Background aerosol composition at Gobabeb, South West Africa

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ABSTRACT

A remote site in the Namib desert at Gobabeb, latitude 23°45′S, longitude 15°03′E, was selected for sampling background aerosols in Southern Africa. This is one of a wide network of stations spanning the Southern Hemisphere in a programme designed to measure the background concentrations of heavy elements in the atmosphere. A first series of twelve samples was collected over a fifteen week period from November 1976 to February 1977, using a single-orifice cascade impactor, which fractionated the particles into six size groups. Analysis was performed using proton induced X-ray analysis (PIXE).

The following elements were measured in all twelve samples: S, Cl, K, Ca, Ti, Mn, Fe, Br and Sr. Elements observed occasionally, generally at very low concentrations, were: V, Cr, Ni, Cu, Zn and Pb. The results over the three month period show that the aerosol in this region was stable and well mixed. No direct correlations with wind direction were observed, excluding strong local or regional sources of particles. K, Ca, Ti, Mn and Fe can be identified with a dust dispersion source. Cl, large particle S and Br, and part of the Sr are derived from sea spray. Relative to the soil components small particle K is not enriched as it normally is in regions with less scarce vegetation. V, Ni, Cu and Zn enrichments in the aerosol are lower than practically all values measured at any other location hitherto. Minimal Pb concentrations, well below 3 ng/m^3, were found, indicating that the region is free from automobile exhaust pollution and thus confirming the suitability of the site for background aerosol sampling. A bimodal size distribution of sulphur concentrations was found. The larger size fraction was assigned to an oceanic origin, while the smaller fraction is assumed to be the natural background level in the atmosphere of sulphur particulates condensed from the gaseous phase. The concentrations of the small particle sulphur, 150 ng/m^3, are among the lowest concentrations measured over an extended period anywhere in the world.

1 INTRODUCTION

In the Northern Hemisphere, the input of particulate matter to the atmosphere by human activities is already large enough to affect the atmospheric composition not only in areas close to the pollution source points but also in remote areas. Efficient long range transport of atmospheric pollutants especially of submicron aerosol particles which may have long atmospheric residence times, has indeed led to the contamination of most non-urban areas of the Northern Hemisphere, and reliably pollution-free locations for baseline measurement stations are not easily found. Yet knowledge of the natural background levels of sulphur and trace elements in atmospheric particulates is of basic importance also for urban air pollution work, since all anthropogenic atmospheric particles are imposed on the natural background, and an understanding of their relative importance is necessary to design efficient air pollution control strategies.

The Southern Hemisphere contains considerably fewer pollution sources, and the mixing time of the atmospheres of both hemispheres is well in excess of the typical atmospheric residence times of aerosols. Therefore truly remote areas of the Southern Hemisphere are potentially suitable for natural background aerosol composition studies. Recently, stations for long term aerosol collection have been installed in the Southern Hemisphere at the South Pole (Maenhaut and Zoller, 1976), the island of Samoa in the Pacific Ocean (Maenhaut *et al.*, 1978) and Fernando de Noronha in the Atlantic Ocean (Van Grieken *et al.*, 1978) and in the uplands of Central Bolivia (Adams *et al.*, 1977). Short term sampling has been carried out at several remote locations on the South American continent (Lawson and Winchester, 1978) and on shipboard sites (Darzi *et al.*, 1978).

Since no aerosol composition data from the African continent have been available hitherto, and since nowhere in the Southern Hemisphere has long term sampling been carried out in a really central desert location, where organic processes cannot add significantly to local aerosol concentrations, an aerosol sampling project was initiated in the Namib Research Institute situated at Gobabeb in the Namib desert, South West Africa. This site adequately satisfies most of the requirements for sampling background aerosols: It is reasonably accessible to qualified servicing personnel, has a mains electricity supply and laboratory facilities, yet it is remote from all possible sources of anthropogenic aerosols, specifically industrial centres and major highways, and not downwind in the prevailing wind direction from such sources.

Its situation at latitude 23°45′S, longitude 15°03′E is 100 km in direct line from the nearest town Walvis Bay (population 25 000). The only other city of any size in the region is Windhoek, which is 250 km to the north west. The relative isolation of Gobabeb from major through roads is shown in the sketch map in Map 1. Vehicle movements in the direct vicinity of the station, which is 200 m south-east of the central area of activity of the Institute, are limited to two to four per day. Geographical features of Gobabeb are its position on the ephemeral Kuiseb river, on the Northern edge of the Namib dune sea and the Southern edge of an extensive sparsely vegetated gravel plain. The closest distance to the Atlantic Ocean is 60 km. The location of Gobabeb and its climate and soils have been more fully described by Schulze (1969), Goudie (1972) and Scholz (1972).

At this location sampling was continued for 15 weeks using a six stage impactor as a size fractionating sampling tool. Elemental analyses were afterwards performed by means of proton-induced X-ray emission (PIXE). Size distribution aerosol analysis was thought to be essential in view of the objectives of this study. Knowledge of the elemental size distributions is helpful in identifying aerosol sources since large size fractions point to dispersive source processes and smaller particle sizes to condensation from a gas phase. Moreover, intelligent monitoring of ecologically harmful aerosols requires size distribution information since the penetration and deposition efficiency of particles in the respiration system strongly depends on the aerosol size distribution. Finally, important clues about long range transport and atmospheric removal of aerosols and about ageing and mixing of different aerosol populations can be derived from elemental size distributions, if one takes into account the shorter residence times of larger particles and looks for size distribution similarities between different elements.

In this paper we present initial elemental analyses of the aerosol from a central Namib Desert station, provide evidence that the site is suitable for atmospheric chemical baseline measurements, and derive preliminary information on the atmospheric chemistry of the region.

2 EXPERIMENTAL DETAILS

All samples were collected with a single orifice Battelle-type cascade impactor (Mitchell and Pilcher, 1959). The principle of the impactor is illustrated in Fig 1. The aerosol stream is drawn upward into the impactor by a pump, passes through a single orifice and impinges upon the first plate. Particles in the aerosol stream having a large enough inertia will impact upon the plate, and smaller particles will make the turn into the next stage. The orifices of the 5 successive impaction stages are carefully designed so that the aerosol is separated in size fractions of >4 μm, 4-2 μm, 2-1 μm, 1-0.5 μm and 0.5-0.25 μm aerodynamic diameter, when operating at a flow rate of 1.2 l./min. Particles smaller than 0.25 μm diameter which pass through the 5th stage are collected on a back-up filter (also called filter stage or stage 6). The impaction surfaces used in this work were thin (<4 μm) Mylar film, supported by 25 mm metal slides and made sticky by coating with a thin layer of paraffin through evaporation. A 0.4 μm pore diameter Nuclepore filter served as back-up filter.

Sampling began on 1st November 1976 and continued until 14 February 1977. Each sample was collected over a period of 126 hours extending over seven days. Since the diesel powered electricity generator was switched off during the night from 0130 to 0730 hours, these periods were not included in the sampling. As the wind was becalmed during these hours on most nights, the exclusion of these hours does not represent a serious distortion of the wind frequencies actually sampled. Sample 12 was collected over an extended period of two weeks. The results of sample 3 are not included in this report due to a loss of target material during sample preparation, while sample 14 was invalidated by a spider taking up lodging in the impactor during the collection period. The calibrated flow of the impactor was 1.2 l./min. giving a sampled volume of 9 m^3 S.T.P. over a 126 hour period.

As part of the routine meteorological observations carried out at Gobabeb, continuous recordings are taken of wind speed and direction, air temperature and relative humidity. These data were made available for the interpretation of the aerosol data. Precipitating fog occurred on an average of three nights per month at Gobabeb during the sampling period. However, the onset of the fog is usually in the early hours of the morning and it is usually completely dispersed by 1000 h. As this time span was in any case mostly excluded from the sampling period due to the electricity supply hours, the fog is not an important factor in the overall results. The collected aerosol can therefore be regarded to a good approximation as originating from desiccated air with a relative humidity of less than 50 %. Disproportionately high loadings were observed on thfilter) stage of the impactors, indicating incomplete impaction on the earlier stages. This may in part have been caused by electrostatic effects which would be accentuated in dry air. However the masses deposited on the last stages were not sufficient to seriously distort the size distributions or invalidate the conclusions based on these results.

The samples were analysed by proton-induced X-ray emission (PIXE). The PIXE technique is a non-destructive, multi-element technique, which permits fast, precise and sensitive analysis of large numbers of aerosol size fractions. Full details of the analytical procedure have been described by Johansson and Johansson (1976). The main features can be summarised as follows. A proton beam from a Van de Graaff accelerator passes through an evacuated irradiation chamber and is made uniform by means of a diffuser foil or two pairs of electrostatic deflection plates sweeping the beam in two perpendicular directions. The beam is then defined by a series of collimators and directed onto the sample. In case of a thin sample, such as a Mylar film or a Nuclepore filter, the beam passes through it and is collected in a Faraday cup connected to a beam current integrator. X-rays emitted by the sample pass out of the irradiation chamber through a thin Mylar window and are detected with a high-resolution Si(Li) detector. The pulses from the detector are analysed in a multichannel analyser. A typical X-ray spectrum thus obtained is shown in Fig 2. It consists of a number of peaks corresponding to the K_α and K_β X-rays of the elements indicated in the figure. For the heaviest elements such as lead, the L X-rays can appear in the spectrum. The number of counts in a peak is a measure of the amount of the corresponding element in the sample. In samples up to 1 mg/cm^2, the X-ray response as a function of the material being analysed was investigated and found to be linear over more than four orders of magnitude, from about 1 ng to 100 µg (Johansson *et al.*, 1975).

The PIXE analysis of the samples was carried out using the facilities available at Florida State University (Johansson *et al.*, 1975). The proton energy was 5.0 MeV. The irradiation time per sample was typically 3 to 5 min. The charge collected in each irradiation amounted to 10µC. The elemental amounts present in the samples were obtained from the X-ray spectra by means of the computer program REX (Kaufmann *et al.*, 1977). The total execution time per spectrum evaluation, including plotting and printing, was approximately 2 min.

3 RESULTS

The results of the PIXE analyses, expressed as concentrations in ng/m^3 for most elements at each stage are presented in Table 1. Also indicated in Table 1 are the concentration limits for each element. The precision of the present sampling and analysis procedure has been tested thoroughly in a previous study (Van Grieken *et al.*, 1976). A 10 % error arising from the sampler performance should be added quadratically to an analysis uncertainty of 4 to 30 %, depending on the element concentration level, to yield the overall uncertainty on the results. The accuracy of the analysis results has been proven to be in the 10 % range through the use of reference targets and the participating in interlaboratory inter-comparison runs (Johansson *et al.*, 1975). A summary of the data is presented in Fig 3, where the geometric mean of the concentrations over all samples is plotted as a function of particle size for K, Ca, Ti, Mn, Fe and Sr. The error bars shown represent standard deviations on the average, as obtained from the scatter between the different results. A similar plot for S, Cl and Br is presented in Fig 4. Data for V, Cr, Cu and Zn are not included since these elements were generally not found significantly above the detection limits. The values for Pb were below 0.50 ng/m^3 for all size fractions.

4 DISCUSSION

Inspection of Fig 3 reveals a remarkable similarity in the size distribution of K, Ca, Ti, Mn, Fe and Sr. This points clearly to a common source for all these elements. Since the size distributions are strongly skewed towards the larger particle sizes, the dominant source of these elements must be a dispersion process, namely dispersal of soil material. This assumption is further corroborated by the fact that the elemental ratios of K, Ti and Mn to Fe for those elements are always close to the corresponding ratios of average soil and crustal rock material as can be seen from Table 2. Also these ratios are independent of the particle size for these elements.

Ca, however, is significantly more abundant in the aerosol relative to average soil, but this is not unexpected for the Namib Desert which has fairly extensive outcrops of calcium carbonate minerals (Scholz, 1972). While there is some maritime contribution to the Ca, this is clearly not the only source, since the ratio Ca/Sr in the aerosol is consistently greater than 100, in contrast to a value of 50 in sea water.

It also appears from Table 2 that the Sr/Fe ratio is in excess of what could be expected for simple crustal rock dispersal, which suggests an additional Sr source, e.g. sea spray. If one assumes that the Fe in the aerosol is exclusively derived from crustal rock dispersal, while the Cl is purely of marine origin (cf. below), one can calculate the expected airborne Sr concentration in each stage from the Fe and Cl contents and from the Sr/Fe and Sr/Cl ratios in crustal rock and sea-water, since no significant Sr/Cl fractionation occurs during the sea spray generating process (Hoffman *et al.*, 1974). In this way we predicted average concentrations of 1.8, 1.8, 1.1, 0.32, 0.06 and 0.21 ng Sr/m^3 for stages 1, 2, 3, 4, 5 and 6 respectively, while values of 0.9, 1.7, 1.0, 0.28, <0.12 and <0.27 were found experimentally. This gives evidence that both sea spray and crustal material contribute to atmospheric Sr at Gobabeb.

For all these elements, the concentrations measured on stage 1 are smaller than those on stage 2, suggesting that the largest size fraction had settled by gravitation before being sampled. This indicates that the aerosol is aged, and that no strong local winds blow up coarse local dust (the average measured windspeed during the sampling period was 12.5 km/h with a one hour average maximum of 39 km/h). However it cannot be ruled out completely that the size distributions are somewhat depleted in stage 1 by bounce off of particles during impaction. The usual extreme dryness of Namib Desert air during the day, and the loading of the impactor stages after a one week collection period, might be factors enhancing bounce off errors. The resulting distortions of apparent size distributions can be minimised by using shorter sampling periods and by using a different impactor slide coating; the paraffin used in this work will be replaced by vaseline in future sampling under desert conditions.

The size distribution for K closely matches that of Fe and the K/Fe ratios are consistent with that of soil or crustal rock for all stages. Previous investigations in the sparsely inhabited area of Northern Florida (Johansson *et al.*, 1974; Van Grieken *et al.*, 1976; Johansson *et al.*, 1976) and even in Bermuda (Meinert and Winchester, 1977) have shown a distinct K/Fe enrichment in the small particle size fractions except for purely maritime air sampled at a beach location. Also in remote locations on the South American continent (Lawson and Winchester, 1977) a relatively high abundance of small particle K was noted. In all cases, forest fires or emanations from plants were postulated as probable sources. The absence of any significant small particle K enrichment in the Namib desert, which is characterised by an extremely sparse vegetation, supports this assumption.

Table 2 also lists ratios to Fe for V, Cr, Ni, Cu and Zn, calculated either from the results of the few impactor samples in which these elements were found well above blank levels or from detection limits. In spite of the small number of data points some striking preliminary conclusions can be drawn. For all these elements the ratios to Fe in the large particle fractions are very near to the average crustal rock ratios, pointing to simple soil dispersal as the dominant source. Even in small particles the ratios of these elements to Fe are comparable to those in average soil: the detection limits or the few measured concentrations, related to iron, are typically only a factor of 3 to 10 higher than expected. If one adds the data over all six impactor stages, and relates them to the total Fe-concentration, ratios to Fe of 0.004 for Zn and <0.004 for V, Cr, Ni and Cu are calculated from the present data. Comparison of these values to other published data (e.g. Adams *et al.*, 1977) shows that these values are comparable to or lower than corresponding values measured at other locations. Hitherto, Cu and Zn have generally been found to be highly enriched (up to several thousand times), and this effect has been attributed to a world-wide contamination with some anthropogenic combustion aerosol component (Dams, 1974), selective emanation from plant material (Beauford *et al.*, 1977) or selective evaporation from rocks (Goldberg, 1976). The present finding of lower enrichments might be due to greater than usual contributions of unfractionated crustal material to the aerosol or to the absence of vegetation in the Namib Desert. Final conclusions await further aerosol analyses and investigations including careful analyses of soil samples taken from the Namib Desert. Ni and V are often measured in unexpectedly high concentration, particularly close to pollution sources (Duce and Hoffman, 1976). The fact that neither V nor Ni, which are abundant in fuel-oil, are detected in enhanced concentrations at the Gobabeb station indicates that local pollution from the station's diesel generator is insignificant.

Table 2 indicates that the measured Cl/Fe ratios are very much higher than expected for a dust dispersion source, and the very high abundance of the large particle fraction as seen in Fig 4 points to sea spray as the dominant Cl source. Taking into account the elemental ratios of Cl in seawater, one calculates that, even with the present high Cl content in the aerosol, the maritime contribution for the other elements to the aerosol at Gobabeb is negligible, except for Sr (see above), large particle Br and large particle S. As can be seen from Table 2 the Br/Cl ratio in stages 1, 2 and 3 is comparable to the seawater ratio, and it might be slightly lower due to preferential Br loss from the particles. When one does not take into account the high Cl and Br levels measured on the 6th size fraction, which might be partially due to the Nuclepore blank levels not being constant or negligible, and calculates the Br/Cl ratios for the 1-0.25 µm size diameter, (stages 4 and 5), a value of 0.0084 is found. The excess Br in the small particles cannot be attributed to automobile exhaust, as is the case in less remote regions (Johansson *et al.*, 1976), because the detection limits for Pb in the present samples are such that the Pb/Br ratio at Gobabeb is certainly below 0.2, while in automobile exhaust Pb/Br is closer to 5. The low Pb content of the Namib aerosol is unusual indeed. The sum of the average detection limits for the six impactor stages points to a Pb level under 3 ng/m^3, far below most Northern Hemisphere levels (Reiter *et al.*, 1976) and below most remote station levels (Adams *et al.*, 1977).

Sulphur shows a bimodal distribution indicating two sources, probably one from dispersion of solid or liquid phase and one from condensation from the gaseous phase. The large size fraction S probably originates from sea water. The measured S/Cl ratios are consistently higher than expected for simple sea water dispersal yet comparable to the large particle S/Cl ratios of 0.18 and 0.09 measured in maritime air on Bermuda (Meinert *et al.*, 1977) and Samoa (Maenhaut *et al.*, 1977) respectively. This high S/Cl ratio may be due to preferential loss of Cl from the aerosol particles, a process that has been examined e.g. by Berg and Winchester, 1977. The small particle sulphur concentrations average 150 ng m^{-3}, and this value is among the lowest levels yet recorded. This level can be assumed to be the natural background level in the atmosphere of sulphur particles condensed from the gas phase. Other intermittent measurements on the South American continent (Lawson *et al.*, 1978) have given concentrations on a comparable level, but possible additional S sources prevented their unambiguous interpretation as background levels. A more detailed review and interpretation of atmospheric sulphur particulate measurements in the southern hemisphere is at present in preparation. To further distinguish the sources and characteristics of the components of the aerosol, the time variations of the concentrations were plotted, for comparison with the time variation of the wind distance travelled. It was assumed that Gobabeb lies at the conjunction of three distinct geographic areas defined by the coast running North to South and the Kuiseb River running West toward the coast, as shown in the inset to Figure 5. The wind direction data have been arranged to give the wind distance travelled per sampling period over each of these three regions, namely (i) maritime, (ii) dune sand and (iii) gravel plain. The wind direction data are shown in Fig 6. There is only one gross feature in the time variation of the wind travel with which to correlate concentration variations: during sampling periods 1 to 10, the wind was predominantly maritime with an average travel of 1 300 km/126 hr, while the dune sand and gravel plain continental components were small, less than 150 km/126 hr; during sampling periods 12 and 13 (wind data for period 11 not recorded) the maritime component dropped to 800 km/126 hr while the gravel plain component increased to 800 km/126 hr.

The variation in concentrations of K, Ca, Ti, Mn and Fe over the whole sampling period, shown in Fig 7, show a striking similarity, confirming a common source for these crustal elements. There was no dramatic change in the concentrations of these elements during the periods 12 and 13 when the wind travel changed from predominantly maritime to mixed maritime-gravel plain. This indicates that the additional aerosol component generated over the gravel plain North of the Kuiseb is insignificant relative to either the aged aerosol component or the component generated over the region between the coast and Gobabeb.

The variation of the Cl, S and Br concentrations are shown in Fig 8. Since S and Br showed bimodal size distributions, each size fraction was plotted to identify their possible separate origins. Up to period 12 the variations of Cl and Sr concentrations are similar to those of the crustal elements. To a lesser extent so are the variations of large fraction Br and S concentrations similar. However during period 13 the concentrations of Cl, Sr and S (large fraction) drop sharply relative to period 12: concentration (period 13)/concentration (period 12) = C_{13}/C_{12} = 0.53, 0.83, 0.60 respectively. In contrast the concentrations of all the crustal elements increased slightly: Average $C_{13}/C_{12} = 1.21 \pm 0.11$. Although the reduction in maritime component occurred already during period 12, it appears that several days are required to convert the characteristics of an air mass from maritime to continental. This time variation of concentration confirms the source of Cl, S (large fraction), and part of the Sr as of recent maritime origin. For Br (large fraction), $C_{13}/C_{12} = 0.94$. This value is intermediate between the ratios for the crustal elements and Cl, but not distinct enough from earlier variations to associate it unambiguously with the change in wind travel. The S (small fraction) and Br (small fraction) concentrations increase slightly during period 13; C_{13}/C_{12} = 1.11, 1.23 respectively. This indicates that these fractions were not of recent maritime origin and that they were also aged components characteristic of the atmosphere over a large region.

5 CONCLUSIONS

Gobabeb was chosen as a sampling site for remote aerosol measurements. Analysis of size fractionated impactor samples taken under varying wind conditions over a fourteen week period indicated an aerosol of combined soil and maritime origin, which was well mixed and free from local or regional anthropogenic pollution. The measurements have provided valuable baseline values of remote natural aerosol concentrations. K, Ca, Ti, Mn and Fe all showed size distributions strongly skewed towards large particles; these elements varied similarly with wind direction and their concentration ratios were close to corresponding ratios in average soil or crustal rock. These observations pointed to simple soil dispersal as the common source for these elements. The concentrations of V, Cr and Ni relative to Fe corresponded to values measured at other locations. Unexpectedly low concentrations of Cu and Zn may be related to the sparsity of vegetation in the Namib desert. High Cl/Fe ratios and the large particle predominance pointed to Cl being derived mainly from sea spray; sea salt constituted on average 20 % of the total aerosol mass at Gobabeb, assuming that Cl and Fe were derived from only average sea salt and soil respectively. Large particle Br and S were correlated with a sea spray source, based on relative concentrations, particle sizes and wind direction dependence. Small particle Br was not derived from automobile exhaust, as is found in most locations, since the Pb levels were too low to account for gasoline as a measurable source. Small particle S concentrations were amongst the lowest yet recorded.

Future work will be oriented towards expanding the statistical base of the present conclusions, and towards unambiguously separating the maritime, gravel plain and sand dune components, by combining directional control equipment with the cascade impactor for use at different locations around Gobabeb.

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TABLE 1: Individual results (in ng/m³) for the 12 size fractionated aerosol samples taken at Gobabeb, South West Africa

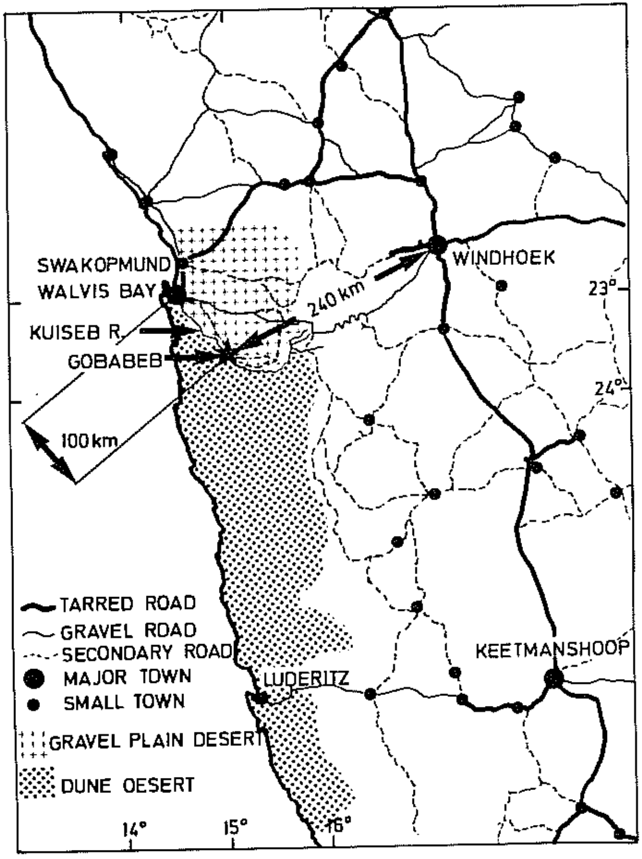
Element and stage number	Impactor run number												Geom. averäge	Std. dev. on the average	Average detection limit
	1	2	4	5	6	7	8	9	10	11	12	13			
S 1	66.	93.	50.	38.	35.	26.	46.	62.	70.	56.	41.	41.	49.	1.11	1.2
S 2	55.	40.	60.	43.	57.	55.	48.	64.	99.	79.	52.	21.	53.	1.12	1.1
S 3	24.	12.	30.	15.	30.	26.	44.	26.	50.	40.	40.	18.	27.	1.13	1.0
S 4	18.	9.0	37.	31.	61.	77.	32.	17.	24.	28.	61.	39.	31.	1.19	0.5
S 5	59.	22.	41.	47.	77.	57.	94.	89.	109.	114.	65.	100.	66.	1.15	0.4
S 6	67.	52.	50.	72.	82.	48.	57.	36.	63.	55.	38.	43.	54.	1.08	1.3
Cl 1	439.	742.	384.	266.	289.	188.	309.	578.	475.	451.	299.	282.	366.	1.12	1.0
Cl 2	288.	185.	403.	190.	382.	215.	176.	474.	512.	382.	317.	82.	269.	1.16	1.0
Cl 3	233.	50.	201.	25.	183.	98.	199.	257.	277.	234.	185.	43.	132.	1.26	0.8
Cl 4	63.	27.	45.	21.	35.	<0.41	46.	65.	28.	53.	15.	17.	34.	1.17	0.4
Cl 5	6.1	3.4	7.5	1.7	1.9	0.97	2.6	4.2	2.8	3.7	0.70	1.7	2.5	1.22	0.4
Cl 6	23.	24.	37.	104.	25.	12.	12.	21.	42.	15.	5.3	12.	21.	1.24	1.3
K 1	47.	66.	39.	29.	35.	21.	38.	41.	42.	32.	26.	31.	36.	1.09	1.3
K 2	42.	34.	59.	35.	67.	56.	30.	54.	81.	53.	32.	31.	45.	1.10	0.7
K 3	34.	15.	39.	14.	30.	36.	29.	36.	48.	34.	22.	20.	28.	1.12	0.6
K 4	13.	7.5	9.7	8.0	9.1	7.5	8.4	9.5	12.	13.	7.9	12.	9.6	1.06	0.3
K 5	3.7	1.6	4.0	4.2	4.8	3.7	3.3	3.8	4.3	3.4	2.0	2.5	3.3	1.10	0.3
K 6	14.	11.	16.	27.	17.	12.	5.7	6.6	12.	5.2	4.1	1.9	8.9	1.23	1.0
Ca 1	235.	311.	167.	163.	157.	99.	131.	194.	179.	143.	96.	128.	158.	1.10	0.6
Ca 2	264.	191.	308.	238.	335.	378.	159.	326.	353.	285.	147.	149.	248.	1.11	0.6
Ca 3	169.	68.	180.	79.	147.	187.	119.	180.	185.	170.	74.	80.	127.	1.13	0.6
Ca 4	52.	22.	37.	16.	29.	24.	24.	35.	30.	54.	22.	46.	31.	1.12	0.3
Ca 5	14.	5.4	13.	12.	9.6	7.2	9.8	14.	9.9	12.	5.9	9.6	9.8	1.10	0
Ca 6	54.	46.	82.	105.	49.	34.	15.	31.	40.	20.	16.	6.4	32.	1.26	0.8
Ti 1	10.	14.	7.1	5.9	6.9	4.3	7.1	6.6	9.2	6.0	4.7	7.2	7.1	1.10	0.4
Ti 2	11.	8.4	14.	8.0	14.	13.	7.5	11.	20.	12.	7.2	8.2	11.	1.10	0.4
Ti 3	9.0	3.7	12.	3.8	7.9	10.	8.0	9.8	13.	9.6	4.4	5.4	7.4	1.13	0.4
Ti 4	3.8	1.4	2.5	2.0	2.2	1.9	11.	2.9	2.4	4.2	1.7	4.1	2.8	1.17	0.2
Ti 5	0.97	0.37	1.1	0.98	0.85	0.66	0.98	1.2	0.97	0.79	0.60	1.0	0.84	1.10	0.2
Ti 6	2.8	2.2	4.0	6.4	2.9	2.2	0.80	1.9	2.4	0.65	0.97	<0.80	2.0	1.23	0.6
Mn 1	1.4	2.2	1.2	1.4	1.3	0.74	1.0	1.1	1.5	0.91	0.94	0.96	1.2	1.09	0.3
Mn 2	1.9	1.5	2.8	1.8	3.3	3.1	1.5	2.4	3.4	2.3	1.3	1.3	2.1	1.11	0.3
Mn 3	1.8	0.82	2.8	0.71	1.9	2.2	1.4	2.0	2.1	1.9	0.80	1.0	1.5	1.14	0.3
Mn 4	0.60	0.27	0.46	0.27	0.49	0.31	0.35	0.60	0.33	0.79	0.26	0.70	0.42	1.12	0.1
Mn 5	<0.21	<0.10	0.17	0.17	<0.12	0.12	0.14	0.14	<0.12	<0.19	0.10	<0.16	0.14	1.09	0.1
Mn 6	<0.46	<0.37	<0.45	0.64	<0.46	<0.40	<0.43	<0.42	<0.43	<0.37	<0.21	<0.52	—	—	0.4
Fe 1	94.	138.	43.	61.	69.	38.	69.	70.	81.	56.	49.	76.	66.	1.11	0.2
Fe 2	112.	91.	168.	87.	179.	176.	81.	142.	224.	132.	79.	85.	122.	1.11	0.2
Fe 3	106.	41.	156.	41.	110.	132.	95.	134.	150.	120.	50.	61.	90.	1.15	0.1
Fe 4	45.	16.	31.	25.	28.	23.	47.	38.	27.	52.	21.	46.	31.	1.11	0.1
Fe 5	9.9	3.6	12.	11.	9.5	7.3	8.6	11.	11.	6.8	4.9	5.8	8.0	1.11	0.1
Fe 6	33.	30.	43.	68.	30.	24.	12.	19.	26.	8.8	11.	4.6	20.	1.24	0.2
Br 1	0.51	0.93	0.39	0.41	0.27	0.23	0.53	0.83	0.95	0.45	0.48	0.61	0.50	1.14	0.1
Br 2	0.30	0.33	0.94	0.26	0.97	0.62	0.32	0.87	1.6	0.63	0.41	0.31	0.53	1.19	0.1
Br 3	0.57	0.14	0.91	0.13	0.43	0.40	0.36	0.47	0.94	0.59	0.31	0.21	0.38	1.20	0.1
Br 4	0.27	0.11	0.38	0.10	0.28	0.31	0.22	0.17	0.21	0.48	0.24	0.30	0.23	1.14	0.1
Br 5	0.24	0.15	0.27	0.09	0.31	0.17	0.45	0.30	0.37	0.49	0.20	0.24	0.25	1.15	0.04
Br 6	0.49	0.61	0.45	0.16	0.93	0.50	0.49	0.47	0.90	0.66	0.35	0.61	0.51	1.14	0.1
Sr 1	1.2	1.9	1.1	0.77	0.87	0.50	0.81	1.1	1.4	0.83	0.66	0.49	0.90	1.12	0.2
Sr 2	1.7	1.2	2.5	1.2	2.1	2.1	1.1	2.5	3.6	2.0	1.2	0.77	1.67	1.14	0.2
Sr 3	1.2	0.34	2.0	0.32	1.4	1.3	0.77	1.6	2.0	1.2	0.66	0.65	0.96	1.20	0.2
Sr 4	0.55	0.13	0.32	0.22	0.34	0.21	0.21	0.33	0.22	0.45	0.25	0.38	0.28	1.12	0.1
Sr 5	<0.13	<0.05	0.14	<0.06	0.09	0.48	0.10	0.10	0.08	0.10	<0.07	0.07	0.12	1.24	0.1
Sr 6	<0.18	0.33	0.41	0.55	0.39	<0.16	<0.14	0.21	0.30	0.23	<0.09	<0.19	0.33	1.14	0.2

TABLE 2: Elemental ratios in the aerosol as compared to the corresponding average ratios in crustal rock (Mason, 1952), soil (Vinogradov, 1959) and sea water (Riley and Skirrow, 1975).

Element	Concentration ratios to Fe							
	in the measured aerosol						in average curstal rock	in average soil
	impactor stage number:							
	1	2	3	4	5	6		
S	0.74	0.43	0.30	0.99	8.32	2.62	0.01	–
Cl	5.51	2.21	1.47	1.07	0.32	1.02	0.063	0.0026
K	0.54	0.37	0.31	0.31	0.41	0.43	0.52	0.36
Ca	2.38	2.03	1.41	0.98	1.23	1.58	0.73	0.36
Ti	0.11	0.09	0.08	0.09	0.11	0.10	0.088	0.12
V	0.0075*	0.0053*	0.0055*	0.0080*	<0.018	<0.026	0.0030	0.0026
Cr	<0.0047	0.0037*	0.0047*	<0.0045	<0.0188	0.038*	0.0040	0.0053
Mn	0.018	0.017	0.016	0.013	0.018*	<0.021	0.020	0.022
Ni	<0.003	<0.003	<0.001	<0.001	0.003*	0.039*	0.001	–
Cu	0.0021*	0.0012*	0.0012*	0.0006*	0.0050*	0.018	0.0014	0.0005
Zn	0.0032	0.0011	0.0014	0.0035	0.0075	0.013*	0.0025	0.0013
Br	0.008	0.004	0.004	0.007	0.031	0.025	0.00003	0.00013
Sr	0.014	0.014	0.011	0.009	0.015*	0.016*	0.006	–
Pb	<0.009	<0.006	<0.007	0.009*	0.038*	<0.028	0.0003	–

Element	Concentration ratios to Cl						
	in the measured aerosol						in average sea water
	impactor stage number:						
	1	2	3	4	5	6	
S	0.13	0.20	0.20	0.92	26	2.6	0.048
Br	0.0014	0.0020	0.0029	0.068	0.099	0.025	0.0036
Sr	0.0025	0.0062	0.007	0.008	0.048*	0.015*	0.004

* includes values above detection limit only.



MAP 1: Sketch map of South West Africa showing relative isolation of the sampling site at Gobabeb from large towns and major roads.

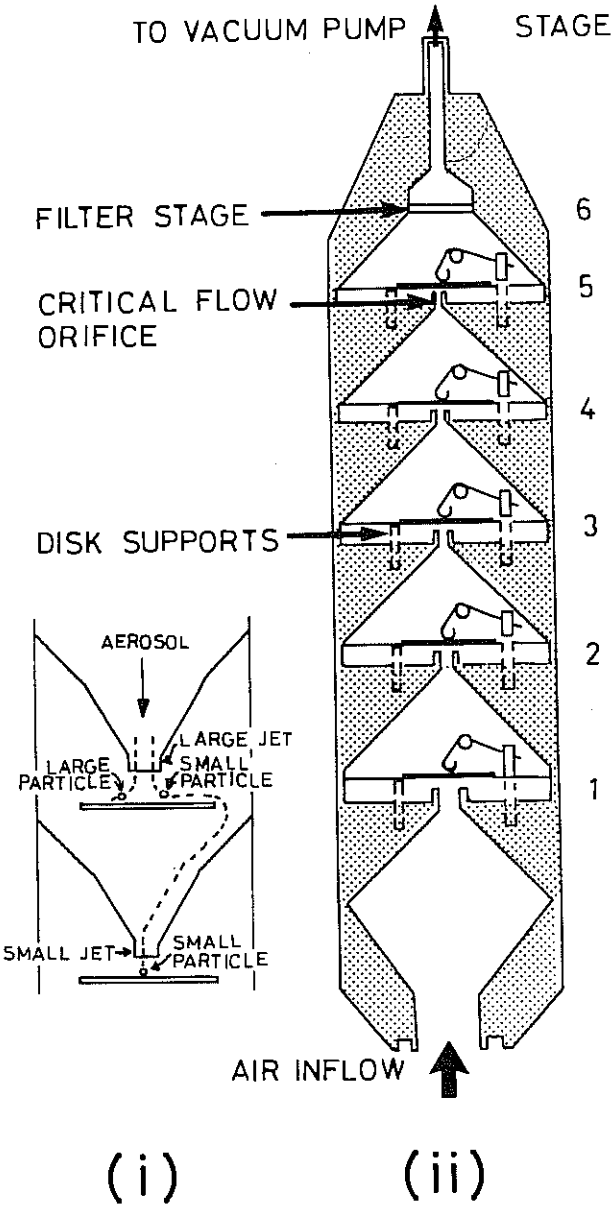


FIGURE 1: (i) Diagrammatic representation of the principle of size differential impaction of particles using a series of orifices of successively smaller diameter.

(ii) Five stage cascade impactor as used in the present project. Calibrated flow rate was 1.2 l./min.

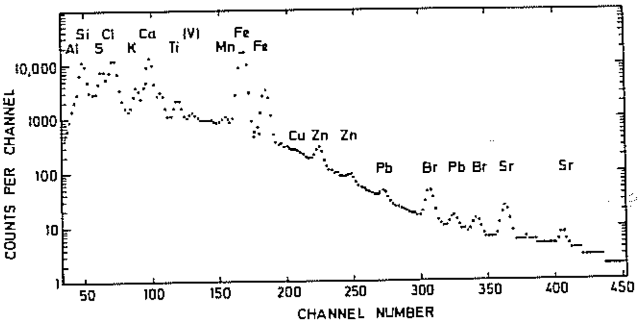


FIGURE 2: Smoothed X-ray spectrum of a Namib desert aerosol sample 11, stage 4 (0.5 to 1.0μm aerodynamic diameter particles).

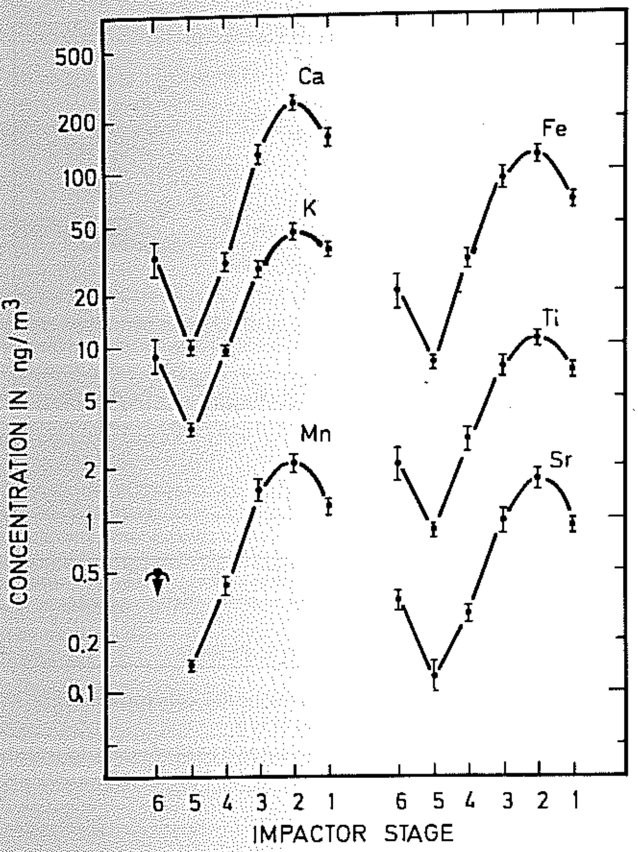


FIGURE 3: Particle size distributions of the geometrical mean elemental concentrations from twelve sets of impactor data. The horizontal scale indicates particle size on a log scale.

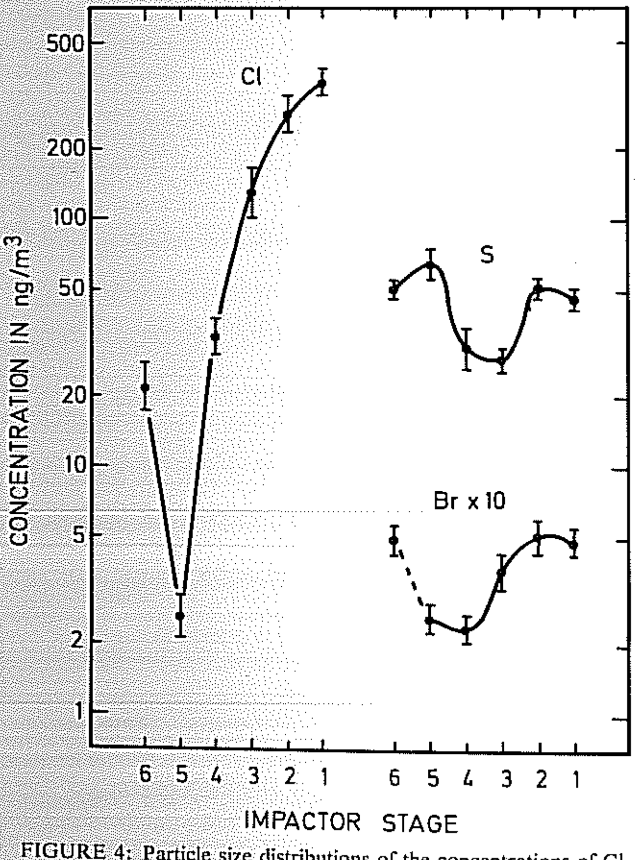


FIGURE 4: Particle size distributions of the concentrations of Cl, S and Br. Concentrations plotted are the geometrical mean of twelve impactor sets. The detection limit for Br = 0.03 ng/m^3.

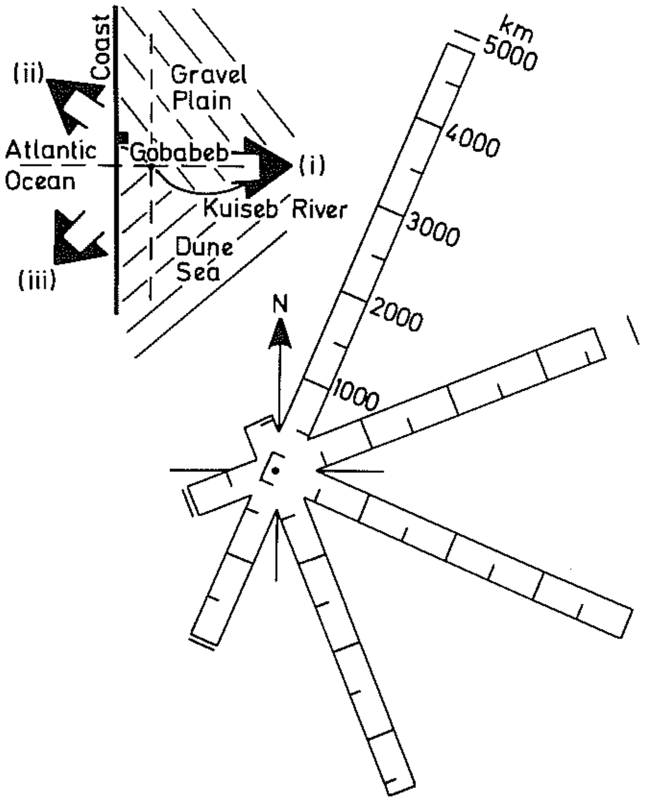


FIGURE 5: Accumulated wind distance travelled into the eight sectors indicated, during the sampling period for the twelve impactor sets e.g. 4 500 km is the distance travelled by SSW winds into the NNE sector. The approximate division of the wind reach into (i) maritime, (ii) continental (sand dune) and (iii) continental (gravel plain) regions as indicated (cf Fig. 1).

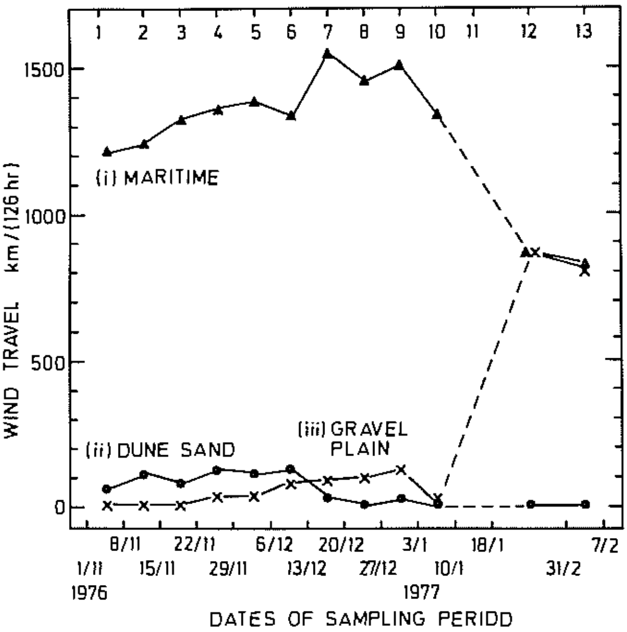


FIGURE 6: Time variation of wind travel over sampling periods in sectors corresponding to the major geographical features of the wind reach:
(i) Maritime, wind direction 180° – 360°
(ii) Continental (sand dune), 90° – 180°
(iii) Continental (gravel plain), 0° – 90°

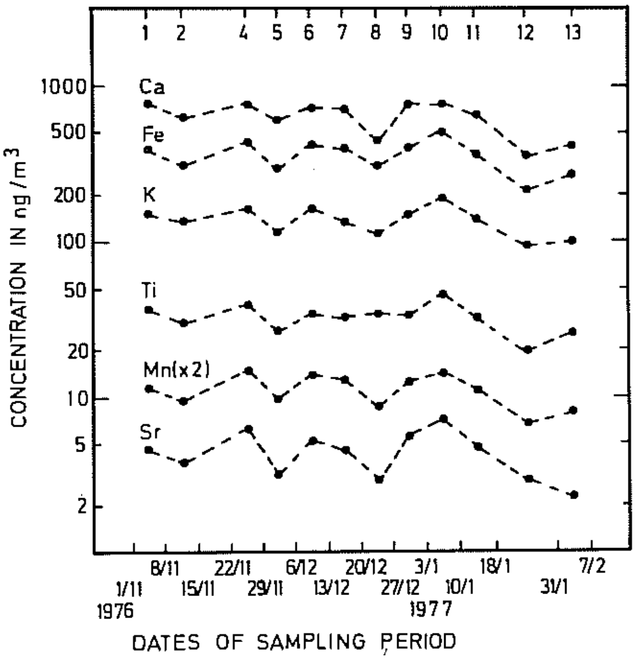


FIGURE 7: Time variation of the elemental concentrations of the aerosol, summed over all six stages.

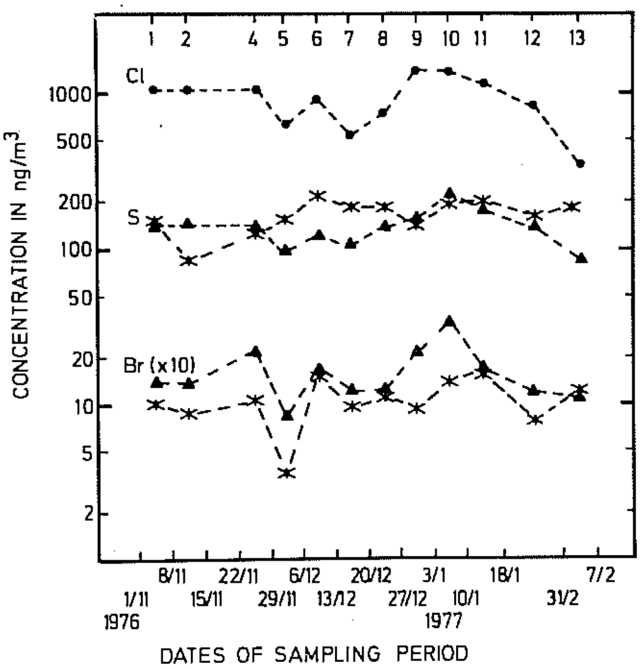


FIGURE 8: Time variation of the elemental concentrations:

(●)	sum of stages 1 → 6
(▲)	large fraction, sum of stages 1 – 3
(X)	small fraction, sum of stages 4 – 6