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Microbiology, Ecology and Microclimatology of Soil Sites in Dry Valleys of Southern Victoria Land, Antarctica*

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I. Introduction

The investigation of Antarctic dry valleys has been undertaken in preparation for detection of life in extraterrestrial environments. These valleys are useful study areas prior to searching for life in Martian soils because of low temperature, low humidities, diurnal freeze-thaw cycles even during daylight hours, low annual precipitation, desiccating winds, high sublimation and evaporation, high radiation, low magnetic field, absence of higher life forms, and the irregular distribution and low abundance of soil micro-organisms. However, the environment of the Antarctic dry valleys is more favourable than Mars because of the large quantity and proximity of water (ocean and sea ice, lakes, glaciers, snow and ice fields and the shallow depth to permafrost), comparatively lower solar radiation flux, abundance of oxygen, higher barometric pressure, and the proximity of sources of microbial colonists and greater opportunity for their influx, although man has only relatively recently arrived in Antarctica. The dry valleys also provide a wider variety of ecological habitats, which are expected to be more limited in the harsher Martian environment.

For our study in Antarctica, five sites were established for approximately one-week periods during austral summers 1966–67 and 1967–68 in McKelvey, Victoria, Taylor, Wheeler, King and David Valleys. Environmental measurements of soil and air temperature, relative humidity, dew point, wind direction and velocity, solar and environmental radiation flux, net thermal exchange, evaporation rate, light intensity, barometric pressure and cloud cover, were made either continuously or every three hours. Additional sites

* This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration. Logistic support and facilities for this study in Antarctica were provided by the Office of Antarctic Programs, National Science Foundation.

in these and other dry valleys were investigated during both summers, and approximately 150 samples were collected from seventy-five sites.* Samples were collected from the surface to depths of hard, icy permafrost (ice-cemented soil) using aseptic techniques developed for sampling, handling, and processing of desert soils (Cameron 1968*a*; Cameron *et al.*, 1966).

Soil physical, physico-chemical and chemical analyses were performed for many of the samples, including mineralogy, mechanical analysis, bulk density, porosity, reflectivity, *in situ* moisture and moisture constants, gases, weight loss on ignition, cation exchange capacity, buffer capacity, pH, Eh, electrical conductivity, elemental abundance, ionic concentrations, inorganic and organic C, H, N and their ratios.

Abundance and distribution of general and specific groups of soil microorganisms were determined by direct inoculation of soil on to agar plates, or by spread plate and dilution culture techniques designed for the investigation and study of low abundances of desert soil micro-flora (Cameron, 1967, 1968*b*; Hall, 1968; Benoit and Hall, 1970, this symposium). Tests were performed at various temperatures (ranging from + 2°C to + 55°C) for aerobic, microaerophilic and anaerobic bacteria, lactose fermenters, nitrate reducers and coliforms. Additional media were used to detect and enumerate actinomycetes (streptomycetes), fungi and algae.

II. Results and Discussion

A. Environmental

During the summer months, when there is a period of continuous daylight, there are diurnal fluctuations in environmental parameters for most of the area within the valleys, not only because of the low angle of incident solar radiation, but because of the interference of mountains surrounding the valleys, which have also been deepened by glaciation. Typical midsummer diurnal temperature, relative humidity, and incident light intensity curves for Wheeler Valley, a North-South oriented valley at 1000 to 1500 m are shown in Fig. 1. Air temperatures were below freezing, although the soil, which absorbed radiation, was above freezing to a depth of approximately 8 cm during periods of incident radiation. Soil thaw was not observed below approximately 10 cm. Although the air frequently had a low relative humidity, the relative humidity of the soil generally increased with proximity to the boundary of hard, icy permafrost and was correlated to some extent with the abundance of microflora. Air relative humidity was correlated with wind velocity and direction. For example, in King and David Valleys a decrease in air and soil surface relative humidity followed a shift in wind direction and

* Some sites were investigated in co-operation with Prof. Robert E. Benoit, Virginia Polytechnic Institute, Blacksburg, Virginia (Benoit and Cameron, 1967).

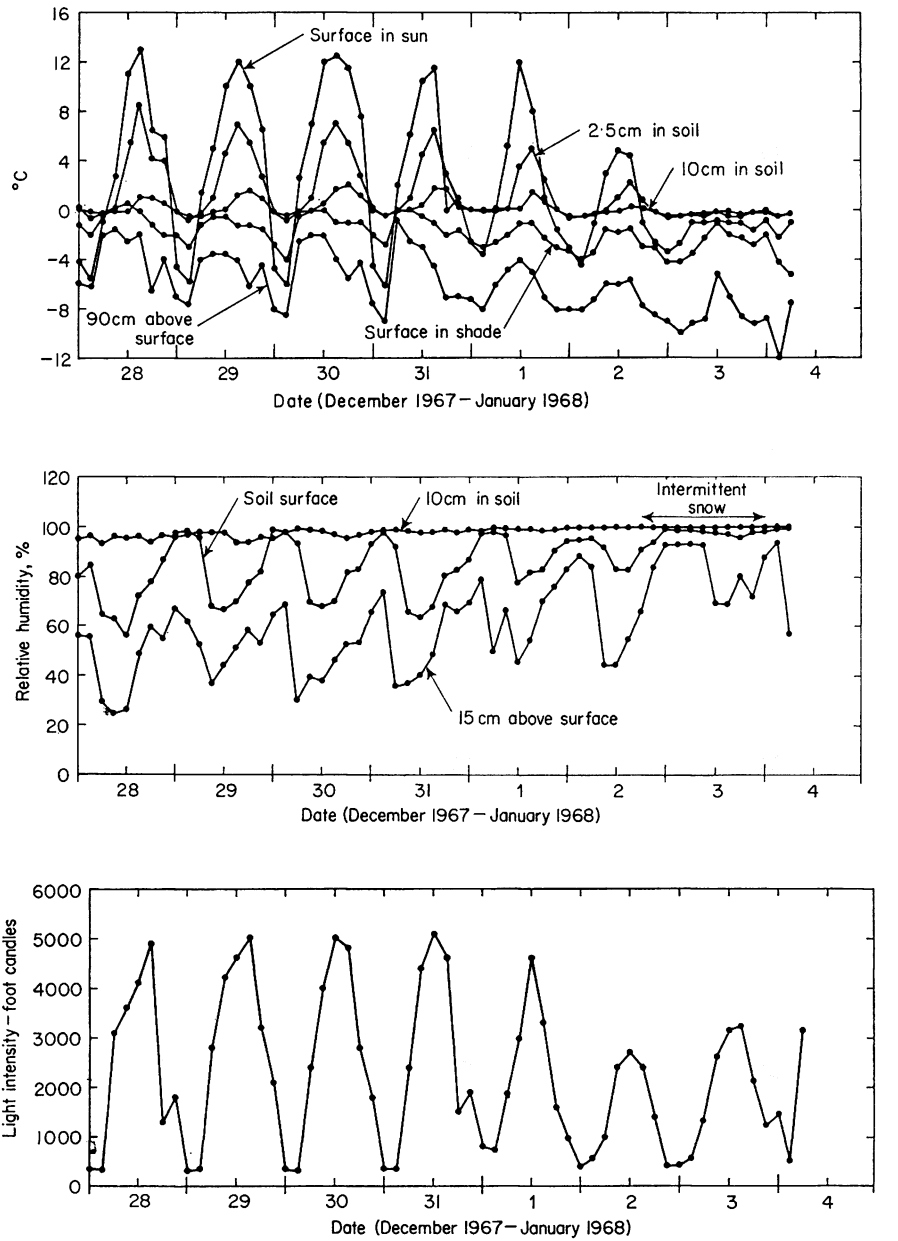

FIG. 1. Diurnal temperature (upper), relative humidity (centre) and light intensity (lower) curves in Wheeler Dry Valley at 1000–1500 m between December 28 1967, and January 4 1968.

an increase in wind velocity (Fig. 2.). Additional information about dry valley climatology has been given by Bull (1966).

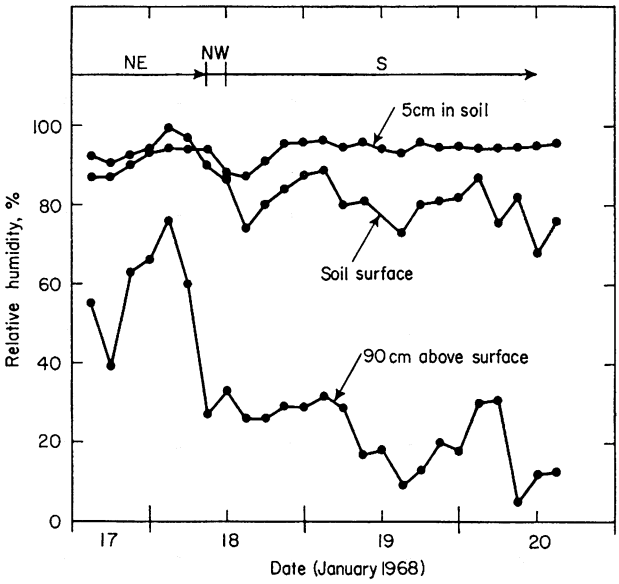

FIG. 2. Changes in air and soil relative humidity in King and David Valleys following a change in wind direction. Wind velocities increased during the period of observation.

B. SOIL PROPERTIES

Soils in the valleys are primarily oxidized desertic saline or alkaline sands and loams with pH values above 7. They are generally overlain by desert pavement, are shallow and show little, if any, profile development. A hard, icy permafrost layer of ice-cemented soil usually occurs at 10–30 cm. Salts, primarily of Na, Ca, Mg, Cl, SO_4, CO_3 and NO_3, may accumulate. Electrical conductivity, buffer capacity and cation exchange capacities are variable, but are within the range of values obtained for other coarse-textured desert soils (Cameron, 1966). Organic N and C levels are the lowest to have been reported for desert soils (Cameron and Blank, 1963). The nature of this organic matter and its origin is not well understood, although it may be old carbon, such as coal. Typical values of ten soil samples collected along a traverse east of the Matterhorn Glacier are cited in Table 1. Available moisture is a limiting factor in most of these soils, although the concentration and balance of ions, and solubility of trace elements, such as boron, are also detrimental, e.g. soil sample No. 664 (Cameron *et al.*, 1968*a*). Additional information and a discussion of Antarctic dry valley soils has been given by Claridge (1965), Tedrow and Ugolini (1966) and by Ugolini (1970, this symposium).

TABLE 1

Properties of Samples from Ten Sites east of Matterhorn Glacier

Sample No.	*Sample depth*	*Texture*	*H_2O in situ %*	*pH Sat. Paste*	*Electrical conductivity EC × 10^6 mhos/cm² at 25°C Sat. paste*	*H_2O soluble ions in 1 : 5 Extract ppm**			*Organic %†*	
						Nitrate	*Sulphate*	*Chloride*	*N*	*C*
661	Surface 2 cm	Sand	0·6	7·6	640	3	72	14	0·008	0·02
662	2→10 cm	Sand	1·0	8·0	520	0	48	18	0·005	0·01
663	Surface 2 cm	Sand	1·4	7·8	1360	10	380	41	0·006	0·04
664	Surface 2 cm	Sandy loam	5·0	8·9	10,000	130	450	2340	0·007	0·04
665	Surface 2 cm	Sand	0·6	7·9	128	0	6	9	0·006	0·04
666	2→10 cm	Sand	0·8	8·0	91	0	4	4	0·006	0·02
667	Surface 2 cm	Sand	1·8	7·5	1420	56	660	496	0·002	0·02
668	2→10 cm	Sand	1·5	7·5	3280	80	950	798	0·003	0·02
669	Surface 2 cm	Loamy Sand	0·8	7·7	5440	640	980	1575	0·001	0·03
670	2→10 cm	Sandy loam	1·5	7·7	5120	400	1160	1525	0·002	0·02

*Analyses by E. S. Babcock and Sons, Riverside, California.
†Analyses by Elek Microanaltical Labs, Torrance, California.

C. MICROBIOLOGY

The number of micro-organisms in samples from the various valleys varied widely from essentially zero to approximately 10^7 per gram of soil. The level of abundance was usually low compared with previously investigated desert soils (Cameron, 1966). The absence or presence of microflora in a number of samples was substantiated by ^{14}C substrate enrichment and radiorespirometric techniques (Hubbard *et al.*, 1968). The highest abundances were generally found at sites in Wheeler Valley (Table 2). Typical values for the Matterhorn Valley are shown in Table 3. Pertinent data concerning plating, media composition, incubation temperatures and the halophilic and psychrophilic nature of Antarctic microflora have been presented previously (Hall, 1968; Benoit and Hall 1970, this symposium). Results of prolonged incubation at high humidities for psychrophilic micro-organisms in these same samples are shown in Table 4.

As also shown previously (Cameron, 1967; Cameron *et al.*, 1968; Benoit and Hall, 1970, this symposium), as many, if not more, micro-organisms were found in subsurface soils, especially at the level of hard, icy permafrost, as in the surface layers. The ratio of surface to subsurface abundance for eighteen sites is shown in Fig. 3. For five sites, shown above the diagonal line, the abundance of micro-organisms was greater at the surface. For thirteen sites, shown below the diagonal line, the abundance of micro-organisms was greater below the surface. The subsurface bacteria were predominantly white, opaque translucent or non-pigmented colonies, whereas the chromogenic bacteria were most abundant at the surface. This abundance ratio is expressed in Fig. 4. The subsurface micro-organisms may represent an ancient "freeze-dried" microflora. Their dormancy is indicated by results of metabolic studies in which the subsurface soils were considerably less effective in dissimilating ^{14}C-labelled substrates than were the surface soils (Hubbard *et al.*, 1968).

The microflora populations were composed primarily of bacteria and included the following major groups: (1) gram positive cocci, *Micrococcus* and *Mycococcus* sp., (2) soil diphtheroids, *Corynebacterium*, *Brevibacterium*, *Arthrobacter* and related sp., (3) gram positive and negative rods, *Bacillus* and *Pseudomonas* sp., and (4) actinomycetes, primarily *Streptomyces* sp.* The opaque or white colonies were usually soil diphtheroids or micrococci, and the translucent or non-pigmented colonies were gram positive or negative rods. Pigmented colonies were generally micrococci. Algal populations were composed of coccoid blue-green algae (*Anacystis* and *Coccochloris* sp.), oscillatorioid blue-green algae (*Schizothrix*, *Microcoleus*, and *Oscillatoria* sp.), and coccoid green algae such as *Protococcus grevillei*, resembling *Chlorococcum* sp. The fungi included various ascomycetes, e.g. *Penicillum* sp., and a few

* Bollen, W. B. and Byers, K. Microorganism Study of Bacteria and Actinomycetes from Harsh Environments, JPL Contract No. 950783.

TABLE 2

Numbers of Micro-organisms in Soil Samples from Wheeler Dry Valley (per gm soil)

Soil No.	*Sample depth*	*Aerobic bacteria*				*Anaerobes*	*Fungi*			*Protozoa*	*Algae*
							Moulds	*Yeasts*			
		+2°C	+20°C	+2°C	+20°C	*Room temp.*	+20°C	+2°C	+20°C	*Room temp.*	*Room temp.*
609	Surface 2 cm	$1{\cdot}8\times10^4$	2×10^4	2×10^4	$3{\cdot}2\times10^4$	0	20	0	0	200	2×10^3
610	2→15 cm	$4{\cdot}4\times10^4$	$4{\cdot}8\times10^4$	$6{\cdot}4\times10^4$	$1{\cdot}2\times10^5$	0	0	0	0	0	2×10^3
611	30 cm	$4{\cdot}8\times10^3$	$7{\cdot}8\times10^3$	$6{\cdot}2\times10^3$	$5{\cdot}8\times10^3$	1·5	0	0	0	0	20
612	60 cm	100	$1{\cdot}3\times10^3$	200	$2{\cdot}2\times10^3$	1	0	0	0	0	200
613	Surface 2 cm	4×10^4	2×10^4	1×10^4	3×10^5	0	0	0	0	40	800
614	2→10 cm	1×10^3	1×10^4	3×10^3	2×10^4	0	0	0	0	0	800
615	Surface 2 cm	$1{\cdot}5\times10^5$	$1{\cdot}2\times10^5$	$9{\cdot}6\times10^4$	$1{\cdot}5\times10^5$	0	200	2	0	40	$6{\cdot}4\times10^6$
616	2→10 cm	1×10^5	2×10^5	2×10^5	2×10^5	0	25	12	0	2	800
617	Surface 2 cm	200	3×10^3	2×10^3	2×10^3	0	35	0	0	0	2
618	2→10 cm	6×10^3	1×10^4	1×10^4	2×10^4	0	15	0	0	0	40
619	Surface 2 cm	1×10^3	8×10^3	8×10^3	1×10^4	0	50	0	0	0	40
620	2→10 cm	2×10^3	2×10^4	2×10^4	1×10^5	0	200	0	0	0	$1{\cdot}6\times10^3$
621	Surface 2 cm	1×10^3	3×10^3	4×10^3	2×10^4	0	0	4	0	2	$1{\cdot}6\times10^3$
622	2→15 cm	1×10^4	2×10^4	4×10^4	6×10^4	0	0	0	0	0	800
623	18→33 cm	500	1×10^3	1×10^3	3×10^3	0	0	0	0	0	40
Media		Trypticase soy agar		Salts (simulated Taylor Valley)+ yeast extract+ neopeptone		TSA in CO_2	Rose Bengal Agar	Dextrose-neopeptone agar pH 4·5		Thornton's salt medium	

TABLE 3

Numbers of Micro-organisms in Soil Samples from Matterhorn Valley (per gm soil)

Sample No.	*Sample depth*	*Aerobic bacteria*				*Anaerobes*	*Fungi*	*Algae*
		+2°C	+20°C	+2°C	+20°C	*Room temp.*		
661	Surface 2 cm	$3{\cdot}7 \times 10^2$	3×10^3	$3{\cdot}2 \times 10^2$	$1{\cdot}8 \times 10^4$	0	$2{\cdot}5 \times 10^2$	2×10^2
662	2→10 cm	20	4×10^4	<10	$1{\cdot}7 \times 10^5$	0	3×10^3	20
663	Surface 2 cm	0	$1{\cdot}6 \times 10^2$	$\sim 10^2$	2×10^3	0	0	20
664	Surface 2 cm	0	<10	0	<10	0	0	0
665	Surface 2 cm	<10	$2{\cdot}8 \times 10^3$	<10	$2{\cdot}5 \times 10^4$	0	0	20
666	2→10 cm	<10	$2{\cdot}7 \times 10^3$	<10	$1{\cdot}1 \times 10^3$	0	0	20
667	Surface 2 cm	<10	30	0	40	0	0	0
668	2→10 cm	<10	<10	0	<10	0	0	0
669	Surface 2 cm	180	90	<10	$2{\cdot}7 \times 10^2$	0	0	0
670	2→10 cm	$3{\cdot}5 \times 10^4$	$1{\cdot}4 \times 10^4$	<10	$4{\cdot}4 \times 10^2$	0	0	0
		Trypticase soy agar		Salts (Simulated Taylor Valley) + Yeast extract + Peptone		TSA in CO_2	Rose Bengal Agar	Thornton's Salt medium

TABLE 4

Results of Prolonged Incubation of Samples at High Humidities (numbers per gm soil)

Sample No.	*Sample depth*	*Incubation period*					
		6 weeks	*3 months*	*6 weeks*	*3 months*	*6 weeks*	*3 months*
661 (VPI 555)	Surface 2 cm	NGD	$2{\cdot}3\times10^{4}$	NGD	$3{\cdot}6\times10^{2}$	NGD	NGD
662 (VPI 556)	2→10 cm	NGD	$1{\cdot}1\times10^{6}$	$1{\cdot}1\times10^{2}$*	$3{\cdot}5\times10^{5}$	$1{\cdot}1\times10^{2}$*	1×10^{3}*
663 (VPI 557)	Surface 2 cm	NGD	$1{\cdot}5\times10^{3}$	NGD	$5{\cdot}2\times10^{3}$	NGD	NGD
664 (VPI 558)	Surface 2 cm	NGD	NGD	NGD	NGD	NGD	NGD
665 (VPI 559)	Surface 2 cm	NGD	$1{\cdot}2\times10^{4}$	NGD	$3{\cdot}2\times10^{3}$	NGD	NGD
666 (VPI 560)	2→10 cm	NGD	$1{\cdot}8\times10^{4}$	NGD	6×10^{3}	NGD	NGD
667 (VPI 561)	Surface 2 cm	NGD	NGD	NGD	NGD	NGD	NGD
668 (VPI 562)	2→10 cm	NGD	NGD	NGD	NGD	NGD	NGD
669 -	Surface 2 cm	NGD	NGD	2×10^{3}	$7{\cdot}2\times10^{3}$	NGD	NGD
670 -	2→ 10 cm	NGD	$7{\cdot}6\times10^{2}$	$6{\cdot}2\times10^{3}$	$2{\cdot}4\times10^{4}$	NGD	NGD
Media		M 12 (Taylor Valley soil extract + peptone + yeast extract)		Trypticase soy agar + Taylor Valley soil e2 sct		M 12+5% NaCI	

*=all counts refer to fungi only.
NGD=<40 bacteria/gm soil.
(Determinations by Prof. Robert E. Benoit, Virginia Polytechnic Institute, Blacksburg, Virginia. Results used with permission of Prof. R.E. Benoit.)

yeasts, e.g. *Candida* sp. No bacteriophages were found by means of the bacterial plaque technique. There was a positive correlation between the abundance of micro-organisms in a sample and the number of species represented (Fig. 4).

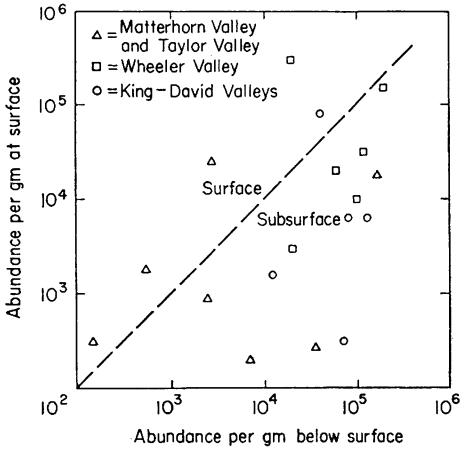

FIG. 3*a*. Relative abundance of micro-organisms in surface and subsurface soils.

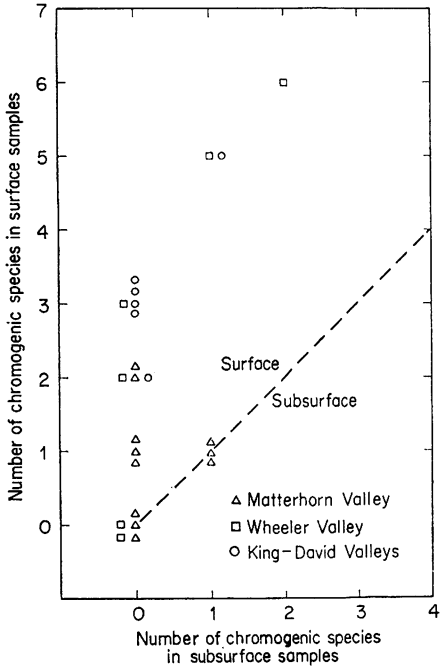

FIG. 3*b*. Relative abundance of chromogenic bacteria in surface and subsurface soils.

Neither coccoid blue-green algae nor coccoid bacteria have been found to be as abundant or as predominant in the soil microbial community in other desert soils. Characteristics of the Antarctic soil bacterial species are not easily resolved, but they appear to be most similar to those isolated from soils of the Chilean Atacama Desert. *Mycococcus* sp., found in Antarctica as well as Chile, also occur in high mountain soils. They exhibit pleomorphism which may possibly aid survival in harsh environments. A study of Antarctic soil

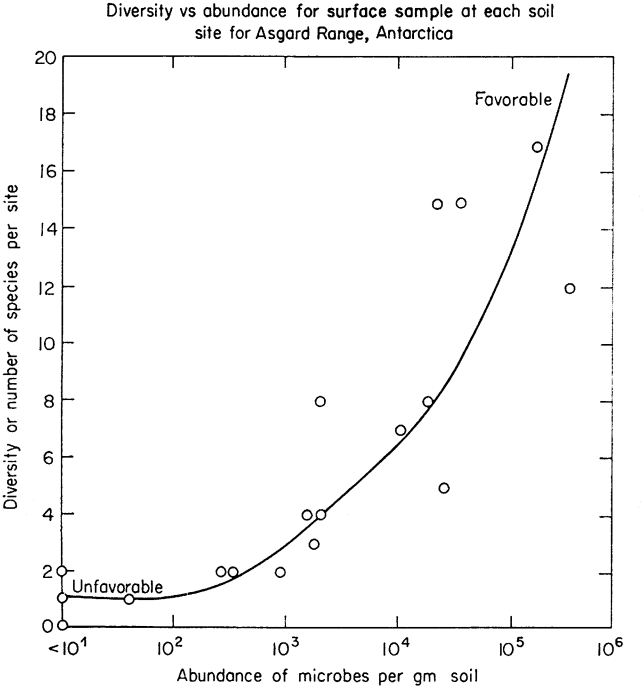

FIG. 4. Relationship between diversity of species and total number of micro-organisms in soil samples.

microflora and the microflora of near-by continents, especially in harsh environments, may substantiate the connection of Antarctica with other land masses (Science Year, 1967). Additional information on the general abundance and distribution of Antarctic dry valley microflora has been provided by Boyd, *et al.* (1966).

D. ECOLOGICAL CONSIDERATIONS

In general, a favourable complex of interacting environmental (microclimatic and edaphic) factors was necessary to obtain an abundance of mixed

populations of micro-organisms. Regardless of elevation, a north-south valley orientation was extremely important, as were slope, drainage and exposure, so as to obtain maximum duration, frequency and quantity of insolation and available moisture and protection from wind, (Table 5). However, it was

TABLE 5

Ecological Factors determining Distribution of Life in Antarctic Dry Valleys

Favourable	*Unfavourable*
N-S orientation	E-W orientation
Northern exposure	Southern exposure
Gentle, north-facing slopes	Flat or south-facing slopes
High solar radiation	Low solar radiation
Microclimate above freezing	Microclimate below freezing
Absence of wind	High winds
Northerly winds	Southerly winds
High humidities	Low humidities
Slow or impeded drainage	Rapid drainage
Lengthy duration of available H_2O (presence of glaciers, lakes, streams, snow and ice fields)	Short duration of available H_2O (absence of glaciers, lakes, streams, snow and ice fields)
Translucent pebbles	Opaque pebbles
Non-salty soils, balanced ionic composition	Salty soils, unbalanced ionic composition
Approx. neutral pH	High (or low) pH
Organic contamination (skuas, seals, etc.)	No organic contamination (no large increments of organic matter)

found that an otherwise favourable environment could be limiting for micro-organisms because of one or more soil properties, such as unfavourable mineralogy, texture, structure, salts, pH or moisture relationships. For example, samples with increasing concentrations of salts, as shown by electrical conductivity measurements, generally had lower abundances of micro-organisms (Fig. 5). With an organic carbon content less than 0·5%, there was no apparent correlation with abundance of micro-organisms in the samples. Also, there was no obvious relationship between abundance of micro-organisms and *in situ* moisture content except that there were more micro-organisms in proximity to the more moist layer of hard, icy permafrost. The diurnal cycling of moisture and heat in the Antarctic dry valleys (Fig. 1), are not advantageous for growth and reproduction of soil micro-organisms. As shown by laboratory and other desert field studies, a relative humidity above ~80% and temperatures above ~15°C for extended time periods are more favourable for most micro-organisms.

Based on the above factors, it was postulated as to which high-altitude valleys would be favourable or unfavourable for life. Subsequently, additional

valleys were investigated and it was substantiated that the abundance or absence of life in the valleys was indeed dependent upon specific climatic, topographic, and edaphic characteristics with respect to valley orientation, slope, drainage, exposure, wind, insolation, moisture supply and soil physical and chemical properties. This was found to be true for King and David Valleys.

With progression from extremely harsh to more favourable environments, especially with increase in quality, quantity, duration and frequency of

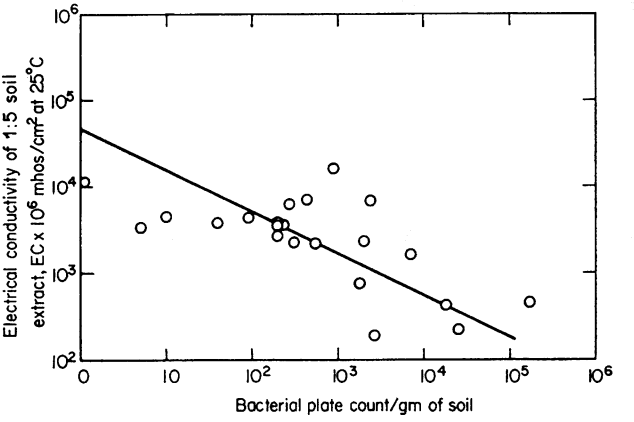

FIG. 5. Relationship between salt concentration and bacterial abundance in soil samples.

available moisture, it was found that there was a sequential increase in abundance, diversity and complexity of organisms. In general, the following sequence was observed: (1) heterotrophic, aerobic, non-pigmented, white, translucent or opaque bacteria, (2) heterotrophic, microaerophilic and chromogenic bacteria, (3) actinomycetes, (4) coccoid blue-green and green algae, and oscillatorioid blue-green algae, (5) moulds, yeasts and protozoa, (6) lichens containing coccoid green algae, and (7) mosses and other algae (filamentous green, nitrogen-fixing blue-green and diatoms) (Fig. 6). More specialized microflora, e.g. sulphate reducers and nitrogen-fixing bacteria, were generally not found unless algae were also present. Anaerobes, obligate psychrophiles, thermophiles, obligate halophiles, photosynthetic bacteria and coliforms were generally not detected. The absence of anaerobes and photosynthetic bacteria is especially significant, since this observation also has been made in investigations of other harsh desert soils, e.g. the Atacama and parts of the Sahara.

The increasing complexity of the life forms encountered as one passes from the harshest to the less harsh habitats is also important in the food chain of lower organisms (Janetschek, 1970, this symposium). The more

complex organisms, which are found in relatively favourable habitats, have more requirements on both the biotic (organismal and communal) level and the environmental level. Although difficult to quantify on an ecological and physiological basis at present, it is more than coincidental that the greater exigency, size and complexity of an organism, the less likely it will gain a foothold and become established in the dry valleys.

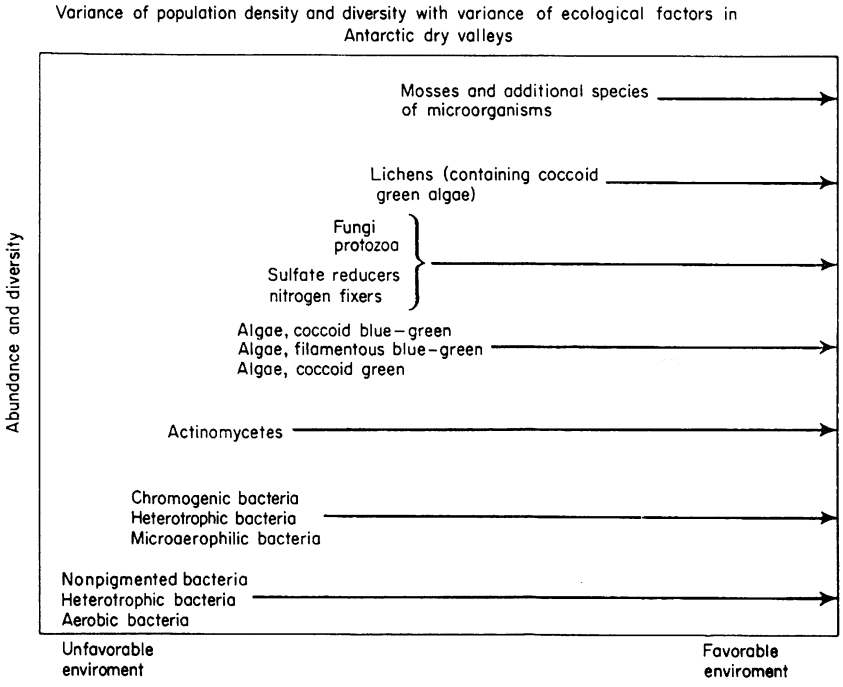

FIG. 6. Sequence of colonization of Antarctic soils by different floral and faunal groups.

III. Conclusion

A favourable complex of interacting topographic, climatic and edaphic factors must be present before there is an abundance of populations of microorganisms, whether broadly distributed throughout an area or at a local site. Consideration of these factors allows the prediction of the abundance and nature of the microflora likely to be encountered in a characterized environment. The investigation and study of Antarctic Dry Valleys has contributed substantially to an understanding of desert soil microbial ecology in a harsh environment prior to the search for life in extraterrestrial environments. The irregular distribution and low abundance of life in the dry valleys provides a valuable test area for life-detection methods (David and King, 1968).

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