Document généré le 16 avr. 2025 19:01

Geoscience Canada

Lichens and Rocks: A Review

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Volume 21, numéro 2, june 1994

URI : https://id.erudit.org/iderudit/geocan21_2art02

Aller au sommaire du numéro

Éditeur(s)

The Geological Association of Canada

ISSN

0315-0941 (imprimé)
1911-4850 (numérique)

Découvrir la revue

Citer cet article

Easton, R. M. (1994). Lichens and Rocks: A Review. *Geoscience Canada*, *21*(2), 59–76.

Résumé de l'article

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Lichens and Rocks: A Review

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SUMMARY
Lichens, especially saxicolous (rock-inhabiting) lichens, are encountered almost daily by the field geologist. Despite the difficulties in readily identifying lichens, there is increasing evidence that many species have a preference for some rock types, and that certain species can chemically modify their substrate. There is also increasing evidence that certain lichens, some of which change colour based on absorbed metal content, may make effective indicator plants in mineral exploration, particularly in areas such as the Northwest Territories.

RÉSUMÉ
À tous les jours ou presque, le géologue de terrain peut observer des lichens et particulièrement les lichens saxicoles. Bien qu'il ne soit pas facile d'identifier rapidement les lichens, un nombre croissant d'indices montrent que plusieurs espèces ont un penchant pour certains types de roche, et que certaines espèces peuvent altérer chimiquement leur substrat. Il est également de plus en plus évident que certains lichens changent de couleur en fonction des métaux absorbés, et qu'il pourrait en cela être de bons végétaux indicateurs pour l'exploration minérale, particulièrement dans des régions comme celles des Territoires du Nord-ouest.

INTRODUCTION

Purpose

Lichens are one of the organisms most frequently encountered by geologists in the field, particularly those working in the Arctic and sub-Arctic regions of Canada. Many field geologists over the years have undoubtedly noted a relationship between certain rock types and the corresponding lichen flora. Few, however, have tried to quantify these observations. What literature that does exist is commonly found in botanical, not geological, journals. Further, to paraphrase Brooks (1983), "although any reasonably intelligent person without botanical knowledge should have little difficulty in recognizing most higher plants, this is not the case for lichens, and expert assistance is needed for studies involving lichens" and their geological applications.

The purpose of this paper is to provide a brief overview of lichen biology and taxonomy, and to review the varied geological information that can be gleaned from detailed lichen studies.

Geological Applications of Lichenology

During the past three decades, interest in geobotanical research has increased greatly. Most of this research is involved with the discovery and the use of "indicator plants" to aid in mineral exploration, or with the use of plants as a geochemical sampling medium (*cf.*, Brooks, 1972, 1983). Interest in lichens as biogeochemical indicators is based on the observation that the accumulation of trace elements by bryophytes and lichens is usually much greater than for other plant groups (*e.g.*, Lounamaa, 1956; Shacklette, 1965a, 1965b, 1967; LeRoy and Koksoy, 1962; Antononvics *et al.*, 1971; Tuominen and Jaakkola, 1973; Doyle *et al.*, 1973; Galun and Ronen, 1988; Richardson and Nieboer, 1980). In addition, lichens are also extremely sensitive to the halogen group of elements and sulphur dioxide and, thus, they serve as very sensitive and effective indicators of atmospheric pollution (*cf.*, Galun and Roen, 1988; Richardson, 1988). Further, lichens can be used to monitor industrial pollution because they absorb a variety of heavy metals from the atmosphere (*e.g.*, Pb, Ni, Ti; see Galun and Roen, 1988; Puckett, 1988 for references). Attempts have also been made to use lichens as a relative age dating tool (lichenometry) by using the relative growth rates of lichens to determine age. Lichenometry has been used mainly to date surfaces less than 500 years in age in glacial regions, which cannot be dated by alternative means (*cf.*, Innes, 1988), but has recently been applied to dating scarps related to prehistoric earthquakes (*e.g.*, Smirnova and Nikonov, 1990). Details on all these applications are provided later in this paper.

LICHEN BIOLOGY

Definition

Lichens consist of two organisms, a photosynthetic component (photobiont) and a fungal component (mycobiont). They exist together in a symbiotic relationship to form the plant we know as a lichen. The most recent definition is that a "lichen is an association between a fungus, usually an ascomycete, but in a few cases, a basidiomycete or deuteromycete, and one or more photosynthetic partners, generally green algae or cyanobacteria. In all lichens, the fungus forms a thallus or lichenized stroma that may contain secondary compounds." (Ahmadjian, 1993).

The term mutualism probably more aptly describes the relationship between the alga and the fungus than does symbiosis. The fungi can be regarded as controlled parasites of the algae, in that they live in a biological equilibrium with the photosynthetic algae. In the relationship, the algal host usually suffers no appreciable harm, and actually receives some benefits; it is shielded from excessive sunlight, desiccation and mechanical injury, and receives inorganic substances from its fungal host. In return, the fungus receives nutrients from the photosynthetic algae.

The efficiency of this relationship can be seen in the widespread distribution of lichens and their ability to grow on almost any substrate. They can be found on every continent, including Antarctica, and can flourish in almost every climatic region. Some 13,500 species are known worldwide (Hawksworth, 1988a), representing 20% of all fungi described.

Origins

When lichens originated is poorly known, mainly due to difficulties in preservation. The oldest, well-preserved lichens date from the Eocene (Pirozynski, Canadian Museum of Nature, pers. comm., 1993), and recently, it has been suggested that some Edicarian trace fossils may, in fact, be lichens (Re-

tallack, 1992). Hawksworth (1988a, 1988b) suggests that lichens evolved in the Permo-Triassic (190-280 Ma) on the basis of co-evolutionary considerations and phytogeographic studies. This is consistent with other work indicating that fungi are present in Devonian strata (Black, 1972), and that the ascomycetes may have been quite diverse by the Silurian (Sherwood-Pike and Gray, 1985).

Evolutionary and Taxonomic Relationships

Lichens and bryophytes (mosses) are commonly considered by the layman to be related to one another. They are, however, quite unrelated by evolution or taxonomy. Living organisms are commonly divided into five kingdoms: Monera, Protista, Fungi, Plantae and Animalia (*e.g.*, Keeton *et al.*, 1986). At this broad level, lichens and bryophytes belong to different kingdoms. Bryophytes are true plants (Kingdom *Plantae*), whereas lichens are composed of a mycobiont (in the Kingdom *Fungi*) together with either (or both) green algae (Kingdom *Protista*) or cyanobacteria (Kingdom *Monera*). *Fungi* are heterotrophic (*i.e.*, dependent on external sources of carbon compounds), filamentous, non-embryo producing organisms with chitinous cell walls, whereas true plants are photosynthetic, non-filamentous, embryo-producing organisms without chitinous cell walls (Nash and Egan, 1988). Lichens probably evolved from free-living fungi, whereas bryophytes probably evolved from protists.

The taxonomy of lichens is based on the fungal component, especially their reproductive structures, although features of the vegetative thallus (including the photobiont) and the secondary chemical compounds they produce, are also important. The type of photobiont in a lichen is proving to be less and less important in its classification, although there is still much to be learned about the specificity of individual species of lichen fungi for their photosynthetic partner (see Ahmadjian, 1993). In any event, the names applied to lichens refer only to the mycobiont, according to Article 13d of the International Code of Botantical Nomenclature.

Taxonomic Usage in this Paper

The last 15 or 20 years have seen many advances in the field of lichen taxonomy, leading to the recognition of more "natural" (*i.e.*, meaningful by evolution) groups, especially at the genus and family level (*cf.*, Hafellner, 1988). The names used in this paper reflect these changes, and are based on the nomenclature and synonymies in Egan (1987, 1989, 1990, 1991) and Santesson (1993), unless otherwise stated. Thus, when referring to the original articles cited herein, particularly those prior to 1985, the user will note differences in some species and genera names (*e.g.*, *Tremolecia atrata* = the former *Lecidea dicksonii*). The reader should also be aware that many textbooks on lichens and identification keys predate this revised taxonomy (*e.g.*, Hale, 1983), and care should be taken in using lichen names found in older references.

Growth Forms

Figure 1 illustrates a typical crustose lichen. The entire lichen body is termed a thallus. Small protuberances on the thallus are sexual reproductive bodies, termed apothecia, which produce spores. The form of the thallus and the nature of the apothecia are important features used in lichen identification.

It is common practice to group lichens according to growth forms as well. This is somewhat misleading, since lichens of the same family may exhibit widely varying growth forms (*e.g.*, Parmeliaceae includes foliose and fruticose forms). The three major growth forms are crustose, foliose and fruticose (Fig. 2a, 2b, 2c). Sometimes the foliose and fruticose lichens are referred to as macrolichens.

Figure 3a shows the tissue organization within crustose lichens. The crustose lichens are in intimate contact with the substrate, and cannot be entirely removed without the substrate. They can grow on rock (epilithic), bark, wood or other materials, or even on other lichens, and may grow into the rock (endolithic), particularly on limestones and sandstones. In endolithic species, such as shown in Figure 2a, the upper cortex is absent, and the algae are scattered beneath the rock surface, with only the fruiting bodies (apothecia or perithecia) breaking through the surface. Increasing specialization of the crustose thallus is accompanied by the formation of a distinct upper cortex, algal layer, and medulla. The border of the thallus may be diffuse or distinct. In many species, a non-lichenized prothallus (fungus) precedes the margin of the lichenized thallus (Fig. 1). Further development of the thallus occurs in Acarosporaceae and Rhizocarpaceae, which have centrally fissured or areolate thalli. More highly developed forms

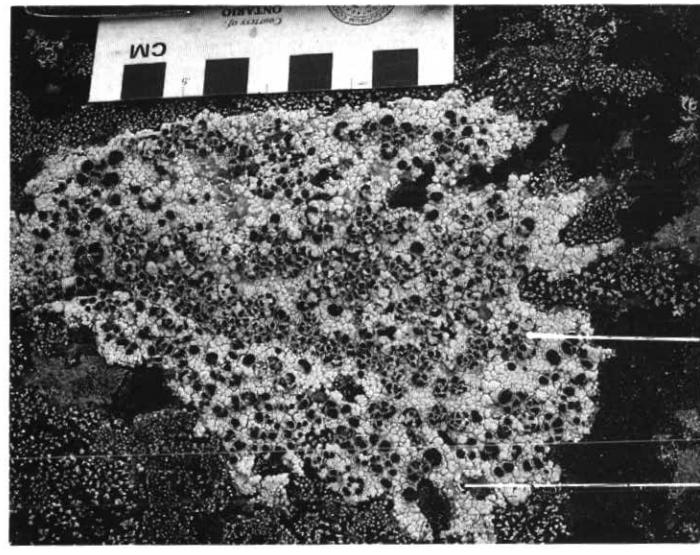

Figure 1 *Morphological features of a lichen. The example is from the Back River in the Canadian Arctic. Two crustose species are present in the photograph. The large, light-coloured (pale yellow-green with red-brown apothecia) lichen is* Lecanora argopholis, *a species common to mafic volcanic rocks and sedimentary rocks. The smaller dark patches are* Rhizocarpon geographicum, *a yellow-green and black lichen that is a widespread boreal to arctic-alpine lichen and is restricted to fine-grained siliceous rocks. In this case, the substrate is an Archean metawacke (greenschist facies).*

such as Lecanoraceae (Fig. 1) form lobes near the margins. The ultimate stage of specialization is the squamulose thallus, which is a discrete, lobe-like structure, partly or wholly free from the substrate, differing from the foliose lichens only by lacking a lower cortex.

The typical foliose lichen is a leafy, dorsiventral body with a distinct lower cortex (Fig. 3b). It is attached to the substrate by rhizines. The more structured growth in this form allows for a greater range in size and branching of lobes than is possible in the crustose group. Umbilicate lichens show a modification of the foliose growth form in that the thallus is fully corticated, yet is circular in outline and attached to the substrate at one point by a central umbilicus (Fig. 2b).

Fruticose lichens (Fig. 2c) are hair-like, shrubby or finger-like lichens and can range in size from 1 mm to 5 m in length. The internal structure (Fig. 3c) is more or less radial, usually with a dense outer cortex, an algal layer, a medulla, and with a hollow centre or a dense central cord in the cases of *Cladonia* spp. or *Usnea* spp., respectively. The "reindeer mosses" or caribou lichens (*Cladina*) belong to this group.

As in rocks, the colours of lichens can be distinctive, yet are subtle and hard to describe. As in rocks, lichen colour is a feature that requires some experience to use with confidence. Colour should be determined from a dry thallus, because when wet, the upper cortex becomes transparent and takes on the colour of the algal layer. Colour typically results from the incorporation of organic (or inorganic) substances in the cortex, with the most common colours being greenish grey, greenish yellow, lemon yellow, orange, brown (tan to black), and slate blue. The colour of the apothecia is rarely the same as the thallus. The form of the thallus, position of the apothecia (do they grow between areoles or within areoles?), shape, colour, surface texture, and distribution of apothecia are also important visual keys in lichen identification.

In addition to morphological study, a variety of chemical tests is used to aid in lichen identification. Three types of tests are used: 1) Spot tests using 10% KOH, household bleach or para-pheylenediane (PD) can be easily done in the field. These tests involve observing colour changes to the thallus upon application (Hale, 1969, 1979 and Brodo, 1988 provide further details on these

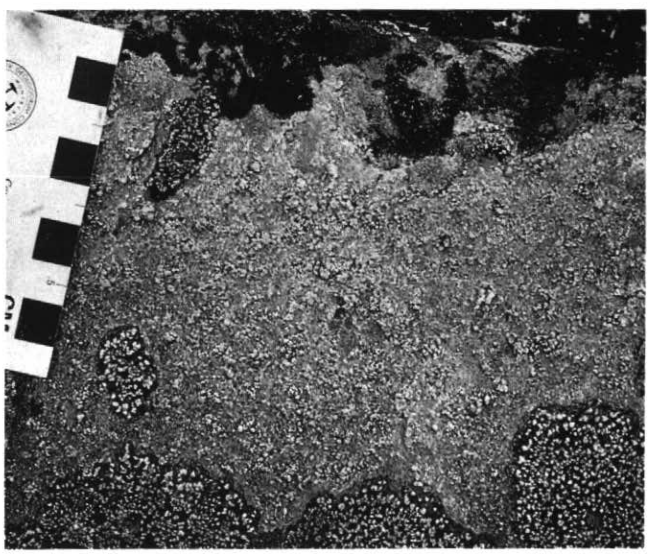

Figure 2 *The three major growth forms exhibited by lichens. All examples are from the Back River area, Northwest Territories, Canada.* **(A) (above left)** *A crustose lichen. The example is* Lecanora polytropa, *an endolithic species growing in an Archean metawacke. Note the lack of a thallus (body), although the apothecia are quite distinct.* **(B) (above right)** *A foliose lichen of the umbilicate type. The example is* Umbilicaria deusta, *which is growing on an argillite substrate.* **(C) (left)** *Fruticose lichens,* Cladina *and* Cladonia *spp. The large, cup-shaped bodies are podetia of* Cladonia.

tests). 2) Crystal tests require heat and microscopic examination, but could be done in a camp setting (Hale, 1969, 1979). Crystal tests have, in recent years, been largely replaced by 3) thin-layer chromatography, which is as reliable and which is relatively inexpensive (Hale, 1983; Brodo, pers. comm., 1993). In addition, examination of sectioned apothecia under a compound microscope is regularly used in identification. Short and long wavelength ultraviolet radiation is also useful in identification, as the secondary compounds in some lichens fluoresce under long wavelength ultraviolet light. With advance planning, the majority of these tests could be conducted either in the field or at camp.

Tissue Organization and Morphology

The photobiont and fungus of many lichens have been separated and grown in the laboratory independently, and a number of attempts to recombine them, even to the fruiting stage, have been successful (*e.g.*, Ahmadjian, 1993; Yoshimura *et al.*, 1993 and references therein). The photobionts belong to two major groups, the cyanobacteria ("blue-green algae") and the green algae. Approximately 28 genera in 14 families are involved in lichenization. The fungi in most lichens are ascomycetes (sac fungi), although there are some basidiomycete lichens belonging to the mushroom order Agaricales that are found in boreal to arctic-alpine habitats in Canada; other "basidiolichens" commonly occur in the tropics.

The tissues of the lichen are differentiated to form three major layers, as well as numerous specialized bodies. Figure 3 illustrates the tissue organization among the three major lichen growth forms.

Cortical layers serve as a protective covering similar to the epidermis of a leaf. In fact, as a whole, the lichen is similar to a leaf. The cortex layers are composed of compressed, gelatinized hyphae (fungal strands) firmly cemented together. The medulla (Fig. 3) forms the bulk of the lichen body, and the hyphae of the medulla are less gelatinized and less compressed than in the cortex, and are irregularly interwoven, forming a loose, fibrous mass. The algal layer is completely surrounded by fungal tissue, and the algal cells and fungal hyphae are in direct contact. The algal layer is usually located between the upper cortex and the medulla. In crustose species the lichen lacks a lower cortex, or is directly attached to the substrate by rhizines. (Rhizines are strands of colourless or blackened hyphae that serve to anchor the thallus to the substrate. They may be single stranded or branched.) In foliose lichens, a lower cortex is present from which the rhizines originate. Fruticose lichens are attached by few points and are pendent or erect.

Figure 4 illustrates some of the morphological terms used in describing lichens. As previously noted in Figure 1, the entire body of the lichen is called the thallus. The undifferentiated, unlichenized part of some crustose lichens that appears at the growing edge and sometimes between the areoles, is called a prothallus. A hypothallus is a highly differentiated, complex development of the lower cortex and rhizinae that occurs in a small number of foliose genera (*e.g.*, *Anzia* and *Pannoparmelia*). Areoles can be regarded as greenhouses built and maintained by the mycobiont for algae, and are also used in identification, particularly in the genus *Rhizocarpon* (see Benedict, 1988). Other important features of the thalli are soredia, isidia, rhizines, apothecia, lobules, tomentum, cilia, cyphellae, cephalodia and perithecia (Fig. 4).

Reproduction

Reproduction in lichens can occur by two means: sexual reproduction involving production of fruiting bodies and spores by the fungal component, and by vegetative dispersal involving both components.

Vegetative dispersal involves transport of vegetative diaspores of the lichen through fragmentation and transport of part of the lichen thallus, and as the diaspores contain a variety of lichenized structures, they are capable of propagation and continued growth. The diaspores are mostly soredia and isidia and include features such as squamules, lobules or thalline fragments. Soredia (Fig. 4) are discrete clumps of a few algal cells closely enveloped by hyphae, and generally give the impression of a powder on the surface of the thallus. The entire thallus of certain crustose lichens, such as *Lepraria* spp., consist of a continuous layer of diffuse soredia. Isidia are cylindrical, finger-like protuberances from the upper cortex in which algal and fungal tissues are incorporated. They are easily broken off and are most common in the foliose and fruticose lichens.

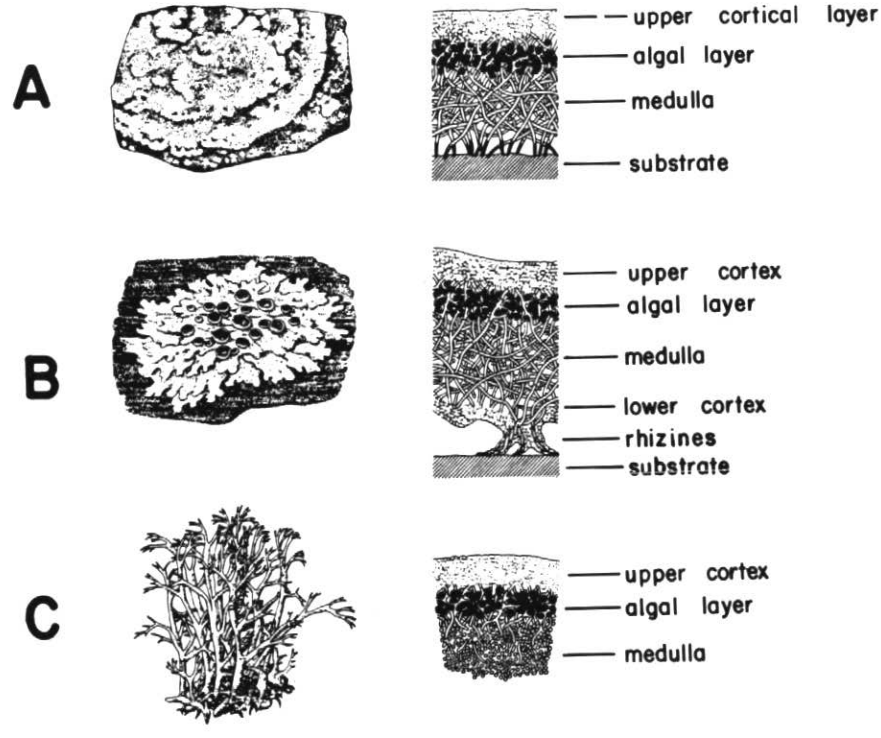

Figure 3 *Cross-sections showing tissue structure in the three major lichen growth forms (modified from Hale, 1983).* (**A**) *crustose lichens* (**B**) *foliose lichens* (**C**) *fruitcose lichens.*

Sexual reproduction is a characteristic of the mycobiont alone and results in the production and dispersal of spores. A lichen thallus can be reconstituted through lichenization, by combining germinating ascospores and a suitable alga.

Apothecia (Figs. 3, 4) are reproductive organs of the mycobiont and are typically open, disc-shaped or cup-shaped structures. Spores are produced in asci present in the apothecium, and are then forcibly ejected into the atmosphere. The shape and size of the apothecia and the spores they contain are important criteria in lichen identification. For example, in certain lichens, the apothecia have margins that are much the same colour as the disk and contain no algae (*e.g., Lecidea* and *Rhizocarpon*), whereas in others, the apothecial margins resemble the thallus rather than the disk in colour and texture and contain algae (*e.g., Lecanora* and *Parmelias*). [NOTE: The families Lecanoraceae and Lecideaceae are actually distinguished by details of their ascus tips and their apothecial anatomy and development, much too detailed for the scope of this paper.]

Physiology

The physiology of lichens has been reviewed in detail by Kershaw (1985), to which the reader is referred for further details. Armstrong (1974) demonstrated that saxicolous species have a wide tolerance of environmental factors, the most critical of these being light intensity, water relations, substrate stability and texture, and pH.

The lichen thallus has been compared to a leaf (both are photosynthetic organs), the main physiological difference being that more tissue in lichens respires than photosynthesizes, therefore lichens need more light (under optimal moisture conditions) before the rate of photosynthesis equals respiration; in leaves, almost all the tissue can photosynthesize. Water is very important in this process, and lichens are able to absorb and lose water rapidly. This shows that lichens are very drought-resistant. Lichens are tolerant to very low temperatures and can quickly adjust their physiological response to seasonal changes (Hale, 1983).

Nitrogen, an important nutrient, can be obtained from the substrate (*e.g.*, on "bird" rocks), rainwater or blue-green photobionts. Field experiments by Armstrong (1984) demonstrate the influence of bird droppings on the growth of saxicolous lichens. The importance of the substrate as a source of inorganic nutrients is unclear (Brodo, 1973). Jenkins and Davies (1966) suggested that atmospheric dust and rainfall were more important than the substrate as a nutrient source. Trotet (1968) found that phosphorous was not absorbed by bark-inhabiting lichens from the substrate, and Kuziel (1973) found that potassium and calcium contents within species was habitat related (*i.e.*, xeric or hydrous). Others, such as Lounammaa (1956, 1965) and Czehura (1977) have shown that lichens have an abnormally high content of some inorganic elements. The importance of the substrate as a source of the elements *versus* other sources, however, is uncertain. This subject is discussed in greater detail later in this paper, as it is important with respect to biogeochemical exploration using lichens.

Lichens, especially crustose species, grow very slowly. The fruticose species are the fastest growing at between 1.6 mm to 10 mm annually, followed by the foliose (0.01 mm/year to 4 mm/year) and crustose (0.25 mm/year to 1 mm/year) lichens. Growth rates can vary from year to year and between habitats (*e.g.*, temperate *versus* arctic) and may vary with age of the lichen (Hale, 1983). The longevity of lichens is poorly known; estimates range from twenty to a few thousand years (Hale, 1983).

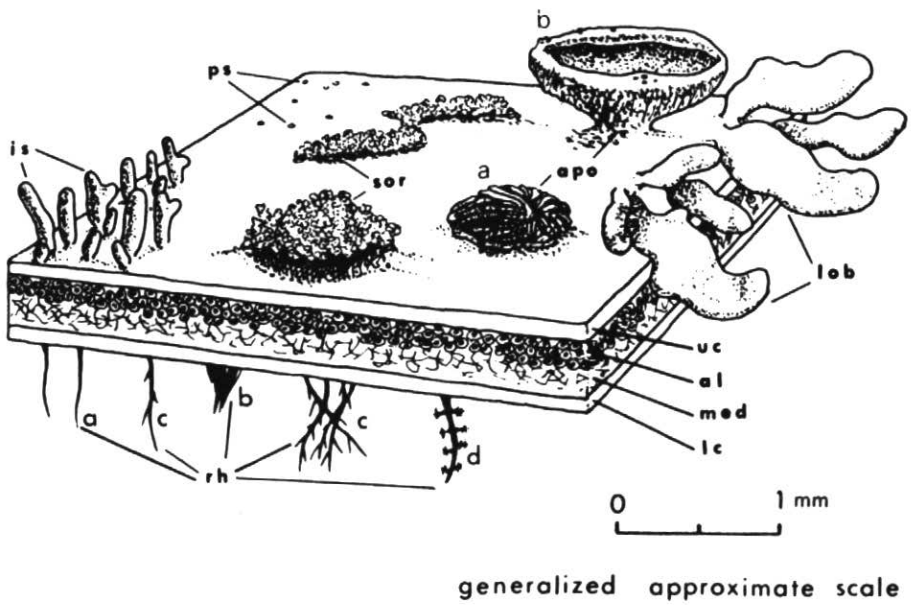

Figure 4 *Some morphological features of a foliose lichen (from Brodo, 1967, 1988).*

Effects on the Substrate

Much has been written on the effects of lichens on the substrate and their role in soil development (pedogenesis), and the subject has been reviewed by Syers and Iskandar (1973) and Jones (1988). There are two views: one is that chemical substances secreted by the lichen are responsible for degradation of rock surfaces, the other is that mechanical action is primarily responsible. Fry (1922, 1927) showed that the mechanical effect produced by expansion and contraction of crustose thalli caused by the gain and loss of water is considerable. Many of the chemical effects are restricted to carbonate rock substrates, mainly due to formation of carbonic or oxalic acids. In either case, the amount of actual soil produced by lichens is not well known, but it is believed to be small. The pioneering role of lichens may simply be that they provide nutrients for later colonizing species.

Further Reading

For more detailed insights into lichen biology, the following publications can be consulted: Hawksworth and Hill (1984), Kershaw (1985), Lawrey (1984), Galun (1988a, 1988b, 1988c), Vitt *et al.* (1988), and Hale (1983). Useful, but somewhat more dated references include Hale (1967, 1968, 1969, 1979), Ahmadjian and Hale (1973), and Seaward (1977). Keys useful in the identification of crustose species, particularly in the Canadian Arctic, include: Fink (1935, all families, now quite dated),

Runemark (1956, *Rhizocarpon*), Thomson (1967, *Rhizocarpon*), Thomson *et al.* (1969, Thomson and Scotter, 1983, 1992, most crustose families), Thomson (1984, most macrolichen species), Thomson (1991, *Staurothele*), Thomson (1993, *Xanthoparmelia*), Brodo (1988, Ottawa region), and Wong and Brodo (1992, southern Ontario). Noble *et al.* (1987) provide a list of species in British Columbia, but no identification key. Egan (1987) provides a checklist of lichens of the United States and Canada; several updates have subsequently been published (Egan, 1989, 1990, 1991). Hale (1969, 1979) discusses in detail many of the common chemical tests used in lichen identification. *The Bryologist* regularly publishes an annotated listing of recent literature on lichens, which is invaluable in keeping abreast of new work in the field. *The Lichenologist* also publishes an annual listing of recent literature dealing with air pollution and lichens.

GEOLOGICAL APPLICATIONS

The Use of Lichens in Dating

The basic principle underlying the use of lichens in dating (lichenometry) is that of the relationship between size and age; if the growth rate of a given lichen taxon is known, then the age of a surface can be inferred from the size of the largest (and oldest) lichens present on it. Lichenometry has been of greatest use in the fields of geomorphology and archeology, particularly in dating Neoglacial deposits in arctic and alpine environments. Recently, lichenometry has been used to date prehistoric earthquake activity (Smirnova and Nikonov, 1990; Xie and Xiao, 1990, 1991; Bull, 1994). Lichenometry is most useful for dating surfaces exposed within the last 500 years, as few other alternative methods (*e.g.*, ^{14}C, thermoluminescence, *etc.*) cover this period. Table 1 summarizes some of the relevant literature on the use of lichenometry in Canada.

Most lichenometric studies deal with the genus *Rhizocarpon* (Fig. 1), which contains many species. *Rhizocarpon* is used because it is long lived and abundant in arctic-alpine environments. Innes (1988) provides a complete listing of all taxa that have been used in lichenometry. Any species used must: 1) be relatively common on all surfaces being studied, 2) have clearly defined margins, and 3) have a growth rate compatible with the ages of the surfaces. Both Locke *et al.* (1979) and Innes (1988) provide detailed guidelines to assist researchers undertaking lichenometric studies. Dyke (1990) provides an excellent case study application of the method in the Canadian Cordillera. Benedict (1988) and Poelt (1988) provide keys to the proper identification of species within the subgenus *Rhizocarpon* (the yellow species).

Several studies have shown that different species within the genus grow at different rates and that each species may have specific environmental controls (Innes, 1983a, 1983b, 1988). For example, in Canada, *Rhizocarpon macrosporum* is known to grow faster than *R. geographicum* (Duford and Osborn, 1978; Luckmann, 1977), however, recognition of individual species in the field is frequently difficult. As lichenometric dating assumes that the size-age relationship of lichens on one deposit can be transferred to another, the difficulty in establishing uniform growth rates, particularly in using aggradated species, can lead to significant errors.

Innes (1988) discusses the problems involved in measuring thallus size (*e.g.*, thalli coalescence, departure from circularity due to crowding, *etc.*) in the field, and recommends use of the longest axis of thalli as the best index of size (in contrast to largest inscribed circle, area or mean axis). Some workers have suggested using only the largest single thalli for dating (Webber and Andrews, 1973), whereas others have suggested using an averaging procedure (Innes, 1984, 1985), generally using the mean of the five largest thalli on a deposit. The mean value method, however, is not useful for dating small surfaces (*e.g.*, gravestones), as microenvironmental variations may affect thallus size to a greater extent than age-related factors (Innes, 1988; *e.g.*, thalli are commonly larger near streams). Innes (1988) suggests that quadrants must be between 8 m to 25 m in size to yield reliable results.

Size-age relationships proposed by lichenometric studies have either linear or negative exponential curves, and it is unclear which model is most appropriate (Innes, 1988). In addition to size, percentage-cover and size-frequency studies have also been used by some workers in lichenometry, and are reviewed by Innes (1988; see also Smirnova and Nikonov, 1990). Percentage-cover studies are best suited for relative-dating studies.

As noted by Innes (1988), "lichenometry provides a possible means of obtaining a date for a surface. ... Provided the technique is applied correctly and with care, dates accurate to about 10% of the surface age should be possible."

Lichens, Weathering and Soil Development

That saxicolous lichens affect their substrate has been recognized since Sollas (1880) first noted that minute pits on limestone surfaces were produced by the lichen *Verrucaria repestris*. since then, there has been controversy over

TABLE 1 **Lichenometric studies in Canada.**

Area	*Reference*
Baffin Island	Harrison (1964, 1966) Andrews and Webber (1964) Loken and Andrews (1966) Barnett (1967) Andrews and Webber (1969) Carrara and Andrews (1972) Miller and Andrews (1972) Miller (1973)
Cordillera	Osborn and Taylor (1975) Luckmann (1977) Osborn (1975) Duford and Osborn (1978) John (1989) Dyke (1990)
Miscellaneous	Beschel (1961a, 1961b)

the ability of saxicolous lichens to degrade rock substrates and hence form soils, as reviewed by Brodo (1973) and Jones (1988). Some workers have argued that lichen effects on the substrate are restricted to mechanical action only (*e.g.*, Fry, 1922, 1927), and that lichens are insignificant in soil formation. Other studies, however, show strong evidence of chemical interaction and degradation of the substrate (*e.g.*, Schatz, 1963; Ascaso *et al.*, 1976; Jackson and Keller, 1970; Wilson and Jones, 1983, 1984; Hallbauer and Jahns, 1977; Gehrmann *et al.*, 1992; Adamo *et al.*, 1993) and thus a significant role for lichens in chemical weathering and soil development. Both views are probably correct, with some species showing little effect on the substrate, whereas others modify their substrate significantly.

Several studies indicate that certain lichen compounds, some of which are acids, are able to form soluble metal complexes and to effect weathering of minerals and rocks (Schatz, 1963; Schatz *et al.*, 1954; Syers, 1969; Iskandar and Syers, 1972). The lichen *Xanthoparmelia conspersa* is particularly effective in reacting with biotite-rich and granite substrates (Schatz, 1963; Syers, 1969). Calcium was notably soluble in comparison with Mg, Fe and Al on surfaces inhabited by *X. conspersa* (Iskandar and Syers, 1972). Ascaso *et al.* (1976) also documented changes in mineralogy at the lichen-substrate interface. Kerr and Zavada (1989) note that increased pH associated with the lichen microenvironment causes silica to become soluble and to be removed from the underlying sedimentary substrate.

In recent years, a number of studies indicate that the formation of oxalic acid at the lichen-rock interface is responsible for decomposition of minerals, particularly magnesium silicates and carbonates (Jones *et al.*, 1980; Wilson *et al.*, 1981; Ascaso *et al.*, 1982; Chisholm *et al.*, 1987; Purvis *et al.*, 1987; Salvadori *et al.*, 1990; Adamo *et al.*, 1993; see also review in Jones, 1988). These studies are particularly relevant to the ability of lichens to serve as indicator plants, as outlined in greater detail in the next section.

Possibly most significant with respect to soil formation is that lichen thalli accumulate a variety of nutrients such as phosphorus, calcium, magnesium, potassium and iron, and that the lichens commonly metabolize these elements into biologically usable forms (Syers and Iskandar, 1973). Thus, lichens serve as a useful substrate for colonization by other species, which eventually leads to the breakdown of the substrate. As noted by Jones (1988), these factors are probably most significant in soil development in extreme environments such as the desert or arctic and alpine areas.

The Use of Lichens as Pollution Monitors

Lichens have been widely used as indicators of atmospheric pollution, particularly heavy metal deposition and accumulation of radionuclides. The topic of heavy metal deposition has been extensively reviewed (*e.g.*, Showman, 1988; Puckett, 1988; Galun and Ronen, 1988; Ferry *et al.*, 1973; Gilbert, 1973; Takala and Olkkonen, 1986), and *The Lichenologist* regularly publishes a listing of current literature related to the use of lichens as pollution monitors. The majority of these studies have been conducted in Europe or Scandinavia. Several studies, however, have been conducted in Canada using lichens as pollution monitors (Table 2).

As alluded to previously, these studies are relevant to the use of lichens in mineral exploration, as the heavy metal content in many lichen species may not be indicative of the metal content of the substrate. Further, lichens can serve as an effective monitor of atmospheric pollution near smelters (Fig. 5), and can be utilized to monitor clean-up activities. A particularly interesting study in this regard is that by Schwartzman *et al.* (1987, 1988), who observed decreases in lead values in foliose lichens in the Washington, D.C. area associated with the phasing out of gasolines containing lead compounds. Similar observations have been reported by Lawrey (1993). Lichens have also been successfully used to monitor toxic gases from volcanic emissions in the Canary Islands (Davies and Notwitt, 1989), although similar attempts in Italy were less successful (Barghigiani *et al.*, 1990).

Research in radionuclide accumulation peaked in the mid-1960s when it was observed that elements such as ^{137}Cs and ^{90}Sr accumulated in the "caribou" lichens and migrated through the food chain from lichen to caribou to humans (generally Inuit populations) (*e.g.*, Touminen and Jaakkola, 1973). More recently, radionuclide monitoring in lichens has resurfaced as an important pollution monitor in the aftermath of the 1987 Chernobyl nuclear accident in the Ukraine (*e.g.*, France *et al.*, 1993).

The use of lichens as monitors of

Table 2 Some Canadian studies using lichens as pollution monitors.

Area	*Element/Compound*	*Reference*
Ontario		
Sudbury	Ni, SO_2	Nieoboer *et al.* (1972) Freedman & Hutchinson (1980) Amiro and Courtin (1981)
Sudbury & N.W.T.	Cu, Fe, Ni, S	Tomassini *et al.* (1976)
Wawa	SO_2	Rao & LeBlanc (1967), LeBlanc (1969)
Elliot Lake	U	Boileau *et al.* (1982)
Thunder Bay	Al, As, Cd, Cu, Hg, Pb, S, Zn	Pfeiffer and Barclay-Estrup (1992)
Newfoundland	F	Roberts and Thompson (1980)
Quebec	F, SO_2	LeBlanc and coworkers (1971, 1972, 1974, 1976)
	Cd, Pb, Hg, Cs	Crete *et al.* (1992)
Alberta	review	Case (1984)

mining activities and industrial pollution is likely to become more common in future as lichen physiology and substrate effects become better understood.

The Use of Lichens in Mineral Exploration

The first suggestion that lichens might be used for mineral prospecting was made by Rosenkvist in 1950, who was disappointed with the results (Brooks, 1983). Their use was revived by LeRoy and Koksoy (1962) who suggested that they would be particularly suited as indicators because of their great age (>500 years) would facilitate elemental absorption. Table 3 provides a summary of studies to date of lichens as indicator plants or as biogeochemical indicators.

The advantages of geobotanical prospecting methods, as outlined by Brooks (1972), are: 1) low costs after the initial orientation survey, 2) different geologic formations as well as mineralization can be identified, 3) aerial methods can be used, and 4) indicator plants can sometimes show mineralization not exposed at depth (through root uptake). In the case of lichens, many of these advantages cannot be realized (*e.g.*, #3 and #4), and consequently, less study has been devoted to the use of lichens as indicator plants than other species. One way around this problem is to use lichens mainly as a biogeochemical indicator.

A major problem with the use of lichens as biogeochemical indicators is determining the source of the metal enrichment. Numerous studies (*e.g.*, Jenkins and Davies, 1966; Dormaar, 1968; Ferry *et al.*, 1973; Antonovics *et al.*, 1974) indicate that many metals concentrated in lichens are transported by air, including elements such as titanium (Takala and Olkkonen, 1986) as well as radionuclides (*cf.*, Touminen and Jaakkola, 1973). Perhaps the most intriguing study in this regard was that of Prussia and Killingbeck (1991), who compared inorganic element contents in two species of foliose lichens growing on both bark and granite substrates in an area subjected to the same atmospheric pollutants. Lichens growing on granite had notably higher Ca contents than those growing on bark (average Ca content in granite was 0.95% compared to <0.10% in bark). There was also indication of slightly higher contents of P and Zn in lichens found on granite substrates. Whether these results can be extrapolated to other species is an open question. There was also a significant seasonal variation in the content of elements such as K and Na, which serve important biological roles. Insufficient studies exist to determine if metal contents show similar seasonal variations.

In the case of saxicolous lichens, considerable care must be taken during sample collection and preparation to ensure only the lichen thallus is being analyzed. Osterman and Wessels (in prep.) suggest that metals may be bound in water-soluble lichen acids, and that water-based cleaning methods to separate lichen and substrate (*e.g.*, LeRoy and Koksoy, 1962; Czehura, 1977) may remove metals from the samples. Brodo (pers. comm., 1993) notes that no water-soluble lichen acids have been described, and thus the need for such a procedure is problematic. Nonetheless, lack of a standardized analytical technique makes it difficult to compare studies, particularly if contrary results are obtained.

Another problem is the lack of baseline studies of metal content for a wide range of lichen species. As indicated in Table 3, certain species show zinc toxicity, whereas others show a tolerance to, or even an affinity for, zinc-rich substrates. Clearly, considerably more research is needed in this area before lichens can be used as an effective indicator plant.

An additional problem is how the metals are bound in the lichens. For example, Pb is firmly bound to extracellular sites, whereas most Zn is loosely held in soluble sites in the thallus (Brown, 1976). As a consequence, Zn levels will remain constant as the lichen ages, whereas Pb content will increase with age (Schwartzman *et al.*, 1987). Trapping efficiencies vary considerably between both lichen species and elements, and more information is needed on the subject before lichens can be considered as reliable biogeochemical indicators for certain elements.

The most promising studies are those of Easton (1976), Czehura (1977), and Purvis *et al.* (1987), who document colour changes associated with Fe or Cu absorption in *Lecanora* and *Lecidea* spp.; and Easton (1976) and Osterman and Wessels (in prep.), who document an association between orange *Xanthoria* sp. and Fe and Zn minerals. In both these cases, the distinctive colouration or colour change allows use of the technique directly in field mapping, in contrast to many other studies that use lichens solely as a biogeochemical indicator.

Certain lichens have been identified as having substrate preferences and, therefore, they may be useful either as indicator plants in mapping or mineral exploration. Further, the observation that many lichens produce oxalic acid ($xC_2H_4.nH_20$ compounds, where x may be Fe, Mn, Mg or Ca, n may be 1 or 2; *cf.*, Jones, 1988), and consequently, have

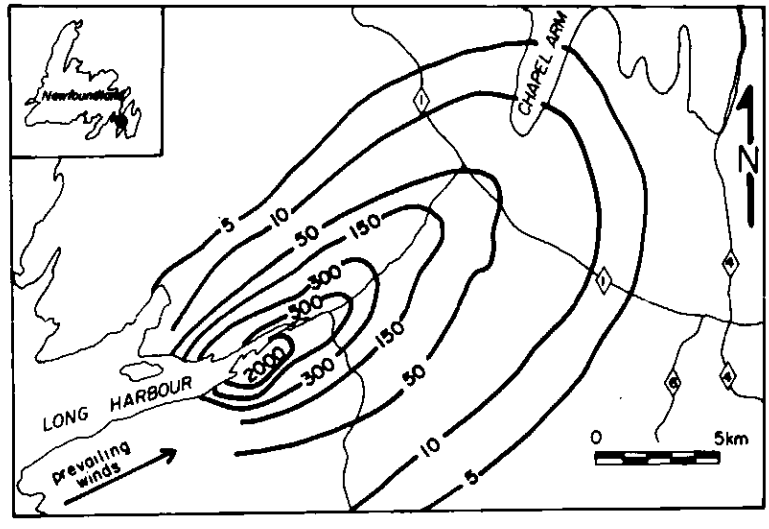

Figure 5 *Composite isopols showing maximum limits of concentrations (ppm dry weight) of total fluoride in samples of* Cladina rangiferina *in 1975. Point source of pollution is the Long Harbour phosphorous plant (modified from Roberts and Thomson, 1980).*

the ability to form metal-oxalate or metal-organic complexes, suggests that it is possible to determine which metals may be preferentially enriched in lichens. Using the Irving-Williams rules that state that the stability of metal-organic complexes is independent of the nature of the co-ordinated ligand or number of ligand molecules involved, Purvis *et al.* (1987) suggest that the divalent cations most likely to form complexes, in order of stability, are: Pt, Pd, Hg, Be, Cu, Ni, Co, Pb, Zn, Cd, Fe, Mn, Ca and Sr. It may not be coincidental that many of the substrate preferential lichens show an affinity for the more stable of these elements (*e.g.*, Cu, Ni, Pb, Zn, Cd). The following sections provide a brief description of the more useful lichen indicators.

Chalcophile lichens. There is increasing evidence that several lichen species show a preference for copper-rich substrates, with some showing colour changes in the thallus that can be related to copper content. As such, these species constitute the most promising lichen indicator plant.

Czehura (1977) documented a progressive colour change from yellow green to green-rimmed to green thallus colour with increasing copper content for *Lecanora cascadensis*, a foliose lichen (Fig. 6). (Ryan and Nash [1993] suggest that *L. cascadensis* is a synonym of *L. garovaglii*.) Czehura (1977) also documented copper enrichment in the lichen thallus (4 wt. % Cu in ash *versus* 1 000-2 000 ppm Cu in adjacent soils). Other *Lecanora* species in Britain and Scandinavia associated with copper-rich substrates are *Lecanora epanora* and *L. handelii* (the latter occurs only on shaded substrates [Purvis and James, 1985]) and *L. vinetorum* (Poelt and Huneck, 1968).

Several species of lecideaceous lichens in Britain and Scandinavia also show an affinity to copper-rich substrates (substrates containing copper-

TABLE 3 Key studies of lichens as indicator plants or biogeochemical indicators in mineral exploration.

Reference	*Metals*	*Comment*
Rosenkvist, 1950 in Brooks (1983)		first to suggest use as an indicator plant
LeRoy and Koksoy (1962)	Cu, Cr, Ag, Pb, Mo, Ni, Sr, Sn, U, V, Zn, Be	metal content of lichens reflects content in sandstone substrate, revives idea of lichens as indicator plants in mineral exploration
Lounamaa (1956, 1965)	Fe, Mn, Ni, Zn	lichens growing on serpentinite in Finland contain high Ni; *Umbilicaria pustulata* selectively absorbs Zn
Yliruokanen (1975); Erametsa & Yliruokanen (1971a, b)	U, Th, Pb, REE, Mo, Y	trace elements in lichens similar to contents in substrate, particularly Mo and U; U enriched in *Cladonia alpestris;* U enrichment very proximal to the deposit; REE values reported for six species of lichens
Brown, 1973 in Brooks (1983)	Pb	Pb enrichment in *Sterocaulon pileatum* growing at old lead mines
Seaward (1973)	Fe	*Peltigera rufescens* near steel mills absorbs iron (up to 9 %) near mills; contamination by iron is an airborne, not a substrate effect
Seaward (1974), Nash (1975), Garty *et al.* (1979)	Zn	zinc toxic to certain lichen species, including *Hypogymnia physodes,* and *Caloplaca citrina*
Easton (1976)	Fe	*Tremolecia atrata, Lecidea lapicida f. ochracea, Porpidia macrocarpa var. oxydata* change from grey to orange in vicinity of iron deposits in Back River area, N.W.T.; colour change may be related to runoff rather than substrate
Easton (1976), Hansen and Graff-Petersen (1986)	Fe	*Xanthoria elegans* prefers iron formation or iron meteorites and is commonly fracture controlled
Tomassini *et al.* (1976)	Cu, Ni, Fe, S	reported high Cu levels at Contwoyto Lake, N.W.T in lichens; copper prospect later discovered by exploration company; saxicolous species absorbed more metals than terrricolous species
Czehura (1977)	Cu	*Lecanora casadensis* changes colour from pale green to dark green over copper deposits in Lights Creek area, California
Purvis (1984) Purvis *et al.* (1985) Purvis & James (1985) Purvis *et al.* (1987)	Cu	descriptions of several chalcophile and ferruginous lichen floras, Cu bound as oxalate compounds
Quihot (1988)	Au	reports gold values of 317 ppb and 1089 ppb in thallus of the Antarctic lichen *Usnea auratiaco-atra*
Hansen (1991)	Pb-Zn	description of flora near an old zinc mine in Greenland; no distinctive characteristics noted
Osterman & Wessels (in prep.)	Zn	*Xanthoria* sp. favours outcrops containing smithsonite

minerals such as chalcopyrite), and include *Lecidea lapicida* s. lato (including *L. lactea* and *L. theiodes*), *L. lithophilia, L. inops,* and *Miriquidica* (*"Lecidea"*) *atrofulva* (Purvis *et al.*, 1987; Purvis and James, 1985; Purvis, 1984). Some show colour variations as well, and thickening and changes in thallus shape and texture are common on copper-rich substrates (Purvis and James, 1985). Purvis *et al.* (1987) also report that *L. bullata* changes colour from white to yellow green on copper-rich substrates. One problem with the aforementioned studies on *Lecidea*, is that analytical data for copper is only reported from the lichens, not the substrate, thus the magnitude of copper-enrichment in the lichen thallus *versus* the substrate is unknown. Despite this uncertainity, copper contents in ash of 2 wt. % to 16 wt. % from lichen thalli clearly indicate some enrichment compared to the substrate.

The crustose lichens *Acarospora smaragdula* and *A. rugulosa* are also common on copper-rich substrates (again, no analyses on substrate concentration of copper is provided) in Britain and Scandinavia (Purvis and James, 1985; Purvis 1984). Purvis *et al.* (1985) report a colour change from reddish-brown through pale-yellow to lime-green in samples of *A. smaragdula* from Scotland growing on copper-rich surfaces, and suggest that the species *A. isortoqensis* and *A. undata* are simply colour variants of *A. smaragdula*. In West Greenland, Alstrup and Hansen (1977) found that three species, namely, *Lecanora polytropa, Pseudephebe pubescens*, and *Umbilicaria lyngei*, were able to live on copper-rich surfaces.

Purvis (1984), Purvis *et al.* (1987), and Chisholm *et al.* (1987) document the presence of copper oxalate complexes in the lichens growing on copper-rich substrates, and structural changes in the cortex, suggesting interaction with the substrate. Purvis *et al.* (1990) also report copper-psoromic acid compounds in lichens from cupriferous substrates, suggesting that more than one type of lichen acid may be involved in binding metal compounds in lichen thalli. An unanswered question, to which there may be more than one answer depending on the species involved, is why there is a preference for a copper-rich substrate. Factors involved in this preference include: 1) is the species acidophilic, 2) is the species copper-tolerant or copper-dependent, or 3) is the species prevalent simply because competition with other species was reduced? The work of Purvis (1984), Purvis and James (1985), and Purvis *et al.* (1987) suggests all these factors may be involved. Regardless of the reason for the affinity, the spatial association between these lichen species and flora can be effectively used as in geobotanical exploration.

Of related significance is the fact that some of these species also show a preference for rusty-weathering zones (Purvis and James, 1985), and colour changes associated with iron-rich substrates have been noted for several species of *Lecanora* and *Lecidea* lichens, as discussed next. This suggests an ability of these species to bind a variety of metals, and the resulting colour changes make these lichens particularly useful as indicator plants.

Ferruginous lichens. Several species of lecideaceous crustose lichens (*e.g., Porpidia macrocarpa* and *Lecidea lapicida*) have "oxidized" forms on rocks containing iron, or where subjected to ferrous iron runoff (Brodo, 1973; Easton, 1976) (Figs. 7, 8). In these forms, iron is absorbed by the thallus and laid down in the cortex as red-orange iron oxide (Weber, 1962). A few species are only found in "oxidized" states (*e.g., Rhizocarpon oederi* and *Tremolecia atrata* [syn. *Lecidea dicksonii*]).

In Britain, Purvis and James (1985) note several other ferruginous lichens, including *Miriquidica atrofulva, Micarea lutulata, Scoliciosporum umbrinum*, and *Acarospora sinopica*. Rambold and Schwab (1990) also report rusty-coloured species of *Miriquidica* in Norway. Many of the same species are associated with rusty rock surfaces in West Greenland (Hansen, 1991). Some of the same species, or related species, are also associated with copper-rich substrates, as noted above. Consequently, it may be possible to define local floras (Fig. 9) associated with mineralization.

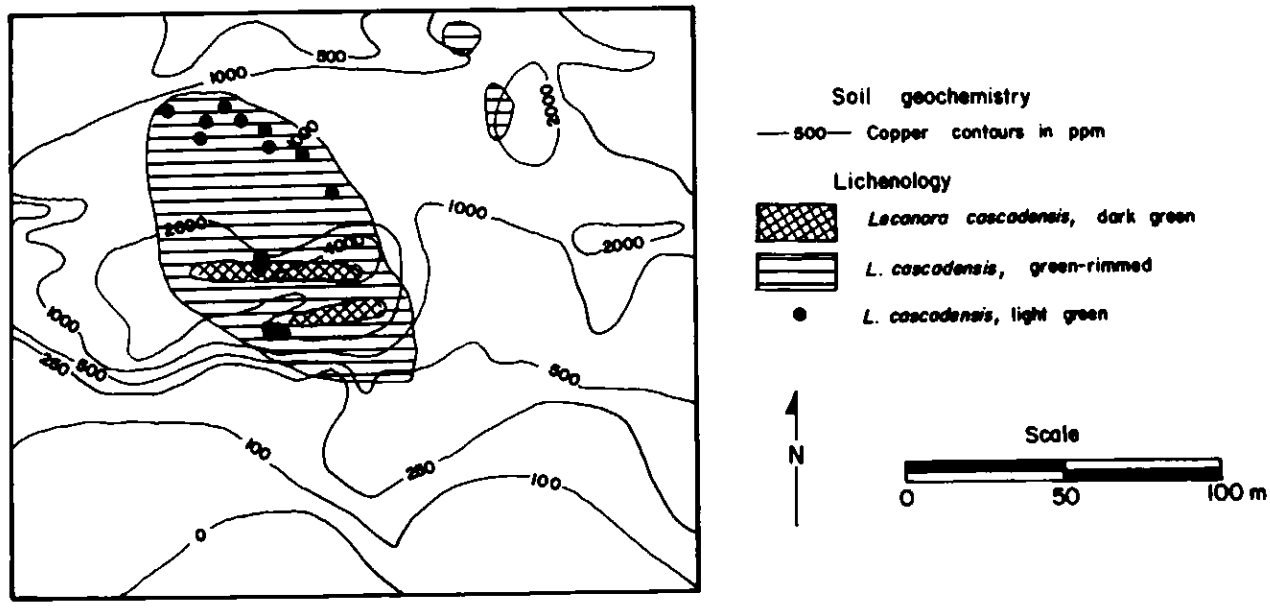

Figure 6 *Geobotanical map showing distribution of* Lecanora cascadensis *and copper anomalies in the Lights Creek District, California. Host rocks are Jurassic and Triassic metavolcanic rocks (modified from Czehura, 1977).*

Most studies (*e.g.*, Purvis, 1984; Purvis and James, 1985) have focussed on examination of floras at abandoned mine sites. The studies of Easton (1976) and Czehura (1977), however, demonstrate the potential use of these floras over broader areas of lower elemental concentration in the substrate.

Xanthoria elegans (Fig. 10) has been reported to show an affinity for iron-rich (generally magnetite) substrates (Easton, 1976; Hansen and Graff-Petersen, 1986). *Xanthoria*, however, is found on a variety of substrates, and its distribution is commonly influenced by fractures (Fig. 10; Easton, 1976; Hansen and Graff-Petersen, 1986) and extrenal enrichment (pH, nitrogen, phosphorous [as in "bird rock" habitats], *etc.*). The bright orange colour in *Xanthoria elegans* is not related to iron compounds, however, but is due to the presence of hydroxy-anthraquinones, lichen-produced organic compounds (Culberson, 1969).

Calcicolous and magnicolous lichens. Lichens showing affinities to calcium- or magnesium-rich substrates are referred to as calcicolous or magnicolous lichens, respectively. In the case of calcicolous lichens, calcium seems to be a limiting factor in development; consequently, these lichens show a preference for Ca-rich substrates, most commonly limestones. Indeed, distinct calciphile floras exist, and many species of lichens are calcicolous, showing a wide range of "calciphily" (Brodo, 1973; Hertel, 1967). Not surprisingly, many calcicolous lichens are endolithic. Several studies indicate clear distinctions

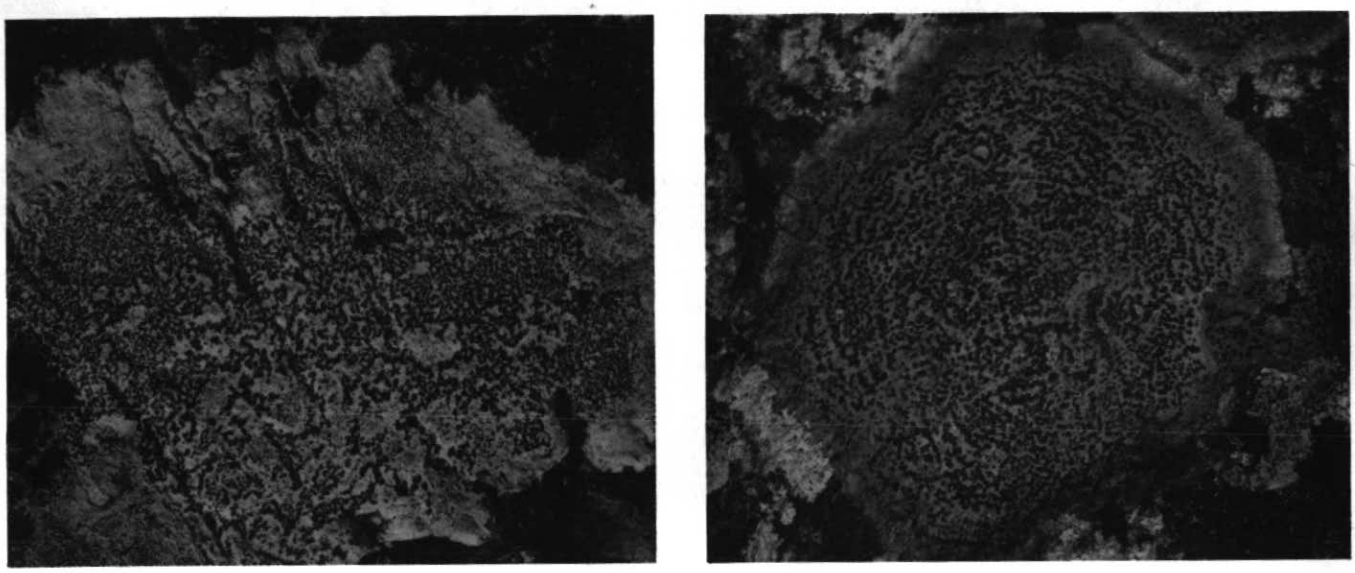

Figure 7 *Colour variations in oxidized lichen species, 1.* (**A**) *Typical, grey-coloured, Porpidia macrocarpa* growing on dacite, Back River area, Northwest Territories. (**B**) Porpidia macrocarpa *var. oxydata growing on dacite, Back River area, Northwest Territories. Note significant colour change compared to* (**A**).

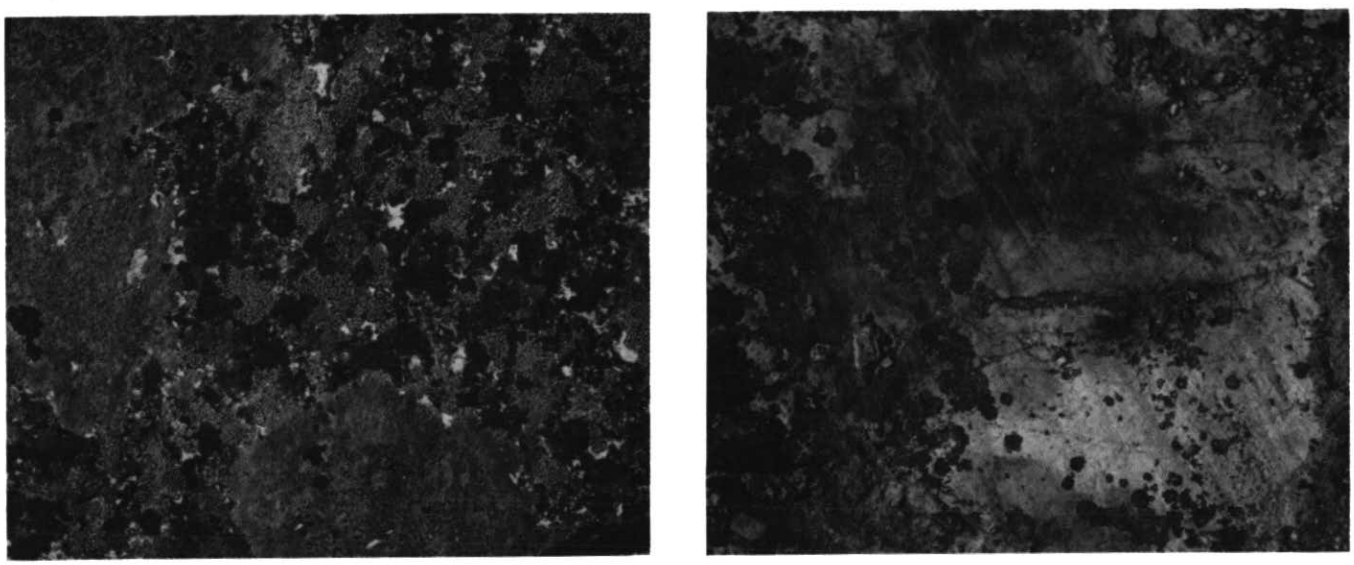

Figure 8 *Colour variations in oxidized lichen species, 2.* (**A**) *Typical lichen cover for a rhyolite includes* Lecidea *sp. (large, grey),* Rhizocarpon disporum *(small, dark grey),* R. geographicum *(green), and* Umbilicaria deusta *(black, raised relief). Back River area, Northwest Territories.* (**B**) *Lichen cover for a pyrite-bearing rhyolite, 50 cm north of* (**A**). *Note the abundance of the orange-red lichen* Tremolecia atrata.

between flora present on limestones *versus* dolostones (Gilbert, 1984; Steele, 1955; Ferreira, 1963; Cooper and Etherington, 1974). Dormaar (1968) found that a specimen of *Caloplaca* growing on dolomite showed no indication of Mg or carbonate, yet was rich in calcium. This suggests a differential ability to absorb calcium, and suggests that distinctive magniphile flora may also exist. Whether these distinctive carbonate flora can be used in exploration has not been attempted.

Other substrate specificities. A few species have been identified as serpentinite specific (*e.g., Rhizocarpon sphaericum, Aspicilia serpentinicola, A. polychroma* var. *ochracea,* and *A. crussi* (Ritter-Studnicka and Klement, 1968, cited in Brodo, 1973). Whether this reflects a tolerance for heavy metals such as Cr or Ni, or an ability to colonize rapidly weathering surfaces, or both, is not clear. Magnesium oxalate compounds have also been reported from lichens growing on serpentinite (Adamo *et al.*, 1993; Wilson *et al.*, 1980, 1981) although magnesium enrichment has not been reported in lichen thalli growing on such surfaces. From a mapping perspective, serpentinites generally have distinctive weathering patterns and rock associations, and thus, the presence of a distinctive lichen flora is not likely to be of use in mapping.

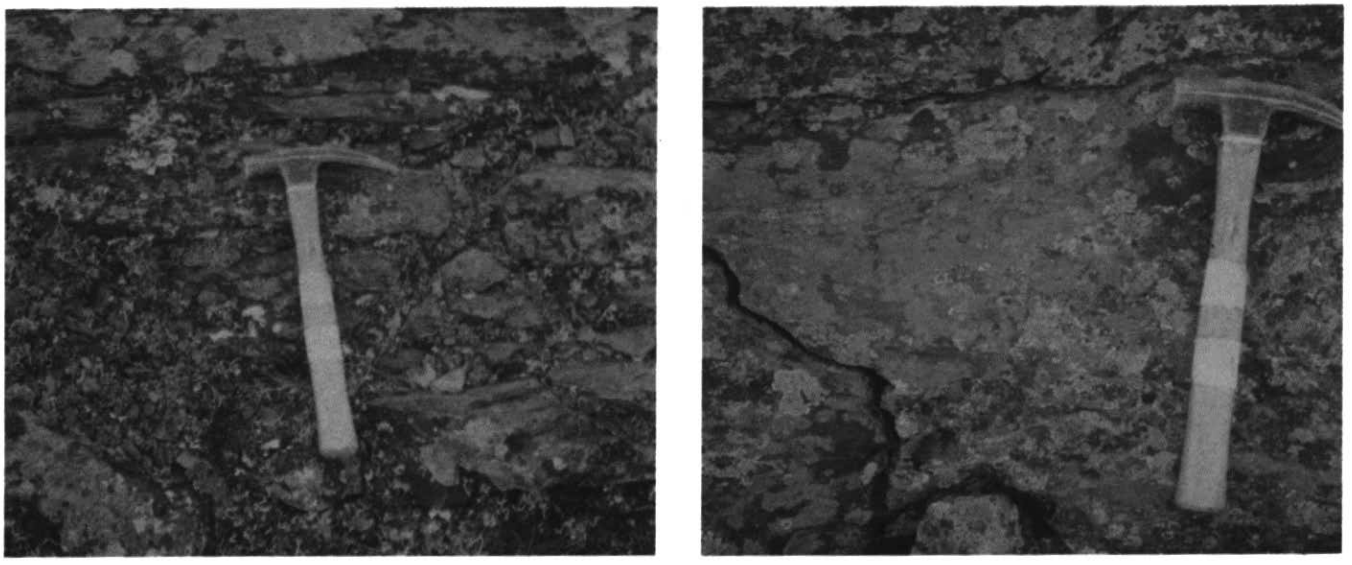

Figure 9 *Colour variations in oxidized lichen species, 3.* (**A**) *Typical lichen cover for an argillite. Back River area, Northwest Territories. Note only minor colour change.* (**B**) *Lichen cover for a pyrite-bearing argillite, 15 metres north of* (**A**). *Note the abundance of the orange-red lichen* Tremolecia atrata.

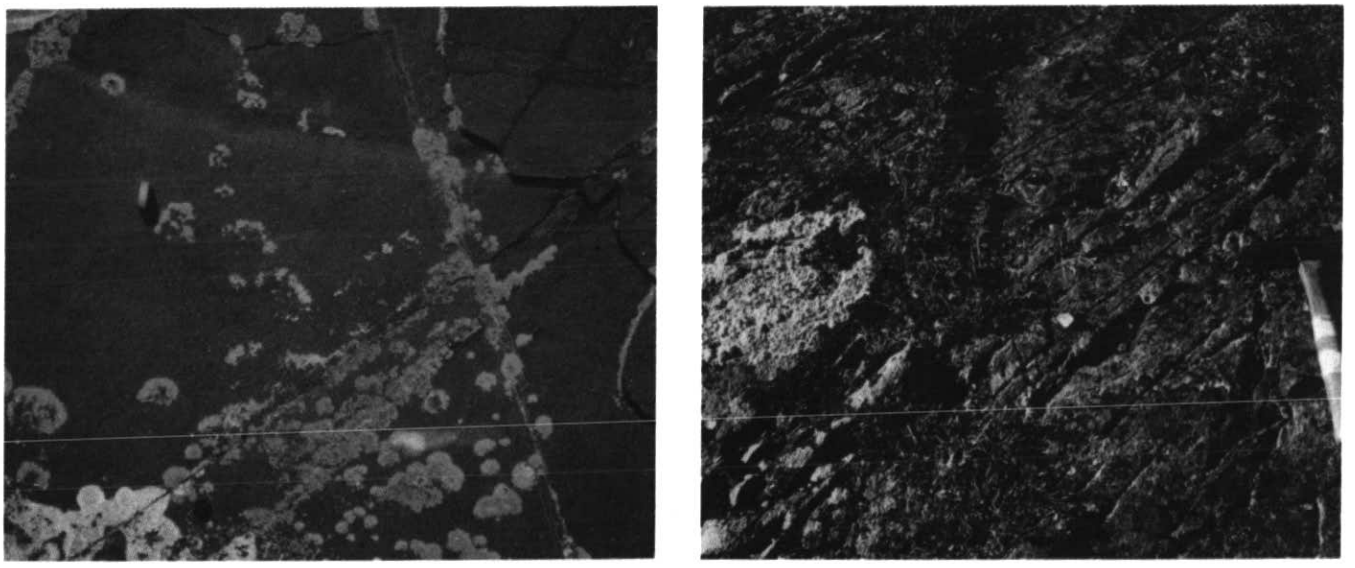

Figure 10 Xanthoria elegans *growing on magnetite iron-formation, Back River area, Northwest Territories. View is of a vertical surface. Note also fracture-control on lichen distribution. Magnet in upper left hand corner is 2 cm long.*

Figure 11 *Contrasting lichen floras on a gabbro dyke (1 metre wide) and a feldspar porphyritic andesite. Note abundance of* Lecanora argopholis *(large lichen, left centre) on the andesite and its absence on the gabbro. Back River area, Northwest Territories. Table 4 summarizes the lichen species on the dike* versus *the andesite.*

Lichens showing an affinity for granitic and siliceous rocks are *Rhizocarpon geographicum* (Brodo, 1973; Easton, 1976), some species of *Umbilicaria*, and *Xanthoparmelia conspersa* (Brodo, 1973).

The effect of zinc on lichens is varied. Osterman and Wessels (in prep.) document an association of *Xanthoria* spp. and smithosonite outcrops in Namibia, and also report the precipitation of zinc in the lichen thallus. Zinc absorption has also been reported in *Umbilicaria pustulata* (Lounamaa, 1965). Zinc toxicity has been described by Seaward (1974), Garty *et al.* (1979), Nash (1975) and Osterman (written comm., 1993). The data so far show that certain species may prefer zinc-rich substrates, and thus effective geobotanical indicators may be found.

In contrast to these substrate specific species, there are several species that have very low substrate preferences. Examples are *Xanthoria parietina* and *Parmelia sulcata* (Brodo, 1973).

The Use of Lichens in Geologic Mapping

The only investigation of lichens solely as a geological mapping tool in Canada was conducted by Easton (1976, 1977) above the tree line in the Northwest

Figure 12 *The effect of different weathering rates on lichen floras. Note the lack of lichen cover on the rapidly weathering mafic volcanic fragment compared to the resistant surrounding dacite. Back River area, Northwest Territories.*

Figure 13 *Fracture-oriented lichen growth along cleavage planes and glacial striae in a argillite and siltstone sequence in the Back River area, Northwest Territories. Bedding is oriented 135°/75° (horizontal in photo), prominent cleavage defined by* Lecanora polytropa *and* Umbilicaria *sp. trends 150°/80° (diagonal), faint glacial striae defined by* Umbilicaria *sp. trends 205°/85° (near vertical).*

Figure 14 *Fracture-oriented lichen growth along cleavage planes in a metaconglomerate near Noranda, Quebec. In this instance, the fractures have influenced thallus shape.*

Figure 15 Umbilicaria *sp. growing along pillow selvedges in a pillowed, andesite flow, Back River area, Northwest Territories.*

Territories in the Archean Slave Province. This area was selected because the absence of trees and uniform topography reduced shading and topographic effects as significant influences on lichen distribution. This is consistent with the results of Armstrong (1981), who found microtopographic effects to be significant in controlling colonization of rock surfaces by lichens. Distinctions could be made in characteristic floras found on various rock types, as shown in Figure 11 and Table 4. These changes, however, were commonly subtle and difficult to detect, and, consequently, of little use in mapping except for the various ferruginous floras (Figs. 7, 8, 9, 10) already discussed, that were associated with iron formations and sulphide-occurrences in the study area.

Easton (1976) also found that microtopographic features were more significant than the composition of the substrate in controlling lichen flora. Such effects include differential weathering (Fig. 12), fracture-controlled growth (Figs. 13, 14), hardness and grain size (Fig. 8a, *Rhizocarpon* sp. and *Parmelia* sp. showed an affinity for fine-grained, silicic rocks), and differential weathering along primary textures such as pillow selvedges (Fig. 15).

Hansen and Dawes (1990) examined the relationship between saxicolous lichen communities and rock substrate at Qaanaaq (Thule) in northwestern Greenland and noted seven distinct floral communities, three of which had discrete host rock associations. All three rock-specific communities showed an affinity for iron-rich substrates and included species common to the ferruginous lichen group discussed above. The communities included an *Acarospora sinopica-Tremolecia atrata* community on ironstones, and *Acarospora chlorophana* and *Arctoparmelia incurva* communities associated with iron-rich sandstones. Although Hansen and Dawes (1990) did not use these communities in mapping, their study demonstrates the ability to recognize distinctive, substrate-specific, communities.

The only other mapping study of this type was conducted by Boyle *et al.* (1987) in Ireland, who documented two distinct flora present on exposures of the Creggaun Gabbro in Ireland. One phase of the gabbro, the "green gabbro" was characterized by large crustose thalli, large areas of rock without lichen growth (5-20% lichen coverage), and a restricted flora of 15 species. In contrast, the "lichen gabbro" had a diverse flora (53 species) and typically exhibited 75% to 100% coverage of the rock surface. Boyle *et al.* (1987) found that the lichen gabbro had significantly higher contents of Zr, P, Ti and Cr, and that apart from the differences in lichen flora, the two gabbros could not be distinguished in the field. Boyle *et al.* (1987) speculate that the distribution of the lichens was a result of increased weathering of the "lichen gabbro" after lichen colonization, perhaps related to the release of lichen compounds such as oxalic acid, and not due to chemical affinity. This remains the only study resulting in a significant new finding due to the geological mapping of lichens. It does illustrate, however, the potential rewards of geobotanical mapping using lichens or other species.

Thus, certain lichen species, possibly restricted in their geographic extent, have shown that they are excellent (local) indicator plants, either of the mineralogy of the underlying substrate or of atmospheric pollution. As our knowledge of lichen-substrate relationships improves, so will our ability to apply lichen occurrence to pollution monitoring, geologic mapping, and mineral exploration.

Table 4 Lichen species recorded across a 3-metre-long transect across the gabbro dike shown in Figure 11. Lichens listed in order of abundance.

Gabbro	*Andesite*
Lecidea sp.	*Lecanora argopholis*
Miriguidica graovaglii	*Rhizocarpon geographicum*
Lecanora rupicola	*Umbilicaria deusta*
Umbilicaria deusta	*Umbilicaria krascheninnikovii*
U. hyperborea	*Rhizocarpon disporum*
Rhizocarpon geographicum	*Parmelia* sp.
R. disporum	*Physcia* sp.
Lepraria sp.	*Collema* sp.
	Lecidea sp.

ACKNOWLEDGEMENTS

This paper has benefited from detailed reviews by Irwin Brodo and Chris Osterman. Irwin Brodo is also thanked for his considerable efforts in ensuring correct lichen nomenclature throughout the paper, although the author bears full responsibility for any errors or omissions.

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Accepted as revised, 15 January 1995.