of Environmental Quality*]. The book was translated and published in Russian 5 a later (FORTESCUE, 1985a) with a foreword by M. A. Glazovskya (GLAZOVSKAYA, 1985). In her foreword, Glazovskaya summarized a number of important Soviet researches in landscape geochemistry which were not available to the writer when the book was prepared. She concluded (ibid., p. 10) as follows:

> On the whole, the book . . . is of interest to the Soviet reader as a positive experience in the systematization and development of geochemical ideas of Soviet and foreign scientists and their application to real problems in the utilization of natural resources, ecology and environmental protection.

Between 1980 and 1990, the writer continued to apply the landscape geochemistry approach in Ontario and elsewhere. For example, at the 1982 Missouri Conference he suggested an approach to the study of the acid rain problem in the Canadian Shield

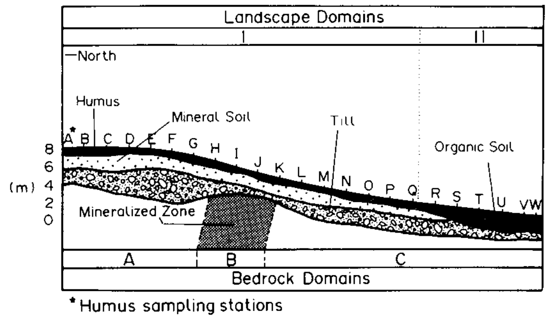


FIG. 19. The "*Hemlo Landscape Model*" of a hypothetical landscape used to select the seven sites for the humus geochemical investigation in central Ontario (from FORTESCUE, 1985b).

1. The section represents a landscape orientated N–S, 200 m long.
2. The surface of the bedrock is relatively smooth covered with a uniform layer of overburden 5 m thick.
3. The difference in elevation between the top and the bottom of the slope is not more than 10 m.
4. The bedrock, which includes a mineralized zone halfway down the slope, strikes at right angles to the section.
5. Three types of bedrock underlie the slope which are referred to as "*Bedrock Domains*". Bedrock Domain A controls the geochemistry at the top of the slope. Bedrock Domain B is the mineralized zone and Bedrock Domain C is located in country rock downslope from the mineralized zone. Bedrock Domain C acts as the substrate for a secondary geochemical anomaly derived from Bedrock Domain B.
6. The continuous layer of overburden is uniform in texture without iron pan or clay layers and nowhere deeper than 15 m deep locally. The overburden may be till, sand, silt or organic matter and support a zonal soil and should be well drained. Ideally, the overburden would have a uniform thickness and texture and have a single soil type developed upon it.
7. The daylight surface of the landscape section is divided into "*Landscape Domains*". Landscape Domains are identified by a characteristic soil and/or plant-cover type, a local change in slope, or some other landscape feature which is easily mapped. Two Landscape Domains (I and II) are included in the diagram. Landscape Domain I (sample points A–Q) includes a zonal soil lying on till and Landscape Domain II includes a deep layer of organic matter developed directly upon the till.
8. The *Hemlo Landscape Model* can be described for the collection of a single sample material (e.g. humus) or for multi-media sampling (e.g. rock, sub-soil, mineral soil horizons, humus and ground, understory and overstory vegetation).

based on landscape geochemistry (FORTESCUE, 1982) and he also suggested that landscape geochemistry might be applied to waste disposal in landfills (FORTESCUE *et al.*, 1982).

Since 1982, the writer, and several co-workers at the Ontario Geological Survey, completed a number of landscape studies relating to the geochemistry of acid rain problem (FORTESCUE, 1984a, 1985c, 1986a; FORTESCUE and STAHL, 1987). For example, one project demonstrated how a study of diatoms (obtained from lake sediment cores) could describe 100 a of the pH history of acid lakes in landscapes of central Ontario (DICKMAN and FORTESCUE, 1984).

Other landscape geochemistry research completed at the Ontario Geological Survey involved the study of the geochemistry of humus collected from seven similar landscape sites. The landscape sites were selected on the basis of a conceptual model of a hypothetical landscape site ideal for the study. Six of the landscapes included known, mineral showings (four Au, one Pt and one Zn) and the seventh was a control (FORTESCUE, 1985b; FORTESCUE and WEBB, 1986; FORTESCUE *et al.*, 1988a,b). The data from this study, which was plotted in Clarke units, demonstrated that forest humus is a surprisingly reliable medium for geochemical prospecting in areas of shallow overburden in central Ontario.

The writer and his co-workers also developed methodologies for modern regional geochemical mapping based on stream sediments (FORTESCUE, 1983a,b, 1984b, 1986a) and lake sediment cores (FORTESCUE and STAHL, 1988; FORTESCUE, 1988; FORTESCUE and VIDA, 1989, 1990a,b). All these projects make extensive use of a Clarke Index transform using values listed in Table 4.

Regional geochemical maps based on lake sediment cores are based on an average sample density of one sample per square kilometer. They include geochemical data for 35 elements (Ag, Al, As, Au, Ba, Be, Bi, Br, Ca, Cd, Co, Cr, Cu, Fe, K, Hf, La, Lu, Mg, Mn, Mo, Na, Ni, P, Pb, Sb, Sc, Sr, Ta, Th, Ti, U, V, W and Zn). Using strict quality control procedures it was found that the data for 19 of these elements were suitable for direct input into a Geographic Information System (GIS) from the diskette provided as a part of the map release. Data for the other elements were less reliable and caution was recommended. This information is typical for regional geochemical mapping in the late 1980s.

Recently, FORTESCUE and VIDA (1990a) demonstrated how *the same* lake sediment cores can be used to make geochemical maps based on pre- and post-anthropogenic samples. For example, one of these map projects involved the determination of Pb, As, Sb, Au, Cu, Mn and Zn in 742 lake sediment cores collected from a 1000 km^2 area northeast of Wawa, Ontario (FORTESCUE and VIDA, 1990b). The post-anthropogenic Pb, As, Sb and Au map patterns show: (1) effects of contamination by non-point source (Pb); (2) point source (As, Sb) atmospheric fallout; and (3) contamination due to gold mine tailings and prospecting activities in the area (Fig. 20a,b,c,d). The pre- and post-anthropogenic geochemical maps patterns for two control elements (Cu and Mn) were very similar in both core segments. These geochemical maps are not accompanied by maps of the geochemical landscapes in which the survey was completed although some preliminary research along these lines has been completed (FORTESCUE and SINGHROY, 1985a).

In summary, throughout the 1980s a few papers on Soviet landscape geochemistry continued to be pub-

Table 4. Clarke Index-I values for crustal abundance (from FORTESCUE, 1985b). Note: The value for Bi appears to be set too low, otherwise all elements which have been tried have been satisfactory

Element	Clarke (ppm)	Element	Clarke (ppm)
Oxygen	45.6%	Gadolinium	6.14
Silicon	27.3%	Dysprosium*	5.00
Aluminum	83,600	Erbium	3.46
Iron	62,200	Ytterbium	3.10
Calcium	46,600	Hafnium	2.80
Magnesium	27,640	Cesium	2.60
Sodium	22,700	Bromine	2.50
Potassium	18,400	Uranium	2.30
Titanium	6,320	Europium	2.14
Phosphorus	1,120	Tin	2.10
Manganese	1,060	Beryllium	2.00
Fluorine	544	Arsenic	1.80
Barium	390	Tantalum	1.70
Strontium	384	Germanium	1.50
Sulphur	340	Holmium	1.26
Carbon	180	Molybdenum	1.20
Zirconium	162	Tungsten	1.20
Vanadium	136	Terbium	1.18
Chlorine	126	Thallium	0.72
Chromium	122	Lutecium*	0.54
Nickel	99.0	Thulium	0.50
Rubidium	78.0	Iodine	0.46
Zinc	76.0	Indium	0.24
Copper	68.0	Antimony	0.20
Cerium	66.4	Cadmium	0.16
Neodymium	39.6	Mercury	0.086
Lanthanum	34.6	Silver	0.080
Yttrium	31.0	Selenium	0.050
Cobalt	29.0	Palladium	0.015
Scandium	25.0	Bismuth	0.0082
Niobium	20.0	Gold	0.0040
Gallium	19.0	Tellurium*	0.0040
Nitrogen	19.0	Ruthenium*	0.0010
Lithium	18.0	Rhenium	0.0007
Lead	13.0	Platinum*	0.0005
Praseodymium	9.10	Rhodium*	0.0002
Boron	9.00	Osmium*	0.00002
Thorium	8.10	Iridium*	0.000002
Samarium	7.02		

Crustal abundance data from RONOV and YAROSHEVSKI (1972) unless otherwise stated.

* Based on crustal abundance data for rocks from BOWEN (1979).

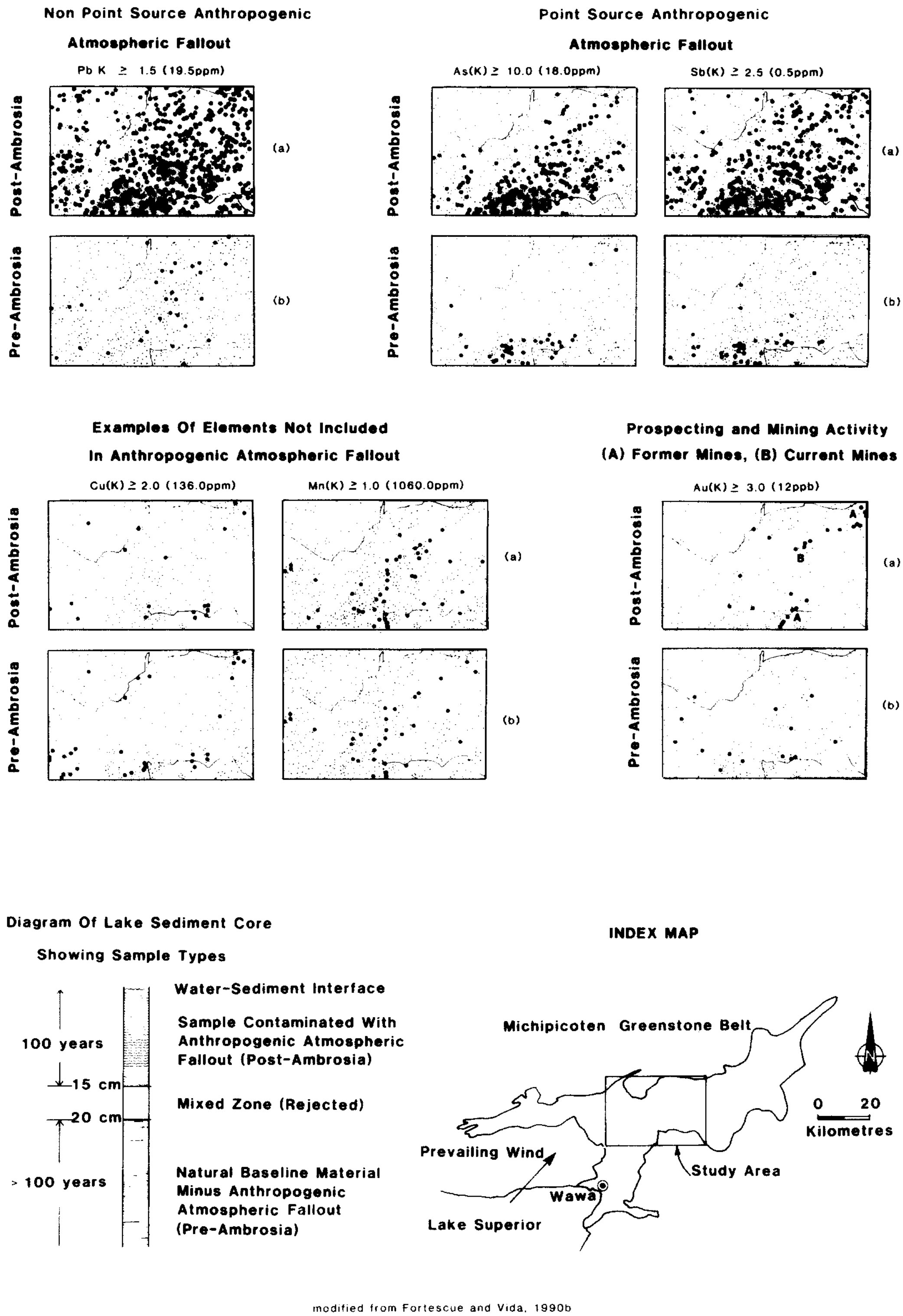


FIG. 20. Selected examples of geochemical contamination in the Michipicoten Greenstone Belt, near Wawa, Ontario (modified after FORTESCUE and VIDA, 1990b).

lished in English in the non-Soviet world. Otherwise, with the exception of the writer's book and his research at the Ontario Geological Survey, relatively little research on traditional landscape geochemistry was reported in the non-Soviet world in the 1980s.

Non-Soviet environmental geochemistry 1980–1990

At the beginning of this review it was noted that no generally accepted, integrated, non-Soviet discipline of environmental geochemistry now exists. However, during the 1980s several attempts were made to describe a discipline of "environmental geochemistry". Two of these will now be briefly reviewed. The first is a collection of papers entitled *Environmental Geochemistry* (FLEET, 1984) published by the Mineralogical Association of Canada. It includes the papers read at a meeting on "environmental geochemistry" held in London, Ontario, in May 1984. The papers include one by FYFE (1984) concerned with the concept of the "major geochemical cycle"; two papers (NESBITT, 1984; SHOTYK, 1984) which reviewed details of the geochemistry of natural waters; a paper by VELBEL (1984) describing details of weathering of rock-forming minerals; and a paper by KRAMER (1984) on the human pertubation of the geochemical cycle. Another paper by NIEBEOR and SANDFORD (1984) described biological functions of metals, and modern methods of chemical analysis were reviewed by MCINTYRE (1984). LUSH (1984) provided an overview of regional geochemical mapping, and GARISTO and LYON (1984) discussed the geological disposal of nuclear waste. Other papers in the volume described soil organic matter (SCHNITZER, 1984) and groundwater contamination (CHERRY, 1984).

These papers are all informative and some are very well researched and written. The problem is, when they are taken together, they reveal both the lack of a central focus and a lack of a common geochemical terminology to describe "environmental geochemistry". As might be expected, reference to traditional landscape geochemistry is missing from this collection of papers. The writer of this review finds it difficult to agree with FLEET (1984, p. iii) when he refers to the publication just reviewed as a "comprehensive and up-to-date instructional text on environmental geochemistry".

The scope of the second collection of papers on environmental geochemistry, *Applied Environmental Geochemistry* edited by THORNTON (1983a), is similar to that just described. Professor J. S. Webb in a foreword to Thornton's book (WEBB, 1983, p. viii), suggests that the book:

> . . . is unique in that it is the first to bring together major contributions in nearly all the component parts of environmental geochemistry and pollution, which contribute to the knowledge of the quality of the environment in which we live.

As in the previous case, the Thornton volume includes a series of papers each describing a different topic in theoretical, or applied, environmental geochemistry. For example, papers by PLANT and RAISWELL (1983) on the *Principles of Environmental Geochemistry*, and HOWARTH and THORNTON (1983) on *Regional Geochemical Mapping and its Application to Environmental Studies* show promise of a systematic coverage of the entire subject. Unfortunately, the papers which follow these two do not fulfil this promise. The book is somewhat confusing because many of the papers overlap. There are also some omissions in the later papers. For example, there is no mention of the "acid rain" problem and the reviews do not provide information on the importance of the exploration geochemistry experience in relation to environmental geochemistry.

In summary, both these collections of papers on "environmental geochemistry" failed to convince readers that environmental geochemistry was a scientific discipline. This is not because individual papers are badly researched. It is because they lack a unifying conceptual framework such as that supplied to pre-1950s geochemistry by its four pioneer thinkers, and by Polynov, Perel'man, Glazovskaya and their co-workers to landscape geochemistry prior to 1970.

Non-Soviet exploration geochemistry 1980–1990

Readers unfamiliar with the scope of exploration geochemistry in the 1980s may obtain this information from bibliographies by HAWKES (1985, 1988) and papers in volumes 13–36 of the *Journal of Exploration Geochemistry*. A useful series of review articles on the scope of exploration geochemistry between 1977 and 1987 are included in GARLAND (1989). Geochemical exploration in China developed very rapidly during the 1980s. Some idea of the scope of this development can be obtained from the collection of papers presented at the Third Chinese Exploration Geochemistry Symposium held in Guilin, Guangsu, 10–15 September 1986 (XUEJING and JENNESS, 1989). A collection of papers on exploration geochemistry applied in the search for hydrocarbons is to be found in JONES (1984).

Very few direct references to landscape geochemistry were found in the literature of exploration geochemistry published during the decade. An exception was in GOVETT (1987), who, in a review of *Geochemical Exploration in Some Low Latitude Areas*, referred to landscape geochemistry and stressed the importance of the landscape conceptual models included in BUTT and SMITH (1980). BUTT (1987) also referred to landscape geochemistry. He (BUTT, 1987, p. 15) summed up his experience with landscape conceptual models applied to geochemical exploration in tropical terrains as follows:

> Despite a general increase in the general understanding of geochemical dispersion in these terrains, as expressed in the model systems, the best and most appropriate sampling, analytical and interpretational procedures have to be determined for each region.

Unfortunately, he did not mention the importance of landscape maps in this decision-making process.

For readers unfamiliar with non-Soviet exploration geochemistry during the 1980s, reviews of selected papers presented at two meetings during the decade will now be reviewed. The meetings selected are: the 12th International Geochemical Exploration Symposium and the 4th Symposium on Methods in Geochemical Prospecting held in Orleans, France, 23–26 April 1987 (JENNESS, 1989) and Prospecting the areas of Glaciated Terrain—1988 a meeting held in Halifax, Nova Scotia 28 August–3 September 1988 (MACDONALD and MILLS, 1988).

The proceedings of the Orleans meeting include 55 papers arranged into the following sections:

Section	Number of papers
Gold, including lateritic environments	8
Exploration in tropical terrains	8
Biogeochemistry	3
Exploration using transported overburden	8
Analytical methods/Isotopes	4
Data processing interpretation	6
Rock geochemistry	10
French papers	6
Workshop reports	2

The paper most pertinent to landscape geochemistry in this series is that by BUTT and ZEEGERS (1989). These writers discussed the classification of general conceptual models for geochemical exploration in weathered tropical terrain. They also described why landscape models are particularly useful for geochemical exploration in these terrains. They then point out that it is now feasible to establish a set of generalized models for exploration in *all* terrains between 35°N and 35°S. These models would be based on common features of weathering and erosional histories of landscapes. BUTT and ZEEGERS (1989) end their paper with a plea for more "well documented" exploration case histories from tropical terrain which can be used for the synthesis of these comprehensive landscape models. This thoughtful paper reminds one of the classic papers by MILNE (1935, 1936), except that the former are concerned with exploration geochemistry and the latter with soil science. All these writers required systematic study of the geochemical history of the landscapes they described.

Two other papers presented at the Orleans meeting are pertinent to landscape geochemistry. Both described geochemical mapping based on "low density" sampling. The paper by KOLJONEN *et al.* (1989) considered a geochemical map of Finland based on 1057 composite till samples. Each sample represents an area of 300 km^2. The resulting geochemical dot map for Ba (Fig. 21b) is particularly interesting because it outlines clearly the Raahe–Ladoga main ore belt and the Cu-Ni sulphide province in southwest Finland (see Fig. 21a). These writers noted that results from partial extraction methods (i.e. aqua regia) on the till composites provided better element map patterns when compared with data from total extraction methods. The implications of these Finnish element patterns in landscape geochemistry have yet to be worked out.

The paper by OTTESEN *et al.* (1989) also described "low density" geochemical mapping. The Norwegian work is based on "overbank" sediment sampling (Fig. 22) and compliments the information on low density till sampling by KOLJONEN *et al.* (1989) just described. The geochemical map of Norway was

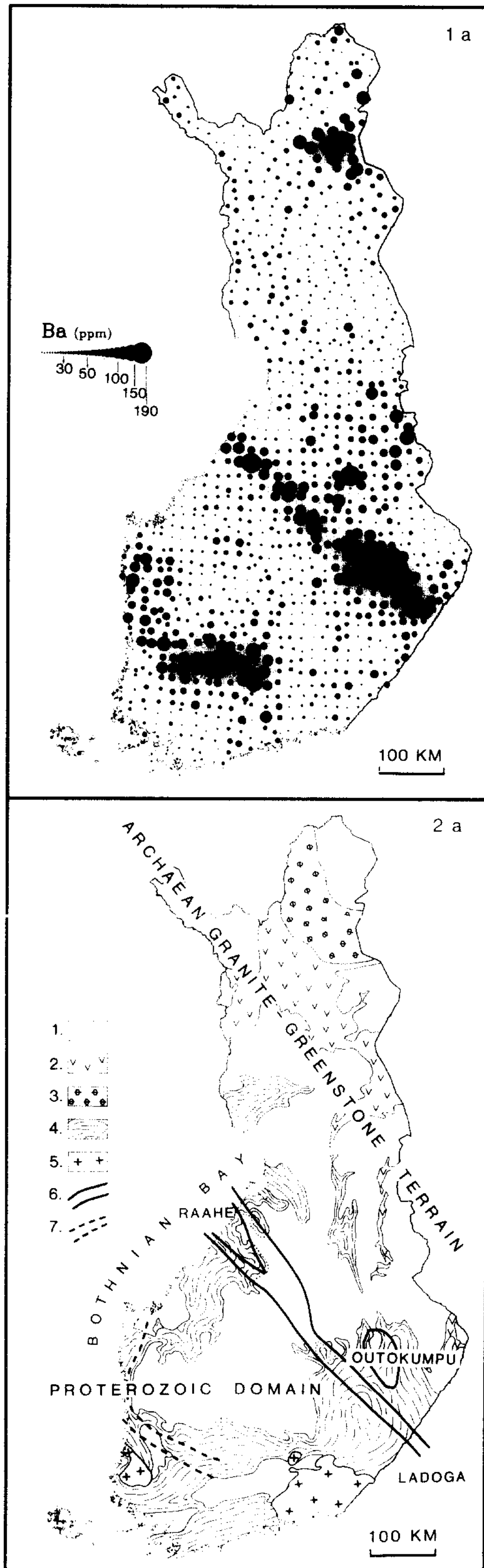


FIG. 21. An example of "low density geochemical mapping". Lower diagram—a generalized geological map of Finland; Upper diagram—geochemical map of Finland based on low density till sampling showing the geochemical patterns for Ba (from KOLJONEN *et al.*, 1989).

based on 690 overbank samples, each representing a drainage area of 60–300 km^2 (Fig. 22B). As an example, regional Mo patterns described by this mapping procedure are also included in Fig. 22. The Mo data were obtained using a hot HNO_3 extraction. On the geochemical map (Fig. 22C) a "geochemical province" pattern for Mo is clearly delineated in southern Norway. The same pattern occurs on a geological map showing Mo occurrences (Fig. 22B). This is another example of large-scale geochemical patterns being delineated by low-density geochemical sampling. As in the previous example, the relation between these Norwegian geochemical patterns and the geochemical landscapes in which they occur has yet to be explored.

In summary, with the exception of the paper by BUTT and ZEEGERS (1989), papers presented at the Orleans meeting did not refer directly to landscape geochemistry. The two papers from Finland and Norway describing different kinds of "low density geochemical mapping" are of considerable interest to exploration geochemists and are of potential interest in landscape geochemistry.

A total of 33 papers were read at the Halifax Meeting, which was arranged in seven sessions as follows:

Session	number of papers
Tills and till prospecting	8
Stream sediments	3
Lake sediments	4
Case histories: gold	5
Case histories: tungsten plus	5
Biogeochemistry/Remote sensing	3
Data interpretation	5

From the viewpoint of landscape geochemistry, the most interesting paper at this meeting was probably that by SHILTS and SMITH (1988). These writers identified seven distinct stages in the evolution of the landscapes they studied, during prospecting for buried gold placer deposits in southeastern Quebec. SHILTS and SMITH (1988) used data from rotasonic drilling to construct landscape sections for each of the seven evolutionary stages they described. The landscape stratigraphy sequence started with a "deep Tertiary weathering" stage and ended with a "modern Post-glacial deposition" stage. The original paper should be consulted for further details of this interesting study.

In another paper read at the Halifax meeting, OGDEN *et al.* (1988), described the biological and geochemical stratigraphy of a "long" lake sediment core from Chocolate Lake, near Halifax. The importance of "long" lake sediment core studies in landscape geochemistry is that they provide detailed information on the ecological and geochemical history of the lake and its catchment area. The Chocolate Lake core was related to well-documented evidence for known ecological and geochemical changes in the Chocolate Lake area since 1750. OGDEN *et al.* (1988) concluded their paper by stressing the importance of lake sediment cores as "historical records" of ecological and geochemical change.

In a third paper read at the Halifax meeting, a GIS approach for the integration of regional geochemical map data with data from the distribution of gold occurrences and the geology of Nova Scotia was described by WRIGHT *et al.* (1988). This paper is important because it is one of the first describing a geoscience GIS developed by a government agency in Canada.

In summary, the reviews of papers at the two meetings indicate the "state-of-the-art" in non-Soviet exploration geochemistry in the mid-1980s. In both meetings the science was of a high standard but usually limited in scope by the absence of a formal landscape geographic component. Exceptions were found in a few special investigations, such as SHILTS and SMITH (1988) and OGDEN *et al.* (1988), where information was presented in a context of the historical evolution of the landscapes described.

Non-Soviet regional geochemical mapping 1980–1990

During the 1980s geochemists outside the U.S.S.R. generally paid little attention to the geographic mapping of landscapes and considerable attention to regional geochemical mapping. For this reason this section of this review is almost entirely concerned with regional geochemical mapping.

Regional geochemical mapping during the late 1970s and early 1980s was summarized by HOWARTH and THORNTON (1983). Further developments in stream sediment geochemical mapping were reviewed by PLANT *et al.* (1989). Recent developments in lake sediment geochemistry were reviewed by HORNBROOK (1989) and the use of geochemical domains in regional geochemistry was described by BEAUMIER (1989).

By the end of the 1970s it was realized by geochemists that the data obtained from traditional "reconnaissance" geochemical mapping was of limited value for modern mineral resource appraisal and environmental geochemistry. Scientists involved in geochemical mapping reacted in three ways to this state of affairs. First, the Geological Survey of Canada continued traditional reconaissance geochemical mapping at a density of one sample/13 km^2 with sample intensity being doubled in areas of high mineral potential across Canada (HORNBROOK, 1989). Second, the British Geological Survey, as a result of research by Dr Jane Plant and her co-workers in the 1970s (PLANT, 1971; PLANT and MOORE, 1979) commenced geochemical mapping of Scotland, Wales and England using stream sediments collected at an average sample density of one sample/km^2 (PLANT *et al.*, 1984). Third, the Scandinavian countries experimented with "multi-media" and "low density" sampling over large areas (BOLVIKEN, 1986; OTTESEN *et* *al.*, 1989; KOLJONEN *et al.*, 1989; BOLVIKEN *et al.*, 1990). The net result of all this activity was that it was found that similar "geochemical anomaly" and "geochemical province" patterns could be discovered by geochemical mapping at any sample density. This led B. Bolviken of the Norwegian Geological Survey to suggest that "geochemical anomaly" and "geochemical province" patterns are fractal in nature (B. BOLVIKEN, Oral Commun., 1990).

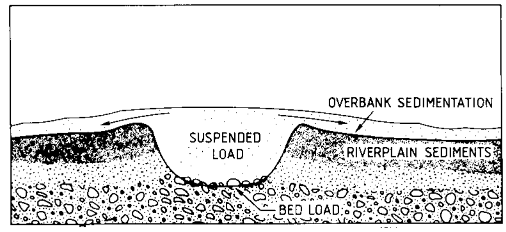
Another approach to regional geochemical mapping is the "multi-media" survey which involves the collection of several kinds of material from each site in a geochemical survey. Perhaps the best example here is the Nordkallot Project (BOLVIKEN, 1986) which produced geochemical maps for an area including parts of Norway, Sweden and Finland.

The Nordkallot geochemical survey was based on samples of various materials collected from 7,276 sites in a 250,000 km^2 area. In this survey one catchment area of ~10 km^2 was sampled per 30 km^2 of the entire area sampled. Where possible, samples of till, stream sediment, stream organic matter and stream moss were collected from each sample site. The till samples were divided into "light" and "heavy" mineral fractions, which were analysed separately. The elements determined in each material are listed on Table 5. The geochemical data generated during the Nordkallot Project were published in a series of 134 geochemical maps. The maps were designed for use in a variety of purposes, including mineral exploration, documenting pollution, forestry and agriculture, and epidemiology and geomedicine. BOLVIKEN (1986, p. 7) described the results of the survey as follows:

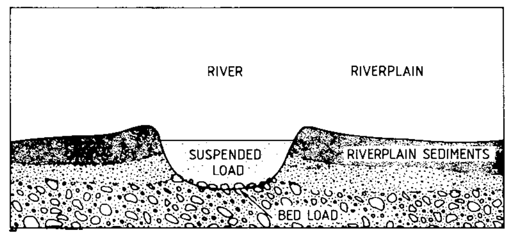
> Most of the geochemical maps show broad distribution patterns including regions and provinces with characteristic element concentrations. These large scale element patterns are most evident on the maps of the element contents in the heavy mineral fractions (of tills) and on principal component maps. Based on the contents in the heavy mineral fraction of till, 18 geochemical provinces were defined. . . . Enrichment factors were calculated for each of 22 elements defined as the ratio between (1) the average content in the heavy mineral content of the till within each province and (2) the average for the whole survey region. The enrichment factors vary between 0.1 and 3.0.

An unexpected finding during the Nordkallot Project was the presence of regional linear geochemical features which often crossed borders between lithological units and other geochemical patterns. Some of these patterns coincided with lineaments on LANDSAT images (BOLVIKEN *et al.*, 1990).

By the time the Nordkallot mapping was completed, it was clear that the major geochemical province patterns in the survey area could have been detected by sampling at a much lowser density. This led to the development of the low-density sampling geochemical mapping methods described previously. Another finding was that, in general, the geochemical patterns in different sample media were similar



A(i)



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C

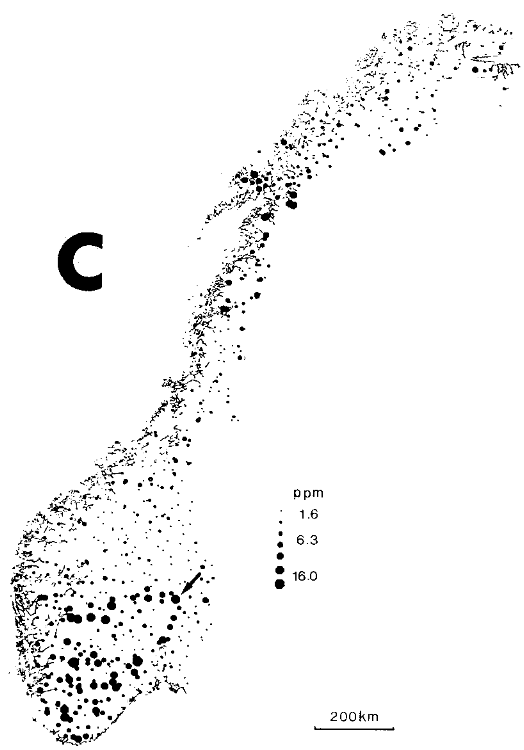
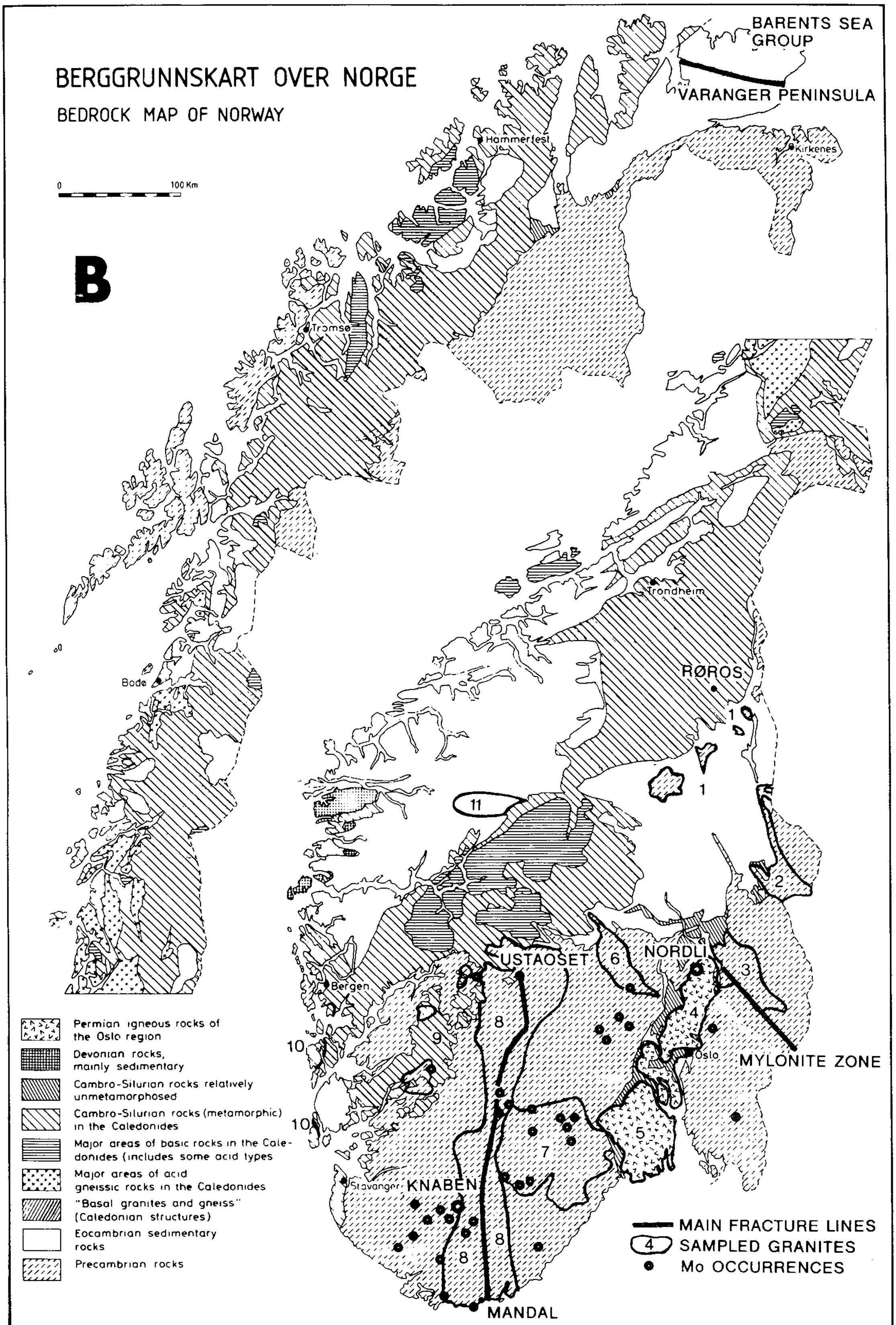


FIG. 22. Molybdenum geochemical map of Norway based on low density, overbank sampling. A. cartoons showing (i) the process of overbank deposition during a "catastrophic flood" and (ii) deposition of stream sediments during "normal stream flow"; B. geological map of Norway showing Mo occurrences (on facing page); and C. a geochemical map of Norway showing distribution of Mo based on only 640 samples (from OTTESEN *et al.*, 1989).


BERGGRUNNSKART OVER NORGE
BEDROCK MAP OF NORWAY
0 100 Km
B
BARENTS SEA GROUP
VARANGER PENINSULA
Hammerfest
Kirkenes
Tromsø
Trondheim
RØROS
Bodø
Bergen
USTAOSET
NORDLI
Oslo
MYLONITE ZONE
Stavanger
KNABEN
MANDAL
1
2
3
4
5
6
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10
11
Permian igneous rocks of the Oslo region
Devonian rocks, mainly sedimentary
Cambro-Silurian rocks relatively unmetamorphosed
Cambro-Silurian rocks (metamorphic) in the Caledonides
Major areas of basic rocks in the Caledonides (includes some acid types
Major areas of acid gneissic rocks in the Caledonides
"Basal granites and gneiss" (Caledonian structures)
Eocambrian sedimentary rocks
Precambrian rocks
MAIN FRACTURE LINES
SAMPLED GRANITES
Mo OCCURRENCES

FIG. 22B

both with respect to element levels and their spatial distributions. The data from the Nordkallot Project also showed (BOLVIKEN, 1986, p. 18) that, although there were five glaciations in the area surveyed:

> the glacial displacement of geochemical patterns in the fine fractions of till and consequently in stream sediments and organic samples seemed to be negligible in relation to the scale of the geochemical maps.

In summary, the Nordkallot Project advanced the methodology of geochemical mapping in several respects. The full implications of these developments have yet to be considered worldwide. A start in this direction has been made by the IGCP Project 259 on International Mapping (DARNLEY, 1988, 1990a,b).

By 1984 Dr Plant's group at the British Geological Survey had completed research on another important aspect of regional geochemical mapping. This is image processing of regional geochemical data for mineral resource appraisal purposes (PLANT *et al.*, 1984). Since then, this group has demonstrated the importance of the GIS approach to the interpretation of regional geoscience data, particularly in areas of complex geology and high mineral potential (PLANT *et al.*, 1988; FORREST and HARDING, 1988; PLANT *et al.*, 1989, 1990a,b). This research has revolutionized methods worldwide for the interpretation of geoscience data collected by government agencies for mineral resource appraisal. Also, as a result of the introduction of GIS, the importance of regional geochemical mapping has increased substantially. This development has underlined the need for the highest quality methods for collecting and processing geochemical map data everywhere.

In summary, by the end of the 1970s the "reconnaissance" geochemical mapping methodology developed during the U program in North America (CARPENTER, 1980) was considered inadequate for mineral resource appraisal purposes. By the end of the 1980s this had led to worldwide emphasis on three kinds of geochemical mapping. One was based on a sample density of one sample per square kilometer (i.e. the regional level of geochemical mapping); another was the adoption of a sample density of one sample every 300–500 km^2 (i.e. the "low density" level of geochemical mapping) and a third was progress toward "global geochemical mapping" as described for Europe by BOLVIKEN *et al.* (1990) and DEMIETRIADES *et al.* (1990). All this geochemical mapping activity was not usually accompanied by parallel geographic mapping activity involving the delineation of landscape types. It seems clear that, as GIS becomes more popular, geochemical map data must be accompanied by appropriate geographic map data as a matter of course.

Non-Soviet health and nutrition geochemistry 1980–1990

Non-Soviet geochemistry and health research developed rapidly during the 1980s to become an important component of environmental geochemistry worldwide. This activity was usually separate from exploration geochemistry, although it was often related to regional geochemical mapping (see BOLVIKEN, 1986).

The series of annual meetings on *Trace Substances in Environmental Health* (HEMPHILL, 1966–1980) described previously, continued into the 1980s. A "Society of Environmental Geochemistry and Health", which was founded at the Missouri meetings in the 1970s, gained stature worldwide in the decade. By 1990, this society regularly published proceedings of meetings both in North America and in Europe (DAVIES, 1989). Since 1985, the society has published a quarterly journal *Environmental Geochemistry and Health* which often includes papers of general interest in landscape geochemistry.

Near the beginning of the decade, THORNTON (1983b) published a useful review of the development of geochemistry in health and nutrition in relation to agriculture. COUNSE *et al.* (1983) and LAG (1983) reported progress in geomedicine at the same time. There is generally little reference to landscapes in these papers although Thornton's paper included excellent case histories of trace element problems due to Cu, Co, Mo and Se in plants and livestock discovered during geochemical mapping in the British Isles.

More recently, the Royal Society of London has sponsored the *First and Second Symposia on Geochemistry and Health* which included contributions from Norway, China, the U.K., the U.S.A., Yugoslavia, the U.S.S.R., Canada and India. Other collections of papers of interest in this aspect of environmental geochemistry are included in DAVIES (1987).

Since 1980 there have been numerous detailed studies of relations between geochemistry and health which are pertinent to the general concept of landscape. A good example is the study by FLATEN (1986), in which he investigated systematically the chemical composition of Norwegian drinking water and its relations with human epidemiology. His study involved the determination of 30 constituents in four samples of drinking water from each of 384 water sources which supply water to 70.9% of the population. Norway is a particularly good country for this type of study because the population is usually not mobile and genetically homogeneous. Another advantage is that Norwegian disease records are relatively good compared with those of other countries. FLATEN (1986) reached two conclusions from his study. One is that the research lends some support to the hypothesis that acidification of the environment may be associated with increased mobility of Al. This, in turn, is associated with an increased frequency of Alzheimer's disease. The other conclusion was that incidence of cancer of the rectum was 20–30% higher in males and females in 57 municipalities chlorinating their drinking water com-

Table 5. Elements determined in different types of geochemical sample media collected during the Nordkallot Project (from BOLVIKEN, 1986)

Sample type	Fraction (mm)		Elements
Till	−0.062		Co Cr Cu K Mg Mn Ni Pb Ti V Zn
	−0.062		As Au Ba Br Cs Fe La Na Rb Sb Sc Sm Ta Th U W
	0.062–0.50	HM	Al Ba Ca Cl Co Cr Cu Fe K Mg Mn Mo Na Nb Ni P Rb Si Sr Th Ti V Y Zn Zr
Stream sediments	−0.18		Ag Al Ba Ca Ce Co Cr Cu Fe K La Li Mg Mn Mo Ni P Sc Sr V Zn Zr
	0.18–0.60	HM	Al Ba Ca Cl Cr Cu Fe K Mg Mn Na Nb Ni P Si Sn Sr Ti V W Y Zn Zr
Stream organic material	−0.1	Ash	Al Ba Ca Cl Co Cr Cu Fe K Mg Mn Mo Na Ni P Rb S Si Sr Th Ti U V Y Zn
Stream moss	−0.1	Ash	As Au Ba Br Co Fe La Lu Mo Sb Sc Sm Th U

pared with 21 municipalities where no chlorinating occurred.

This type of study is of considerable importance for future generations, although the detection of low, but possibly significant, levels of some elements in waters on the scale required was not generally practical in the mid-1980s. For example, FLATEN (1986) notes that Ti, Pb, Ni, Co, V, Mo, Cd, Be and Li were looked for in his water samples but hardly ever found.

More recently an interesting paper by FUDGE (1988) described the amount and distribution of the halogens in the environment. He quoted PEREL'MAN (1977) for the suggestion that Br may play a role in animal and human nutrition.

In summary, the study of relations between geochemistry, nutrition and health grew rapidly in importance worldwide during the 1980s. Consequently, the account given here is only a small sample of the available literature on the subject. These studies are important because they underline the general lack of geographic (i.e. landscape) data collected by geochemists during studies of this type.

Non-Soviet landscape study and soil science 1980–1990

In the concluding chapter of his book on *Soils and Landforms* GERRARD (1981, p. 188) predicted:

> A present challenge for geography, geomorphology and pedology lies in the reawakening of interest in the workings of the environment and the exploration of man environment relations.

A good modern response to this challenge is found in the book *Soil Landscape Analysis* by HOLE and CAMPBELL (1985). These writers reviewed in detail the relation between soils and landscape from the viewpoints of soil science and geography. HOLE and CAMPBELL (1985, p. 42) described methods of soil/landscape analysis and include the following:

> The material presented in this chapter may be looked upon as a kind of primer on the subject and as a prelude to exhaustive studies that will be made in the future with the help of computers.

In chapter 6 of their book they distinguished between "traditional" and "other" soil geographies, and list properties of each one (Table 6). Although they do not refer directly to landscape geochemistry, HOLE and CAMPBELL (1985) frequently quoted the work of the Russian geographer V. M. Fridland (1919–1983), and his book *Pattern of Soil Cover* is recommended as an essential reference for all soil geographers.

The work of HOLE and CAMPBELL (1985) is important in landscape geochemistry because it provides a succinct introduction to contempory thinking by non-Soviet soil scientists regarding soils and landscape study. Further information on this topic may be obtained from the collection of papers edited by RICHARDS *et al.* (1985).

Detailed studies of the relation between landscape

Table 6. Components of two soil geographies (based on HOLE and CAMPBELL, 1985)

Some components of traditional soil geography

Global placement of major soil taxa
Soil genesis
Interactions between soil and environment
Interactions between soil and mankind
Soil survey and mapping
Paleosols
Soils–geomorphic relations

Some components of the other soil geography

Definition of the fundamental area units of soils
Areal properties of individual soil bodies
Geographic properties of individual soil species
Genetic links between neighboring soils
Cartographic representation of soil patterns
Generalizations of soil boundaries
Origins of soil patterns
Place-to-place variations within landscapes and soil units

position and soil chemistry were rare in the soil literature of the early 1980s. An exception is an account of landscape position and particle size effects on soil P distributions on a hillslope in northwest Florida by DAY *et al.* (1987).

A more comprehensive treatment of the details of the relation between soils, landscape and geochemistry is included in CALDAS and YAALON (1985). This collection of papers is derived from a symposium on Volcanic Soils: Weathering and Landscape Relationships of Soils on Tephra and Basalt.

Recently, FANNING and FANNING (1989) have provided a modern review of Jenny's five factors of soil formation which includes reference to the importance of soil catenas. These writers make no reference to Perel'man's landscape geochemistry although, predictably, both Davis and Penck are mentioned. The recent book by ROSS (1989) entitled *Soil Processes: a Systematic Approach* provides a comprehensive introduction to the inorganic and organic chemistry of soil.

In summary, during the 1980s, non-Soviet soil scientists showed a renewed interest in the landscape concept and the problems associated with geochemistry of soils in landscapes.

Non-Soviet ecology and landscape study 1980–1990

Since the 1960s, traditional ecology has included "biogeochemical cycling" as one of its basic concepts. From the viewpoint of landscape geochemistry, many of these ecological studies have taken place in ecosystems located in eluvial (i.e. terrestial), superaqual (i.e. organic terrain) and aquatic (i.e. lakes and rivers) landscapes. A few studies have adopted a more holistic approach and included the simultaneous study of ecosystems and landscapes of several types within an area of country. For example in *An Ecosystem Approach to Aquatic Ecology* LIKENS (1985) extended the Hubbard Brook study to include nearby Mirror Lake and its catchment area, and KIMMINS (1987) provided a useful perspective to modern studies of biogeochemical cycling in forest ecosystems.

The geochemistry of ecosystems in organic terrains was reviewed by CLYMO (1987) and SHOTYK (1988) and detailed geochemical information on lakes is reviewed by HAWORTH and LUND (1984) and many other publications.

The literature of ecology includes detailed examples of the methodology of modern ecological investigations. For example BROCK (1985) described a detailed limnologial investigation and HARRISON *et al.* (1990) described the methodology for the study of nutrient cycling in terrestial ecosystems. Many of these methods and approaches are pertinent to the landscape geochemistry of the future.

A good overview of the scope of modern ecological theory is provided by a series of papers in *Perspectives in Ecological Theory* (ROUGHGARDEN *et al.*, 1989). For example, one of the papers in this series reviews modern ecological ideas concerning hierarchy and scale (O'NEILL, 1989) which is of particular interest in landscape geochemistry. Other modern thinking on hierarchies is found in the book *Hierarchy: Perspectives for Ecological Complexity* by ALLEN and STARR (1988).

In general, since 1985, there has been a revival of non-Soviet ecological interest in the study of "landscapes", which are now seen as the link between "community ecology" and "regional ecology". For example, this trend was apparent in many of the papers read at the meeting of the Ecological Society of America in Toronto, June 1989 and reported in the supplement to volume 70, No. 2 of the *Bulletin of the Ecological Society of America*.

Other aspects of modern ecology closely related to landscape geochemistry are discussed in the proceedings of the Cary Conferences (LIKENS *et al.*, 1987; LIKENS, 1989). These conferences are designed as forums "to consider the status and future of ecosystem science" and might provide a forum for the discussion of the future of landscape geochemistry. Still another trend in modern ecology is toward "global ecology" as discussed in the collection of papers edited by RAMBLER *et al.* (1989). Global ecology is also pertinent to landscape geochemistry. Traditional landscape geochemistry is not mentioned in either LIKENS (1989) or in RAMBLER *et al.* (1989).

Non-Soviet landscape ecology 1980–1990

Since 1980, landscape ecology has become an important sub-discipline at the interface of ecology and geography and may in the future supply much descriptive information for landscape geochemistry and urban geochemistry.

NAVEH and LIEBERMAN (1984) described the early evolution of landscape ecology and stressed its close links with geography. In reviewing the sciences close to landscape ecology these writers mentioned landscape geochemistry briefly but did not elaborate. This book has recently been enlarged and reprinted as *Landscape Ecology: Theory and Application* (NAVEH and LIBERMAN, 1990).

Probably the best known book in North America on landscape ecology is by FORMAN and GODRON (1986). More advanced information on landscape ecology is also available. For example, the collection of papers edited by TURNER (1987) provides detailed information on several important aspects of the subject. The new discipline is also served by a journal called *Landscape Ecology* (SPB Academic Publishing, The Hague, Vol. 1: 1987). Landscape geochemistry and landscape ecology have much in common and a symbiotic relation between the two disciplines is likely to develop in the near future. FORMAN and GODRON (1986, p. 11) stress the importance of the following three aspects of the "landscape" concept which are common to both disciplines as follows:

1. LANDSCAPE STRUCTURE, the spatial relationships among the distinctive ecosystems or "elements" present-more specifically, the distribution of energy, materials and species in relation to the sizes, shapes numbers and kinds and configurations of ecosystems.
2. LANDSCAPE FUNCTION, the interactions among the spatial elements, that is, the flows of energy, materials, and species among the component ecosystems, and,
3. LANDSCAPE CHANGE, the alteration in the structure and function of the ecological mosaic over time.

It is evident from the above that landscape change is of considerable importance in landscape ecology. This aspect of the subject has been explored in a collection of 14 papers entitled *Changing Landscapes and Ecological Perspective* (ZONNEVELD and FORMAN, 1990) which contains information of particular interest in landscape geochemistry.

Landscape ecology studies utilize the traditional methodologies of ecology (e.g. as described by HARRISON *et al.*, 1990) and geography (e.g. as described by GOUDIE, 1990) plus more recent methodologies including remote sensing, image processing and GIS (TURNER, 1987). The application of statistics to landscape ecology was outlined clearly by JONGMAN *et al.* (1987). Readers interested in landscape ecology should refer to the books and the periodical mentioned above for further information on this interesting subject.

Summary of the development of landscape geochemistry 1980–1990

Part III described progress in Soviet and non-Soviet landscape geochemistry and related subjects during the decade of the 1980s. The 1980s have seen a major increase in "environmental geochemistry" worldwide, particularly in relation to man's effects on the environment. This has been accompanied by rapid advances in methodologies for landscape description and landscape geochemistry. This progress is now summarized under 12 headings.

1. The mapping of landscapes and geochemical patterns in the non-Soviet world during the 1980s increased sharply in effectiveness as a result of three technological breakthroughs. These were: (1) the introduction of modern methodologies of multi-element chemical analysis; (2) the introduction of the personal computer which led to the wide application of mathematical models to the study of landscape and the geochemistry of landscapes; and (3) the introduction of image processing and GIS technology, again assisted by the widespread use of personal computers.

2. Traditional Soviet landscape geochemistry continued to grow in importance during the 1980s. The few accounts of this growth which are available in English suggest that Soviet geochemists are well aware of the problems of modern environmental geochemistry, particularly with respect to the study of man's effect on landscapes both in retrospect and in prospect.

3. Attempts to introduce the Soviet paradigm of "landscape geochemistry" into the non-Soviet world failed during the 1980s. Progress in traditional landscape geochemistry research was at a low point in the non-Soviet world during the decade.

4. Non-Soviet attempts to provide environmental scientists with accounts of "environmental geochemistry" during the 1980s failed. This resulted from the lack of a generally accepted paradigm for environmental geochemistry among non-Soviet geochemists.

5. Non-Soviet exploration geochemistry flourished during the 1980s. This was largely without reference to traditional landscape geochemistry. An exception was the application of "landscape conceptual models" for the synthesis of data from geochemical exploration—particularly in tropical landscapes.

6. Much progress in the development of modern geochemical mapping was made in the non-Soviet world during the decade under review. This was usually to: (1) update the effectiveness of traditional "reconnaissance" geochemical mapping methods (as used in the 1970s); and/or (2) to provide geochemical map data for use in GIS studies of comparable scientific tenor to regional data gathered by other geosciences for mineral resource appraisal purposes.

7. The "mapping of geochemical landscapes" was generally not included in regional geochemical surveys completed during the decade in the non-Soviet world. However, the growing importance of "geochemical province" patterns on geochemical maps was universally recognized. Geochemical provinces were shown to be of importance in mineral resource appraisal, environmental geochemistry, and geomedicine, health and nutrition geochemistry.

8. In the non-Soviet world, interest in geomedicine and health/nutrition geochemistry expanded rapidly during the 1980s. This was usually without reference to traditional Soviet landscape geochemistry.

9. During the 1980s non-Soviet soil scientists and geochemists showed a renewed interest in the quantification of the description and geochemistry of landscapes.

10. The very rapid increase of interest in remote sensing and GIS during the later 1980s led to the development of new and effective ways of mapping landscapes. Some of these are pertinent to landscape geochemistry.

11. Many aspects of ecology underwent rapid development during the 1980s. Some of these developments are of considerable potential importance to students of landscape geochemistry.

12. By 1990, landscape ecology, which was little

known in 1980, had become a popular and important branch of ecological research.

PART IV. LANDSCAPE GEOCHEMISTRY: RETROSPECT AND PROSPECT

Introduction

Details of the evolution of landscape geochemistry during the past 90 a have been described in the conclusions drawn to the first three parts of this review. Part IV includes a summary of the overall development of landscape geochemistry and the writer's views on the future development of the subject in a "green" world.

Retrospect: Paradigms of landscape and geochemistry 1900–1990

KUHN (1970), in his classic book *The Structure of Scientific Revolutions*, described how progress in science usually does not occur as a smooth curve. Kuhn maintained that science moves ahead in a series of "jumps", or "paradigms", each associated with one (or a small number of) creative and innovative scientists. After being defined, a paradigm forms a base for a relatively large number of practitioners who promote the use of the paradigm. The practitioners in turn usually firmly resist change when a later paradigm appears.

Soil science and landscape evolution. The evolution of landscape geochemistry provides several good examples of the birth and evolution of paradigms. For example, in the U.S.S.R., V. V. Dokuchaev's paradigm for "soil science" has lasted from 1890 onward. In the non-Soviet world, the W. H. Davis paradigm for "landscape evolution by physical processes" also commenced before the turn of the century and guided geographers and geomorphologists thinking regarding the evolution of landscapes for 75 a.

Over time, Dokuchaev's paradigm matured into "landscape science" as exemplified by the writings of L. S. Berg. Similarly, in Europe and North America, the W. H. Davis paradigm incorporated the ideas of W. Penck and others. A knowledge of this background is important to an understanding of the birth and evolution of landscape geochemistry.

Modern geochemistry. Similarly, a paradigm of "general geochemistry" (initiated by F. W. Clarke between 1880 and 1900), was growing vigorously by 1920. The geochemistry paradigm was strongly supported and expanded by the seminal ideas of V. I. Vernadski, A. E. Fersman, V. M. Goldschmidt and many others.

Soviet landscape geochemistry. During the 1920s a combination of: (1) first hand experience gained with the Dokuchavev paradigm of soil science and landscape description; (2) geochemistry's new concepts and ideas; and (3) his original ideas on the *geochemical* evolution of landscapes, led B. B. Polynov to describe a new paradigm of "landscape geochemistry".

By 1950, Polynov had followers with original ideas who added to the "landscape geochemistry" paradigm. These included A. I. Perel'man, M. A. Glazovskaya, V. V. Kovda and others. This group caused the paradigm of landscape geochemistry to grow rapidly in importance in the U.S.S.R. after Polynov's death in 1952.

From the start, Soviet landscape geochemistry formed a conceptual bridge linking geography, geochemistry, ecology and environmental geochemistry. Consequently, from the mid-1950s onward, students graduating from Moscow University specializing in landscape geochemistry could choose to practice their science in relation to mineral exploration, biogeochemistry, environmental geochemistry, medical geochemistry, or some other applied aspect of landscape geochemistry. In retrospect, it is not surprising that landscape geochemistry became popular in the U.S.S.R. in the 1950s and 1960s.

Landscape ecology. It is surprising that a paradigm of "landscape" was not described by non-Soviet scientists until the late 1980s. Then, ecologists and geographers, not geochemists, developed "landscape ecology" (NAVEH and LIEBERMAN, 1990; FORMAN and GODRON, 1986; TURNER, 1987; ZONNEVELD and FORMAN, 1990). In 1990 the non-Soviet world was in the strange position of having a vigorous new paradigm of "landscape ecology" which appeared almost totally ignorant of "landscape geochemistry".

Exploration geochemistry. At the time the Perel'man and Glazovskaya school in Moscow was training the first landscape geochemists, Professor J. S. Webb's school of "exploration geochemistry" at the Royal School of Mines in London was training the first professional "exploration geochemists". Many of these practitioners of the paradigm of "exploration geochemistry", are still leaders in their chosen field. The great practical success of the "exploration geochemistry" paradigm, which was formalized in 1962 by HAWKES and WEBB (1962) in their book *Geochemistry in Mineral Exploration*, led to the training of several general practitioners during the next twenty years.

In the non-Soviet world, during the 1950s and 1960s, the study of applied geochemistry developed in three ways in addition to exploration geochemistry. These were: (1) medical geochemistry; (2) plant and animal biogeochemistry; and (3) environmental geochemistry. These lines of research were pioneered in Professor Webb's group and other research organizations. Unfortunately, the paradigm of Soviet landscape geochemistry, which could have tied all these different aspects of geochemistry together, was omitted from the Hawkes and Webb approach to applied geochemistry. Consequently, even in 1990, there was still no paradigm for environmental geochemistry generally accepted by non-Soviet applied geochemists. What is clearly required is a new paradigm which links the different aspects of the subject by a common conceptual framework.

Non-Soviet soil science. But to return to the evolution of landscape study and geochemistry in the non-Soviet world. After 1920, the ideas of Dokuchaev gradually became known to soil scientists in the non-Soviet world (FANNING and FANNING, 1989, p. 127 *et seq.*). Also, the seminal research on "catenas" in Africa by Milne in the 1930s (MILNE, 1935, 1936) drew the attention of non-Soviet soil scientists to the concept of landscape. Later, the book by JENNY (1941) *The Factors of Soil Formation* derived partly from the ideas of Dokuchaev, reorientated non-Soviet soil science toward the landscape concept with a new paradigm. The Jenny paradigm is still with us today—for example as updated by JENNY (1980) and described recently by FANNING and FANNING (1989, p. 287, *et seq.*).

In general, non-Soviet geography and geomorphology were dominated by the paradigm of Davis and Penck described above until the mid-1960s or later. For this reason, non-Soviet exploration geochemists trained in the 1950s and 1960s had little reason to interface with geographers, geomorphologists or soil scientists. This was because these scientists were not then interested in the geochemical evolution of the landscapes in which "geochemical anomalies" of the exploration geochemists were found.

Another factor here was the practical success of the Hawkes and Webb "exploration geochemistry" paradigm in finding new mineral deposits. This suggested to practitioners that mineral deposits could always be found without the need of a detailed scientific description of landscapes in which they occur.

Landscape in non-Soviet exploration geochemistry: Bradshaw's contribution. A little later, BRADSHAW'S (1975) book *Conceptual Models in Exploration Geochemistry* was an attempt to introduce the concept of landscape into non-Soviet exploration geochemistry. This book, and other collections of case histories based upon it (e.g. KAURANNE, 1976; LOVERING and MCCARTHY, 1978; BUTT and SMITH, 1980) all stressed the need to use conceptual models of landscapes in order to analyse case history data obtained during geochemical prospecting activities.

The need to relate the concept of "landscape" to Bradshaw-type conceptual models was clearly felt by exploration geochemists. For example, the enthusiasm of BUTT (1987) for the use of landscape conceptual models for exploration in tropical terrains is unmistakable.

In summary, Kuhn's idea of a series of paradigms moulding and guiding the evolution of science is well illustrated by the development of landscape geochemistry between 1900 and 1990. In retrospect, it appears that landscape geochemistry probably could only have developed in the U.S.S.R. as early as 1950. Elsewhere, prior to the mid-1980s, geochemists were not interested in the introduction of the holistic concept of landscape into environmental geochemistry.

Landscape and geochemistry in 1990. There was a turning point in the development of landscape geochemistry worldwide around 1980. In the U.S.S.R., the momentum generated by landscape geochemistry between 1950 and 1980 carried the subject to a new and vital importance in the 1980s.

The recent description of the basics of the *Geochemistry of Technogenesis* by LUKASHEV (1990) illustrates modern Soviet thinking in environmental geochemistry. LUKASHEV (1990) explained that technogenesis is a branch of geochemistry which deals with (1) the role of mankind in the circulation of elements in the environment; (2) the formation of new environments as a result of man's activities; and (3) the deliberate formation of new environments by man. As LUKASHEV (1990, p. 21) put it:

> systematization of human impact factors on the environment and an estimation of their geochemical effects, are of primary importance.

Other examples of the modern Soviet view of environmental geochemistry include the rapid development of "Urban Geochemistry" and "Medical Geochemistry" as described by LUKASHEV (1990) and SUDOV (1990).

In the non-Soviet world, in 1990, environmental geochemistry was fragmented without a generally acknowledged central paradigm. In the 1980s attempts to knit together an "environmental geochemistry" (e.g. by THORNTON, 1983a; FLEET, 1984) failed to define a new paradigm.

Prospect: The need for a new approach to environmental geochemistry

In the late 1980s the need for a new approach to environmental geochemistry worldwide was expressed by many geochemists. For example, FYFE (1987, p. 139) reported that the International Council of Scientific Unions (ICSU) in September 1986 had set up a new project to study environmental change in the planet Earth. The focus of the program was to:

> . . . describe and understand the interactive physical chemical and biological processes that regulate the total Earth system, the unique environment that provides for life, the changes that are occurring in the

system and the manner in which they are influenced by human actions.

The project, known as the International Geosphere/Biosphere Project, focused attention on changes likely to influence the Earth during the next 100 a period.

The need for a new approach to environmental and applied geochemistry is also apparent from an editorial in the Soviet journal *Geochemistry* (ANON, 1988, p. 3). The editor discusses the future of environmental and applied geochemical study as follows:

> Vernadski originally formulated the purpose of biogeochemistry, but it will be very difficult to forecast future developments because the scale of the research does not match their significance. Any biogeochemical research requires extensive co-operation with adjacent areas: geochemistry, hydrogeochemistry, soil science, ecology, geography and so on. At the same time one cannot abandon the traditional geological methods involved in mapping and classification, nor can one neglect geochemical cycles for other elements, or general aspects of the geology of the upper crust, the processes in the hydrosphere, and the lithosphere. *Originally, Vernadski saw the main practical task for biogeochemistry as research on living matter as involved in element migration, whereas now the converse is very important: the effects of geochemical conditions on living matter. Various teams and organizations are dealing with the matter, but the central link remains the geochemical approach.*

The italics were supplied by the present writer to emphasize that the proposed Global Landscape Geochemistry (GLG) *can* supply the "central link" between "environmental" and "applied geochemistry".

A Global Landscape Geochemistry (GLG)

The question is: How to initiate a new comprehensive landscape geochemistry to play a role in modern environmental science? The writer's answer to this question is the development of "Global Landscape Geochemistry" (GLG), as described below. A "Global Landscape Geochemistry" (GLG) should be a robust and unique discipline of environmental geochemistry to meet the needs of a "green" world. Two questions are paramount: Are geochemists worldwide prepared to meet this challenge? and What does it take to establish a new scientific discipline in natural science?

An interesting example of the historical development of a natural science discipline over a 40 a period was described by VICKARY (1984), who noted (VICKAVY, 1984, p. 1) that, in 1943, the goals of the then new science of "biosystematics" were defined as follows:

> 1. To delimit the natural biotic units, and,
> 2. To apply to these units a system of nomenclature adequate to the task of conveying precise information regarding their defined limits, relationships, variability and dynamic structure.

Since 1943, biosystematics has developed steadily and increased in importance considerably. In doing so it has easily incorporated within its structure many new methodologies which are a part of modern botany.

If we use the growth of biosystematics as a model, and if the goals of GLG are successfully defined today, we may expect that in 40 a time GLG will be recognized universally as the paradigm for "green" environmental geochemistry.

A second aspect of Vickary's paper pertinent to GLG refers to the classification of data sets. VICKARY (1984) described how a number of different approaches may be applied *to the same botanical data set* for different reasons. He described how nine populations (that represent all six plant species of the section *Erythranthe* of the genus *Mimulus*) were classified using five different methodologies. These were: (1) numerical taxonomy; (2) chemotaxonomy; (3) allozyme analysis; (4) DNA/DNA hybridization; and (5) standard cytogenic approaches.

The important point here is that when the five classification approaches were applied to the same nine populations *they all provided different sets of valid results* as indicated in Fig. 23. VICKARY (1984, p. 12) concluded:

> *Each approach adds to our information about the biology of the group—often permitting distinctions to be drawn between entities that other approaches did not resolve.* Clearly they are all complementary. Therefore it seems fair that they all can be thought of as part of biosystematics in the broad sense.

VICKARY (1984) also tried to make a single classification scheme by superimposing results of all the five classifications as shown in Fig. 24. As expected, this operation does not yield a single synthetic classification.

The italics in the above quotation were inserted by the present writer. This was to stress that the same biosystematics data set, when analysed in different ways, can provide quite different types of information which are important for different reasons.

By analogy, a subset of GLG regional geochemical mapping data (involving most elements in the Periodic Table and related geochemical entities) might also be interpreted in different ways. For example:

1. In relation to the delineation of geochemical provinces;
2. In relation to mineral exploration—for the identification of geochemical anomalies;
3. In relation to baseline environmental geochemistry—as a prelude to the study of airborne anthropogenic inputs;
4. In relation to environmental change of the soil and water by man's activities—both positive and negative;
5. In relation to the nutrition of plants and animals; and
6. In relation to human health.

If GLG geochemical data were to be utilized in this

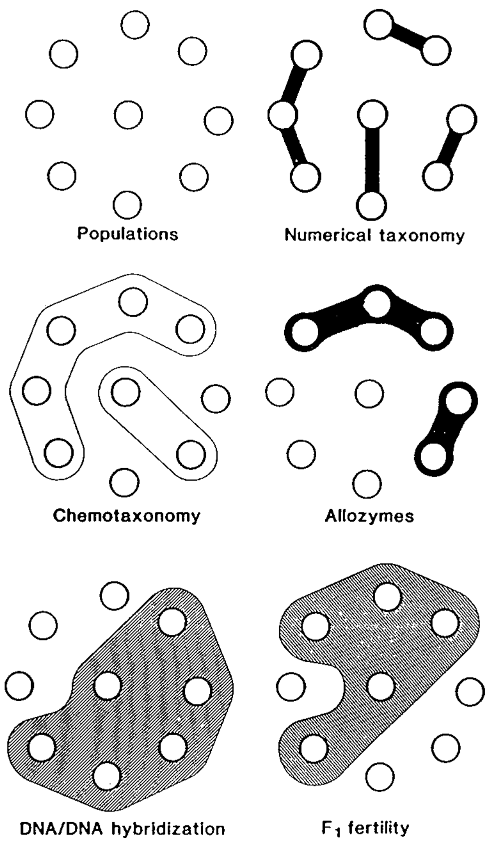

FIG. 23. Five classification systems for nine populations of the section *Erythranthe* (modified from VICKARY, 1984).

Upper left: Circles representing the nine populations of the section *Erythranthe* under study.
Upper right: Groupings of the most closely related populations according to the numerical taxonomy.
Centre left: Two groups of most similar populations based on chemotaxonomy.
Centre right: Two groups of most similar populations according to their allozymes.
Lower left: Six populations indistinguishable on the basis of their repetitive DNA/DNA hybridization results.
Lower right: Five fully inter-fertile populations based on the fertilities of the interpopulation F_2 hybrids.

Similarities are based on dendograms of relationships for each approach.

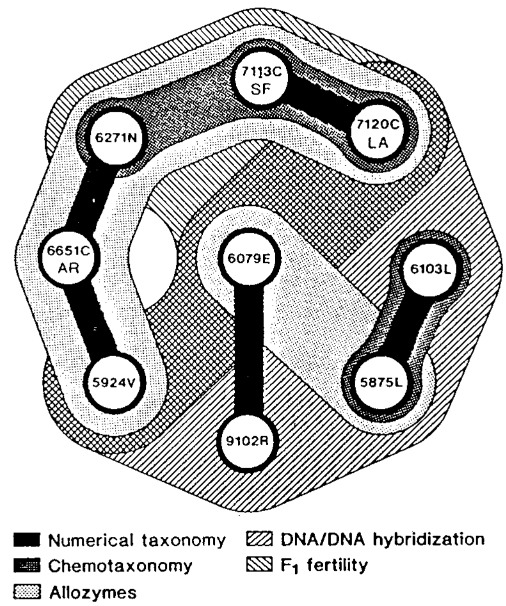

FIG. 24. Comparative groupings of nine taxa of the section *Erythranthe* by five approaches to classification (from VICKARY, 1984).

way it is imperative that it is of the highest quality and that it is accompanied by landscape descriptive data of the same high quality.

General constraints for a Global Landscape Geochemistry (GLG)

A paradigm for GLG should: (1) be firmly rooted in the achievements of pre-1990 landscape geochemistry worldwide; (2) have a clearly defined, distinctive, global, approach to environmental geochemistry; (3) interface smoothly with other disciplines of environmental science (e.g. geography, geomorphology, soil science, forestry, ecology, landscape ecology); and (4) be designed with the long-term development of the discipline in mind.

An experiment in global geochemistry. OLSON *et al.* (1983) provided an interesting example of a relatively simple experiment in global landscape geochemistry. These writers described how they established a data base for a single chemical entity (C in live vegetation). OLSON *et al.* (1983) first prepared a seven-colour global ecology map on a scale of 1:30,000,000 at the equator. Reference was then made to 44 "land ecosystem mosaics" on this map. Each of these was classified further into seven broad groups as follows:

1. Forest and woodland;
2. Interrupted woods;
3. Mainly cropped, residential, commercial, park;
4. Grass and shrub complexes;
5. Tundra and desert;
6. Major wetlands; and
7. Other coastal, aquatic, and miscellaneous.

The limited aims of the project were to map the vegetation and C density for natural, and man-modified, complexes of ecosystems and to illustrate some of the human influences on the global geochemical cycle of C.

The map compiled by OLSON *et al.* (1983) also provided a basis for: (1) making improved estimates of vegetation areas and C quantities of natural biological exchanges of CO_2; and (2) describing the net historic shifts of C between the biosphere and the atmosphere through time.

From the viewpoint of GLG, the map made by OLSON *et al.* (1983) is a first-approximation global C abundance database which might be associated with more detailed geochemical and landscape information obtained from each of the 44 land ecosystem mosaics. Its importance here is that it describes an approach to the solution of a problem in global geochemistry.

Signposts for the development of Global Landscape Geochemistry (GLG)

1. GLG would be established deliberately to meet the long-term, worldwide, needs for a discipline of applied geochemistry.

2. GLG would be firmly rooted in the pre-1990 achievements of landscape and environmental geochemistry but be flexible enough to grow beyond them to provide a truly "green" geochemistry.

3. GLG should be built by global co-operation among geochemists, landscape ecologists, geographers, geomorphologists, soil scientists, foresters, exploration geochemists and other environmental scientists concerned with the geochemistry of the environment. An example of this type of co-operation among geochemists and other scientists today is the International Geochemical Mapping Project (IGCP 259) (Darnley, 1990a).

4. Introductory GLG would be *based* on unique geochemical concepts of Polynov's and Perel'man's landscape geochemistry. Information derived from environmental geochemistry worldwide would be added to this database as required.

5. Comprehensive reviews of the world literature on specific topics important to GLG must become a feature of GLG literature in order to root the discipline in previous experience of landscape geochemistry. Such reviews should be updated at least every 5 a. An annual prize for the best review awarded by each Geochemical Society could act as an incentive for this activity.

6. GLG would aim to become recognized worldwide as the source for all kinds of fundamental and applied geochemical data from the environment, gradually rather than as a fad which burns out after a few years.

7. A major objective of GLG would be to provide global databases on the behavior of all elements (and associated geochemical entities) in landscapes. For example along the lines pioneered by Perel'man (see Fig. 8).

8. Today's environmental geochemists (and other environmental scientists concerned with geochemistry) would require re-education to meet the challenge of the introduction of GLG.

9. This introductory process might also involve one, or more, of the following approaches: (1) the delivery of papers on GLG at conferences in geochemistry and related sciences; (2) university short courses and workshops organized by GLG-orientated geochemists; and (3) comprehensive GLG field schools. These would be open to interested scientists and held in specially chosen landscapes worldwide. In order to gain experience with modern analytical methods, the field schools might be supported by fully equipped mobile GLG laboratory units.

The question is: Are today's environmental and landscape geochemists motivated strongly enough to make GLG a success? Perhaps this article will stimulate a new "Polynov" to champion the GLG cause worldwide? In doing so, he or she, could ensure that GLG will meet fully the new and exacting requirements of the "green" world of the 1990s and beyond.

GENERAL CONCLUSIONS

1. A study of the historical development of landscape geochemistry has demonstrated the importance of communication among scientists worldwide during the development of new natural sciences.

2. The development of landscape geochemistry in the Soviet world since 1900 focuses attention on the importance of having unique, generally recognized, elementary concepts at the heart of a new scientific discipline. Since 1960 the lack of such generally accepted basics for "environmental geochemistry" has led to the fragmentation of this discipline in the non-Soviet world.

3. There is an opportunity today to harmonize environmental geochemistry worldwide by the establishment of a discipline of "Global Landscape Geochemistry" (GLG). Global Landscape Geochemistry would be based on traditional Soviet landscape geochemistry and related disciplines integrated with methodologies developed in the non-Soviet world during the 1980s.

4. The suggestions for the development of a "Global Landscape Geochemistry" (GLG) described here are designed to stimulate interest in this idea and do not in themselves describe a comprehensive plan of action.

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