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A STUDY OF ATMOSPHERIC DUST

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A STUDY OF ATMOSPHERIC DUST

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ABSTRACT

This report discusses the techniques used in and the results of an investigation of the mineral constituency of the dust component of the atmospheric aerosol over White Sands Missile Range, New Mexico, conducted from November 1964 to August 1965. The eighty-one atmospheric dust samples, taken near the surface during this period, were analyzed by the light microscope technique of dispersion staining and by infrared absorption spectroscopy. Dispersion staining was used to determine the concentrations of quartz, kaolinite, illite, gypsum, and the carbonate family when the particle diameters were greater than four microns. Cases of exceptionally high concentrations of gypsum, quartz, and kaolinite, the month-by-month variation of the composite concentration, the seasonal variation of the gypsum concentration, and the lowest single-sample composite concentration are discussed in relation to the mineral content of area soils and meteorological conditions. Comments are made relative to the possible influence of extraterrestrial and sea-salt particles on the observed concentrations. By extending infrared absorption spectra to 40 microns wavelength, it has been possible to identify the minerals gypsum, mirabilite, quartz, kaolinite, illite, calcite, and dolomite in microgram samples of atmospheric dust, although any particular sample might reveal only a few of these constituents.

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INTRODUCTION

One of the factors necessary for defining the environment encountered by infrared energy propagating through the earth's atmosphere is knowledge of the mineral content of those airborne particles whose diameter is of the same order of magnitude as the wavelength of the incident radiation, i.e., 2.5 to 100 microns. Such particles constitute the transient component of airborne dust, dust which is dependent on the wind for support in the atmosphere. The particles may be of terrestrial or extraterrestrial origin.

By virtue of low rainfall, scant vegetal cover, abundant fine soil particles, and strong winds, a number of areas in the Southwest contribute dust to the atmospheric aerosol over White Sands Missile Range. The mineral constituency of the dust component of the atmospheric aerosol over White Sands Missile Range is the subject of this investigation. With particular regard to the transient dust, answers were sought to such questions as:

1) What minerals constitute transient dust?
2) Are there daily and seasonal variations in the mineral makeup of the dust component of the aerosol?
3) What relationships exist between the observed minerals and mineral content of area soils?
4) What role do atmospheric phenomena play in the transport of mineral particles from suspected sources to the sampler?

A sampling system utilizing membrane filters as the collecting surfaces, dispersion staining microscopy, and infrared absorption spectroscopy were used in this study. A vane-mounted membrane filter allowed sampling of the atmospheric aerosol, dispersion staining microscopy allowed quantitative determinations of the concentrations of selected minerals in the transient fraction to be made, and infrared absorption spectroscopy allowed freedom to probe other minerals which may have been present with no restriction as to particle size.

The purpose of this report is threefold: (1) to present modifications and/or adaptations to two standard techniques for the analysis of atmospheric particulates, (2) to present the results of the application of these techniques to a series of atmospheric dust samples, and (3) to relate the resultant mineral concentrations to source regions and atmospheric conditions.

This report, then, will treat the mineralogical analysis and the associated meteorological interpretations of atmospheric dust sampled 81 times from November 1964 through mid-August 1965 on membrane filters 3.5 meters above the surface at the White Sands Missile Range dust sampling site which is located on the western flank of the Tularosa Basin of South-Central New Mexico. Following a definition of dust, as it is treated in this paper, the sampling site, system, and program will be described. In Part I of this report, the modifications to the well-known dispersion staining technique of analyzing individual particles of transient dust size from a bulk sample for mineral concentration will be described and the resultant mineral concentrations presented. In Part II, these concentrations will be analyzed in terms of the mineral content of area soils and in terms of atmospheric conditions. Part III is devoted to the analysis of atmospheric dust samples by infrared absorption spectroscopy utilizing the wavelength range from 2.5 to 40 microns. The analytical technique involved in the identification of 7 minerals is described, and qualitative data are presented on the mineral constituency of 33 samples. Infrared absorption spectra of 13 reference minerals are presented in an appendix.

DEFINITIONS

As pointed out by Fett [1, p. 1], the definition of "dust" is dependent, as a practical matter, upon the particular discipline and application involved: "Leider gibt es keine für alle Disziplinen der Wissenschaff einheitliche Definition des Begriffes 'Staub'." Roughly, atmospheric dust may be defined as the solid material which is normally present in the atmosphere [2, p. 110]. More specifically, and for the purpose of this investigation, atmospheric dust is defined as the small, irregular, solid, heterogenic mineral particles in the atmosphere. Furthermore, the following convention will be followed in regard to the definition of the terms "blowing dust" and "duststorm" as used in this text:

Blowing dust: Dust picked up locally from the surface by the wind and blown about in clouds or sheets that restrict horizontal visibility to six miles or less [3].

Duststorm: Blowing dust that reduces the visibility to less than 5/8, but not less than 5/16 statute mile [3].

Atmospheric dust consists of a permanent phase or component and a temporary or transient phase or component (Figure 1), the two phases overlapping in the region between 1 and 10 microns, a so-called transition region. The permanent particles are submicron, thus

including both Aitken nuclei [4, p. 36] and large nuclei [4, p. 46]; the transient particles are virtually equivalent to giant nuclei [4, p. 55].

The permanent particles are permanent in the sense that gravitational fallout is not significant for this range of sizes [5, p. 67], Malina [6] even estimating "atmospheric dwell times" of 9 to 90 years for particles of one micron diameter. Washout of these particles from the atmosphere by rain is negligible because the particles are carried around the raindrops in the airstream.

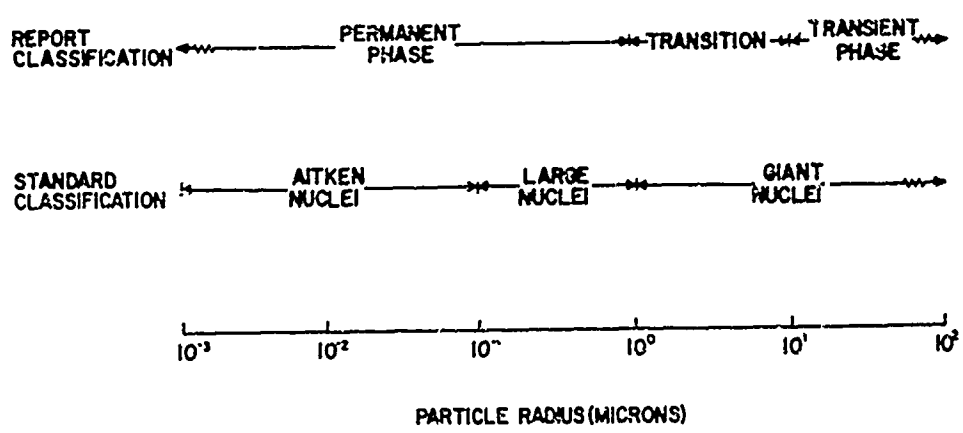

Fig. I ATMOSPHERIC DUST NOMENCLATURE

The region between one micron and ten microns constitutes an ill-defined transition zone between the aforementioned permanent component and the transient component of atmospheric dust. The region is one of transition because, even though subject to gravitational fallout, the particles in this size range remain permanently suspended by virtue of the normal random motions of the atmosphere.

Transient dust is that fraction of the atmospheric dust which is primarily dependent on the wind for its suspension. Just as the lower limit of particle size is lost in the maelstrom of the transition zone, so the upper limit is lost to the vagaries of the wind. After a number of measurements of blown dust from many sources, Udden [7] concluded that the "average largest size of quartz particles that can be sustained in the air by ordinary strong winds is about 0.1 millimeter in diameter." It should be noted that the maximum number concentration of airborne particles is in the 0.01 to 1 micron diameter range [5], but that the transient range spans a significant portion of the infrared spectrum.

The discussion of parts I and II will be confined to the transient particles, while in Part III there will be no discrimination as to particle size.

SAMPLE SITE

The dust sampler is located on the eastern bajada, or alluvial slope, of the Organ Mountains within the Tularosa Basin of South-Central New Mexico (indicated by the large dot in Figure 2) at latitude 32°22'46"N and longitude 106°29'16"W. A view of the sampling site is shown in Figure 3. The Organ Mountains in the background range up to 2600 meters above Mean Sea Level (MSL), the ground surface at the site is at 1311 meters MSL, and the floor of the Tularosa Basin to the east is at about 1200 meters MSL. The stream-built slope on which the sampler is situated extends in a general west-east direction from the intrusive quartz monzonite of the Organ Mountains to the valley fill which comprises the floor of the basin.

The sampling system was located at this particular site for several reasons. Foremost of these was the fact that there was no major source of airborne dust nearby to conceal the presence of dust from other areas. Moreover, the sampling site was remote from the contaminating effects of the artifacts of industrial activity, commercial power was available, there was an operational Aerovane for data on wind speed and direction at the site, and the site was readily accessible.

SAMPLING SYSTEM

The sampling system was to be such that a representative sample of atmospheric dust could be collected on a membrane filter for subsequent laboratory analysis by light microscopy and infrared absorption spectroscopy. The particular membrane filters used were

Figure 2. Relief Map, South-Central New Mexico

Figure 3. Dust Sampling Site, View SW

of 0.8 micron mean pore size and 25 millimeter diameter with an effective sampling diameter of 18.8 millimeters. The efficiency of this filter is close to 100 percent, even for particles in the 0.1 micron range, due to electrostatic charge built up by the air passing through the filter [8]. The membrane filter was enclosed in a vane-mounted sampling head (Figure 4). The seven elements comprising the sampling head are: vaned intake port, teflon gasket, membrane filter, copper screen, stainless steel perforated sheet disc, teflon gasket, and fixed support. The 325 mesh copper screen and the 0.08 millimeter sheet disc provided support for the filter. Such support was necessary because of the pressure drop across the filter which resulted in flow rates ranging from 6 to $10 \times 10^{-2} m^3 min^{-1}$ under actual field conditions. To obtain enough dust on each filter for the microscope and infrared analyses to be described in Parts I and III, approximately 100 m^3 of air were sampled. By using a vane, the sampling orifice was kept normal to the air flow thus allowing directional sampling.

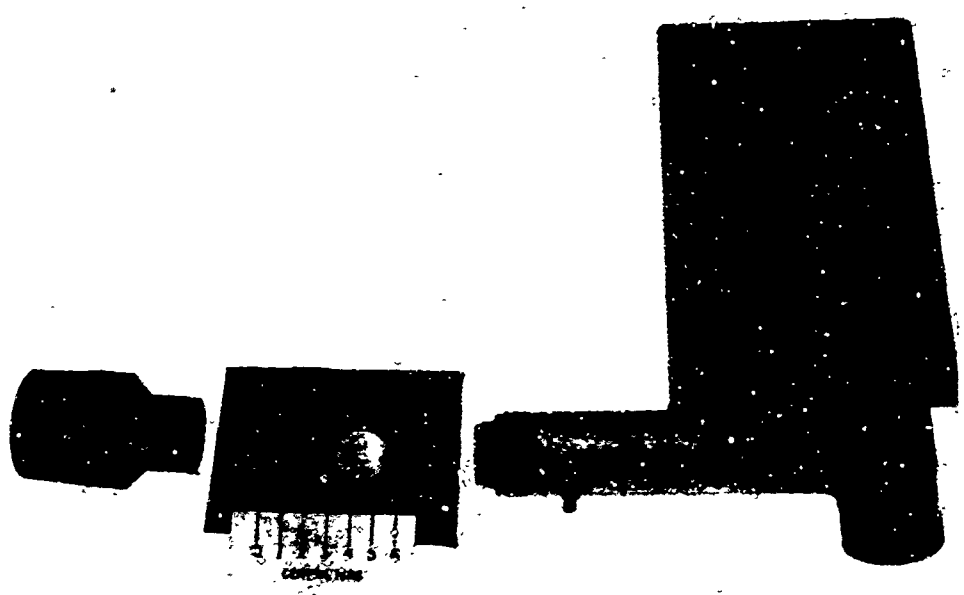

Figure 4. Vaned sampling head, disassembled

The sampling orifice was located 0.8 meter below and 3.9 meters southwest of the Aerovane at a height of 3.5 meters above the ground surface. Thus, the sampling surface was close to the Aerovane, the data from which were used to establish the wind velocity at the sampler prior to and during the sampling period. Moreover, the height of the sampling orifice above the ground was more than adequate to avoid the "moving carpet" layer. It is in this layer, situated within 0.3 meter of the ground surface, that 90 percent of the atmospheric transport of the soil occurs, [9]. By avoiding this layer, the probability of sensing any long period or long range effects on the observed mineral concentrations would be enhanced. Not only would the masking effects of local 'soil dust' be reduced, but the avoidance of the moving carpet layer would reduce the risk of rending the filter and would tend to eliminate from the sample those particles which, by virtue of their mass, are subject to only short range atmospheric transport.

SAMPLING PROGRAM

The purpose of the sampling program was twofold: (1) to provide adequate sample for subsequent analysis by both the microscope and infrared techniques to be described in Parts I and III and (2) to minimize the effects of dust from the local surfaces.

Preliminary work indicated that for the sampling system to be used and for the wide range of mass concentrations which might be encountered over such an exposed location a sampling time of 16 to 18 hours would, in most cases, yield enough dust for the microscope and infrared analyses.

The intensity of entrainment of dust from the surface of the ground into the atmosphere is a function of the wind, of the state of the soil surface, and of the type of soil. The effect of the wind is, in turn, a function of wind velocity (speed, u, and direction) and of the turbulent exchange coefficient, K_z, in the boundary layer. Makhon'ko [10] has shown that from a dry soil surface dust entrainment is primarily dependent on the diurnal variation of u, but that during the daytime both u and K_z play an appreciable role. Generally, K_z is at a maximum during the early afternoon. As demonstrated by Dovgyallo [11], it is at this time that the horizontal transparency of the atmosphere is at a maximum, the vertical transparency at a minimum, value. This inverse transparency is the result of the vertical transport of dust and moisture. Therefore, by confining the major portion of the 16-to-18-hour span to the sunset-sunrise period, most of the dust used for laboratory analyses would be dust which was in the process of settling out of the atmosphere. Thus, samples would be more apt to reflect long distance transport than samples taken during the daytime when transfer from the local surface is so pronounced. Therefore, a sampling period from approximately two hours prior to sunset of one day to approximately two hours after sunrise the following morning was selected. It is recognized that during the early portions of the period K_z is high, but since the dust sampled at this time is necessarily confined to the lower portion of the dust mat on the membrane filter, its effect on the analyses is expected to be small because the analyzed dust is taken from the uppermost 'layers' of the mat.

The soil at the sampling site will be discussed more thoroughly in the Part II, but the soil is normally dry since precipitation averages less than 10 inches per year, with 50 percent of that occurring during July, August, and September. Also, the soil is quite porous and thus dries rapidly in the dry air even during the "rainy season." Because of the year-around low relative humidities, dew formation is negligible.

Sampling of the atmospheric aerosol over White Sands Missile Range for the determination of mineral composition began on 4 November 1964 and continued through 12 August 1965. Samples were scheduled twice weekly, but precipitation and occasional instrument difficulties forced erratic sampling, whereby in some weeks no samples were taken and in other weeks three or four samples were taken. The sequences of three or four consecutive samples, however, did allow the examination of day-to-day changes.

PART I

DISPERSION STAINING DUST ANALYSIS

BACKGROUND

The technique of dispersion staining with the light microscope provides a rapid and reliable method for the mineralogical analysis of the transient and transition fractions of the atmospheric dust over White Sands Missile Range, New Mexico. The technique is not generally applied to the identification of the submicron particles because of the limit of resolution of the light microscope, 0.25 micron, and because of the state-of-the-art limitation of dispersion staining to particles of a diameter greater than 0.8 micron.

Identification of minerals by dispersion staining is a well-known procedure [12]. The particular variant used in this study involved use of a positive phase contrast system similar to the phase contrast systems pioneered by Crossmon in the United States [13] and by Schmidt in Germany [14]. With only a slight modification of the basic technique, involving the choice of appropriate immersion fluids, it is possible to use dispersion staining not only for the identification of the mineral constituents of dust, but also for the determination of their concentrations.

Preliminary local analyses of dust in the atmospheric aerosol over White Sands Missile Range, coupled with an independent analysis of a dust sample from this aerosol by the Concrete Division of the U. S. Army Engineer Waterways Experiment Station in Jackson, Mississippi, indicated the presence of the minerals quartz, kaolinite, illite, gypsum, microcline, calcite, dolomite, and aragonite. Samples of these minerals were obtained, checked for purity by x-ray diffraction, and then used as standard specimens. The dispersion staining technique was adapted for the identification and routine determination of concentrations of airborne particles of diameter greater than four microns of quartz, kaolinite, illite, gypsum, and the 'carbonate' family.

This part will: 1) discuss the selection of test liquids for the dispersion staining identification of the aforementioned minerals, 2) discuss briefly the four minerals and one family, 3) present a technique for the transfer of dust from a membrane filter to a glass microscope slide, and 4) present in tabular form the concentrations of the four minerals and one family as determined for 81 samples spanning the period from 4 November 1964 through 12 August 1965.

TABLE I

Selected Minerals, Test Liquids, and Optical Data

MINERAL OR MINERAL GROUP	REFRACTIVE INDEX* (NaD Line)	DISPERSION* ($\lambda_f - \lambda_c$)	TEST LIQUID OR MIXTURE	REFRACTIVE INDEX** (NaD line)	DISPERSION** ($\lambda_f - \lambda_c$)
GYPSUM	Nx = 1.521 (20°C) Ny = 1.523 Nz = 1.530	0.0078 (Ny)	Ethylsalicylate	1.525 (14.4°C)	0.0206
MICROCLINE	Nx = 1.518 Ny = 1.522 Nz = 1.525	----------	Ethylsalicylate	1.525 (14.4°C)	0.0206
QUARTZ	Ne = 1.553 No = 1.544	0.0081 (Ne) 0.0078 (No)	Ethynylbenzene	1.552 (12.5°C)	0.0338
KAOLINITE	Nx = 1.560(1.553-1.563) Ny = 1.565(1.559-1.569) Nz = 1.566(1.560-1.570)	----------	Salicylaldehyde	1.574 (19.7°C)	0.0315
CARBONATES (Calcite, Aragonite, Dolomite)	Calcite No = 1.658 Ne = 1.486	0.0135 (No) 0.0060 (Ne)	N-Ethyl-1-Naphthylamine	1.648 (15.1°C)	0.0404
	Aragonite Nx = 1.530 Ny = 1.681 Nz = 1.685	0.0128 (Ny)			
	Dolomite No = 1.680 Ne = 1.501	0.0139 (No) 0.0061 (Ne)			
ILLITE (A,B,C)	A = 1.588 B = 1.598 C = 1.588	----------	33.3% N-Ethyl-1-Naphthylamine 66.7% Ethynylbenzene***	1.584	0.0360

*Taken from Winchell [18] and Bradley and Grim [16]

**Taken from the International Critical Tables [19]

***Percent by volume

IMMERSION FLUIDS

The prime requisites for the best color production through dispersion staining are that the immersion liquid have the same refractive index at the sodium D (NaD) wavelength as the mineral to be determined and have a dispersion* value, D, greater than that of the mineral. For his phase contrast system, Schmidt [15] showed that, for the appearance of rich colors, a dispersion ratio $\left(\frac{D_{liquid}}{D_{solid}}\right)$ of about 2 1/2 was necessary. Under these conditions, the dust particulates of the mineral under study will appear a deep sky-blue with a red-orange halo for positive phase contrast.

Moreover, ideally the fluids should be colorless, chemically and optically stable, without disagreeable or noxious odor, have a low vapor pressure, and should not dissolve or react with the minerals. The immersion fluids commonly used in the United States, i.e., the Cargille Immersion Liquids, do possess these properties, but they are generally of low relative dispersion. Hence, for each of the minerals selected for identification, immersion fluids had to be found which had a dispersion ratio greater than two and one half, albeit at a sacrifice in odor and/or vapor pressure. The individual minerals and mineral family and the test liquids with their respective refractive indexes and dispersion are summarized in Table I.

As is evident from the table, the minerals under study are anisotropic. However, with the exception of the carbonates, the birefringence** is small so that the choice of a refractive index fluid is confined to a narrow range of indexes, a range within which the selected fluid would serve to uniquely identify the mineral by dispersion staining if no other minerals had refractive indexes within that range. However, other minerals do have such refractive indexes and hence would be color-identified as the minerals under test, but, based on mineralogical studies of the soils in this area (see Part II), these minerals are not common locally, and thus are neglected as contributors to the observed concentrations. There are certain exceptions; these exceptions will be discussed in the sections that follow.

*difference in refractive index at the F and C Fraunhofer wavelengths, 486.1 mμ and 656.3 mμ.

**difference in refractive indexes of the ordinary and extraordinary rays of uniaxial crystals or the alpha and gamma indexes of biaxial crystals.

MINERALS

Quartz

The omega or ordinary index of refraction for quartz, which is optically anisotropic, is equal to the refractive index for halite, which is optically isotropic. Therefore, by the simple expedient of rotating the stage under polarized light, or vice versa, it is possible, of course, to distinguish quartz from halite without recourse to differences in external morphology.

Gypsum

Both gypsum and microcline have very similar refractive indexes and, therefore, are detected by the same liquid. However, it is possible to differentiate the two minerals because of differences in their external morphology. Gypsum particles in this area have irregular, jagged edges and, under dispersion staining, the blue particles are marked by white spots due to occluded impurities. On the other hand, the microcline particles in this area exhibit smooth, sharp edges, one of which is usually darker than the others and is felt to be a cleavage plain, and the mineral seems to be relatively pure for it is not marked with visible impurities.

Kaolinite

The term kaolinite as used in this context actually refers to the kaolinite group of the crystalline clay minerals which includes kaolinite, dickite, nacrite and anauxite, all of which have refractive indexes clustered about those of kaolinite which are the ones listed in Table I.

Illite

Illite refers to another group of crystalline clay mineral but of the clay-mica type. The optical properties have been generalized by referring to three illite categories, A, B, and C [16].

Carbonates

Among the minerals identified in preliminary analyses of local airborne dust were calcite, dolomite, and aragonite.

All are members of the carbonate family, with calcite and dolomite in the uniaxial calcite group and with aragonite as the prime member of the biaxial aragonite group. The three minerals have a birefringence in excess of 0.15. This would seem to vitiate any refractive index fluid for any of the three minerals such that all particles of that mineral would exhibit the blue coloration with the red-orange halo. Since calcite is the most common of the three carbonates in the area soils (see Part II), it is a logical choice for analysis. Moreover, by selecting a fluid with an index of refraction equal to the omega refractive index for calcite (1.658) and a dispersion greater than 0.0338, it should be possible to test for calcite to the exclusion of certain biaxial minerals of a similar refractive index, such as hornblende and biotite. The omega index is always present independent of the orientation of calcite. Thus, by rotating the stage under polarized light or vice versa, it is possible to color-identify calcite by noting whether the characteristic colors appear four times in 360 degrees of rotation, and also to eliminate isotropic and weakly birefringent anisotropic minerals from the count.

N-ethyl-1-naphthylamine with a refractive index of 1.648 and a dispersion of 0.0404 represents a compromise. It is a commercially available test liquid of refractive index higher than the common indexes of biotite of the mica group and lower than the common indexes of the hornblende series of the amphibole group and yet one which falls within the range of indexes of other common carbonates such as dolomite and aragonite. Obviously, a number of minerals could be identified as calcite, but they are not common.

By choosing a fluid of refractive index slightly different from the omega index of calcite, however, the difficulty of color identification is increased, because the index 1.648 is not present in all orientations of calcite. By taking a sample of pure calcite particles, immersing them in the N-ethyl-1-naphthylamine, noting the number of particles out of one thousand total particles counted that yielded the characteristic colors, and repeating the process ten times it is possible to arrive at a correction factor. Of 10,000 total particles counted, fifty out of each thousand were color identified as calcite, thus indicating a correction factor of twenty. Hence, in an ordinary dust sample, the number of color-identified calcite particles was multiplied by twenty to obtain an estimated total count.

Although specifically designed for calcite, this test would also identify some of the common and highly birefringent particles such as those of dolomite and aragonite present in the sample and hence the term carbonates has been used in lieu of calcite.

PROCEDURE

For the dispersion staining analysis of the dust on a membrane filter using a phase contrast microscope system it is generally not feasible to examine the dust on the filter directly. Therefore, a method of transferring the dust from the filter to the slide is required. The method for removing the dust from the membrane filter depends upon the amount and degree of imbedding of the sample collected. In most cases, it has been possible to use a sterile hypodermic needle to simply scrape enough dust from the filter onto a microscope slide.

If the amount of the sample is very small and/or imbedded in the web of the filter, a procedure originally developed by Dennis [17] may be modified and used for dissolving the filter with acetone and letting the dust settle on a microscope slide. A glass microscope slide, A, (Figure 5) is placed on a metal block, B, which is situated in a large glass dish. The membrane filter, C, is placed

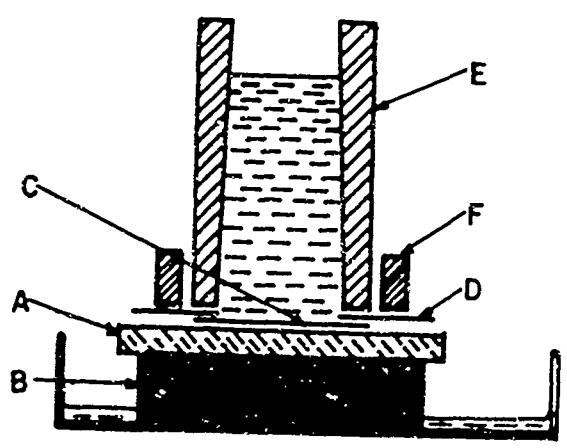

Figure 5 . Apparatus for transfer of dust to glass slide.

on the slide dust side down and wetted with a few drops of isopropyl alcohol. A ring of regular filter paper, D, with a center hole slightly smaller than the dust area, is placed over the membrane filter and, similarly, wetted with alcohol. A short brass cylinder, E, is placed on the regular filter paper and supported by the brass ring, F. Then, acetone is slowly poured into the cylinder and allowed to leak out through the filter paper after dissolving the membrane filter. The cylinder is filled several times to insure complete dissolution of the membrane filter. During this process some particles are dissolved or washed away. However, an adequate number of particles remain on the slide for an analysis.

Testing for a number of minerals from a dust sample on a membrane filter often necessitates a separate slide for each mineral determination. If it is not feasible to scrape samples onto slides, the membrane filter may be divided into n + 1 pie slices, where n is the number of separate mineral analyses which are to be made. The acetone technique described above may then be applied to each pie slice to transfer its dust to a glass microscope slide. The remaining slice may be retained for reference or used in subsequent infrared or x-ray analyses.

After transfer of the dust to the glass slide, a few drops of the proper liquid are added and the dust-fluid mixture covered by a cover glass. As previously stated, the fluid is of the same refractive index as the mineral to be determined, but has a much larger dispersion. This causes the mineral to appear deep sky blue with a red-orange halo. To determine the concentration of each mineral, the usual procedure is to examine, at random, one thousand particles of diameter greater than four microns and note the number of particles exhibiting the characteristic colors for that mineral in that fluid. The concentration data so obtained are presented in Table II. The data were obtained with a Bausch and Lomb phase contrast binocular microscope, utilizing Köhler illumination, a 21x phase contrast objective, and a 10x eyepiece.

An experienced microscopist 'counted' all of the dust samples. Repeated counts for the experienced microscopist indicated no significant difference in counts from the same slide or in counts for a given mineral from different slide preparations of the same dust sample. These test counts disclosed that the error in either case was within $\pm$ 5 particles for counts up to 50 and $\pm$ 10 particles for counts over 50.

Microcline was counted, but the results are not presented because the random error in the determination of concentration was greater than the observed concentrations.

Although only a few minerals of the airborne dust in this area were determined by this method, the technique may be extended to other minerals or other locales by the judicious choice of test liquids. For instance, to detect some forms of opal, 2,4-pentanedione can be used. Fluorite will appear colored in crotonaldehyde, halite in benzaldehyde, and langbeinite in methyl salicylate.

SUMMARY

In addition to the technique of dispersion staining being quick and reliable, it requires only small samples which can be collected in minutes if necessary. The technique was limited to the determination of the mineral composition of particles whose diameter exceeded four microns.

The possibility does exist that more than one mineral may be identified as the specific mineral under test. It is possible, in many cases, to distinguish several such minerals with one test fluid by means of external morphology or tricks with polarized light. Generally the minerals of refractive index similar to the minerals under test are so uncommon that their contribution to the observed concentration may be neglected.

It must be emphasized that the concentrations presented are mineral concentrations (number of particles of a given mineral per one thousand total particles counted) as opposed to number concentration (total number of particles per unit volume) or mass concentration (mass per unit volume). For example, an increase in the mineral concentration of quartz does not necessarily imply an increase in the absolute amount of quartz in the air, but only that the number of quartz particles relative to one thousand particles increased.

TABLE II

Observed mineral concentrations, particles per thousand, for gypsum (G), quartz (Q), illite (I), kaolinite (K), and carbonates (C)

Dates	Time (MST)	G	Q	I	K	C
November	1964					
4- 5	1530-1000	116	72	44	67	60
17-18	1530-0830	24	100	49	40	60
19-20	1430-0830	29	60	76	72	120
23-24	1530-0900	13	101	78	124	80
24-25	1530-0900	24	98	65	49	120
30- 1	1430-0900	28	118	157	121	200
December	1964					
1- 2	1530-0945	140	51	18	51	20
8- 9	1600-0900	38	95	76	66	200
10-11	1500-0930	24	37	53	44	200
14-15	1500-0900	45	68	81	84	220
15-16	1530-0830	27	71	105	128	140
17-18	1500-0800	44	90	160	291	100
21-22	1600-0800	28	81	40	80	140
23-24	1400-0800	34	105	66	75	180
28-29	1500-0800	46	37	32	40	40
29-30	1500-0800	24	68	47	67	100
30-31	1500-0800	24	88	71	114	80
January	1965					
5- 6	1400-0930	39	157	35	49	120
11-12	1530-1000	24	103	86	100	200
13-14	1500-0900	22	83	75	82	200
18-19	1600-1000	22	108	75	95	80
21-22	1500-0800	12	69	36	60	60
25-26	1500-0830	23	56	43	73	40
28-29	1530-0800	19	101	95	106	200

TABLE II (Contd)

Dates	Time (MST)	G	Q	I	K	C
February	1965					
2- 3	1430-0800	20	56	73	80	120
3- 4	1500-0800	16	125	43	74	180
4- 5	1600-0800	20	67	59	107	80
11-12	1530-0830	9	35	12	20	20
15-16	1600-0830	11	96	106	92	40
16-17	1600-1200	9	75	97	157	140
24-25	1500-0900	29	77	39	65	60
25-26	1500-0730	24	85	75	106	100
March	1965					
4- 5	1530-0800	24	76	54	81	160
16-17	1530-0830	23	102	58	37	200
17-18	1530-0830	33	141	29	48	140
18-19	1530-0800	17	80	137	172	120
22-23	1330-0800	48	67	26	45	100
25-26	1530-0730	31	116	25	55	40
29-30	1530-0900	30	131	81	130	80
30-31	1600-0800	30	122	16	39	80
31- 1	1600-0730	41	90	51	62	80
April	1965					
1- 2	1600-0800	43	88	20	61	40
6- 7	1530-0830	22	82	25	56	60
8- 9	1600-0930	24	100	42	50	100
13-14	1500-0900	26	97	43	70	140
15-16	1530-0900	6	104	68	55	20
19-20	1530-0830	27	110	59	74	60
23-24	1600-0800	21	70	7	38	40
27-28	1500-0730	62	104	34	51	280
28-29	1600-0800	28	60	34	50	80

TABLE II (Contd)

Dates	Time (MST)	G	Q	I	K	C
May	1965					
4- 5	1530-0900	45	90	66	80	240
6- 7	1500-0730	35	97	41	78	60
10-11	1600-0930	58	58	73	89	120
13-14	1430-0800	51	165	68	100	120
17-18	1500-0830	51	149	58	97	80
20-21	1530-0900	34	93	61	89	140
24-25	1500-0830	49	66	38	61	60
27-28	1530-0800	27	120	38	52	40
30-31	1900-0830	59	77	35	44	20
June	1965					
3- 4	1530-0800	11	33	22	52	40
7- 8	1530-0830	19	41	51	39	80
10-11	1600-0900	12	41	27	42	40
14-15	1530-0830	25	46	31	57	40
15-16	1530-0800	25	43	9	34	60
17-18	1530-0800	32	68	82	121	20
22-23	1600-0800	32	34	23	47	40
24-25	1530-1030	42	44	30	84	40
28-29	1500-0830	40	43	44	102	20
July	1965					
6- 7	1500-0800	30	23	23	49	40
8- 9	1600-0830	40	24	33	118	60
13-14	1600-0830	51	72	38	84	140
14-15	1500-0830	74	115	30	110	20
15-16	1600-0830	43	130	60	113	80
19-20	1500-0800	56	92	30	96	100
29-30	1500-0800	42	120	22	44	20
30-31	1600-0700	31	126	23	64	60
August	1965					
3- 4	1600-0900	34	101	15	46	40
5- 6	1600-0830	31	56	34	87	120
6- 7	1530-1200	17	83	32	89	120
9-10	1530-0830	123	28	16	34	80
11-12	1600-0900	22	75	31	41	240

PART II

SOIL AND METEOROLOGICAL ANALYSES

BACKGROUND

Neither the mineralogical analysis nor the meteorological interpretation of airborne dust is new. As early as 1842 Dufrenoy [2] determined the mineralogical composition of sirocco dust from the storm of 17 February 1841, which had resulted in a notable dustfall over southern Europe. For the European duststorms of 10 March 1869 and 13 February 1870 Tarry [2] attempted to use meteorological analysis to prove, albeit in a rough manner, that the observed dust originated in the Sahara. During the Dust Bowl days of the thirties in the southwestern United States, Sidwell [20] attempted to link observed mineral content of airborne dust with general weather conditions. Warn and Cox [21] extended the work of Sidwell in the vicinity of Lubbock, Texas, but once again concentrated their efforts on the analysis of dust from duststorms. They compared sediments trapped out of the air with surface soil samples collected in the immediate area, and arrived at general relations between mineral content of airborne material, mineral content of soils, wind speed, and wind direction.

Duststorms contain vast quantities of material, material which may seriously interfere with the transmission of infrared radiation. Over the semidesert terrain of the Tularosa Basin such visual concentrations of dust are, in part, due to the wind action on the soils of the Basin, but also to the wind originally acting on soils up to hundreds of kilometers from the Basin, such as the plowed lands of the western Great Plains; the desert country of western New Mexico, Arizona, southern California, and northwestern Mexico; and the waters of the Pacific Ocean and Gulf of Mexico.

Studies on the mineral content of the atmosphere which are based on samples taken at times of visibility restrictions as defined by blowing dust or duststorms (see page 2) may prove to be of limited usefulness for "overall" general mineral content studies due to the infrequency of occurrence. (For example, see Clements [22] for the Southwest in general or Hoidale [23] for the White Sands Missile Range dust sampling site in particular.)

In addition, it would be folly to assume that the dust in the air over the Tularosa Basin resulted solely from the wind scouring the Animas Playa near Lordsburg, New Mexico, a cold front transporting dust in from the Great Plains, or a dust devil on a lazy summer afternoon. The dust sampled during the November 1964 to August 1965 period may include various oceanic salts from the Gulf of Mexico or the Pacific Ocean, cosmic dust of unknown origin,

volcanic dust from Bali, natural ash from a fire on the southern slopes of the Organ Mountains, industrial dust carried north from El Paso.

The purpose of Part II is to put the data of Part I into a comprehensible pattern and to offer a rational explanation for this pattern. The role of the atmosphere in this pattern is admittedly complex, but it is hoped that the systematic collection of data, liberally salted with speculation, will allow some unchaining of the myriad of secrets the atmosphere conceals relative to the insoluble mineral particles classified as atmospheric dust. To effect this, a threefold presentation has evolved: (1) presentation of a summary of the mineral content of selected soils of the Southwest, soils which could be the source of the airborne dust over White Sands Missile Range; (2) relation of the observed mineral particle concentrations in the airborne dust to these soils by analysis of the attendant atmospheric conditions; and (3) speculation on the unidentified fraction of the dust mixture.

After a brief introduction to the geology of the area, four types of surface soil deposits within the Tularosa Basin are discussed as sources of airborne dust. The basis for the selection of the 27 local soil samples is then presented. The resultant analyses of these samples, coupled with the analysis of playa samples from the southwestern United States by other investigators, lead to generalizations regarding source regions for gypsum, quartz, kaolinite, illite, carbonates, magnetic minerals, sodium sulfate minerals, and halite. Following comments on the wind-dust relation, with emphasis on those atmospheric factors which influence the wind-dust relation in this area, the data of Part I are analyzed specifically and generally. Three cases of high gypsum concentration are discussed as examples of three different meteorological conditions whereby gypsum may be transported from a highly localized interior basin source to a sampler less than 50 kilometers to the south southwest. Three cases of high quartz concentration are related to mountain waves, thunderstorms, and wind shift. The effect of frontal passage on the kaolinite concentration is exemplified by three cases. Following a month-by-month meteorological analysis of a running-mean, 11-sample composite concentration, the seasonal variation of gypsum and the sample of lowest composite concentration are discussed. Inferences are made relative to the influence of cosmic dust and sea salt particles on the observed concentrations.

AREA SOILS

Regional Geology

Since the first geological study of the Organ Mountains by Antisell [24], a number of investigators have treated the geology of the area [25, 26, 27]. On the basis of their work the following brief sketch of the geologic history of the area from the last major submergence to the present detrital fill is given.

The last major submergence of the area occurred during the Cretaceous Period, some 50,000,000 years ago. Then the land emerged from the sea and weathering and erosion began. As a result, vast quantities of detrital material accumulated in the rift Tularosa Basin and the synclinal-trough Jornada del Muerto Plain [27, p. 12, section c-c].

Tularosa Basin Surface Deposits - General Comments

The sediments comprising these Quarternary and Tertiary valley fills consist of lake, wind, stream, and volcanic deposits. The lava beds are probably only a minor source for airborne dust because of the small area they cover and, more important, because the beds contain virtually no soil except that which has been deposited by the wind in the crevices of the lava, plus a miniscule amount derived from disintegrated lava. The stream deposits and wind deposits are closely linked since stream deposits from the slopes of the surrounding mountains provide a partial source of material for the wind deposits. Area-wise these deposits cover most of the local basins though sparse vegetation may restrict them somewhat as a major source of airborne dust except under certain wind conditions. These deposits consist primarily of the gypsum and quartz dunes of the White Sands National Monument and the extensive red beds to the south of the White Sands. The lake deposits include lacustrine clays and saline deposits and, although covering a small percentage of the area, can serve as good sources for airborne dust since the "lakes" are normally dry, mechanisms are available for disturbing the surface crust, and particle size is generally small.

For a description of various desert surface types common to the southwestern United States see Clements, et al. [28].

Soil Sampling

Realizing that certain local soils may contribute more heavily than others to the airborne dust over the Tularosa Basin, it became

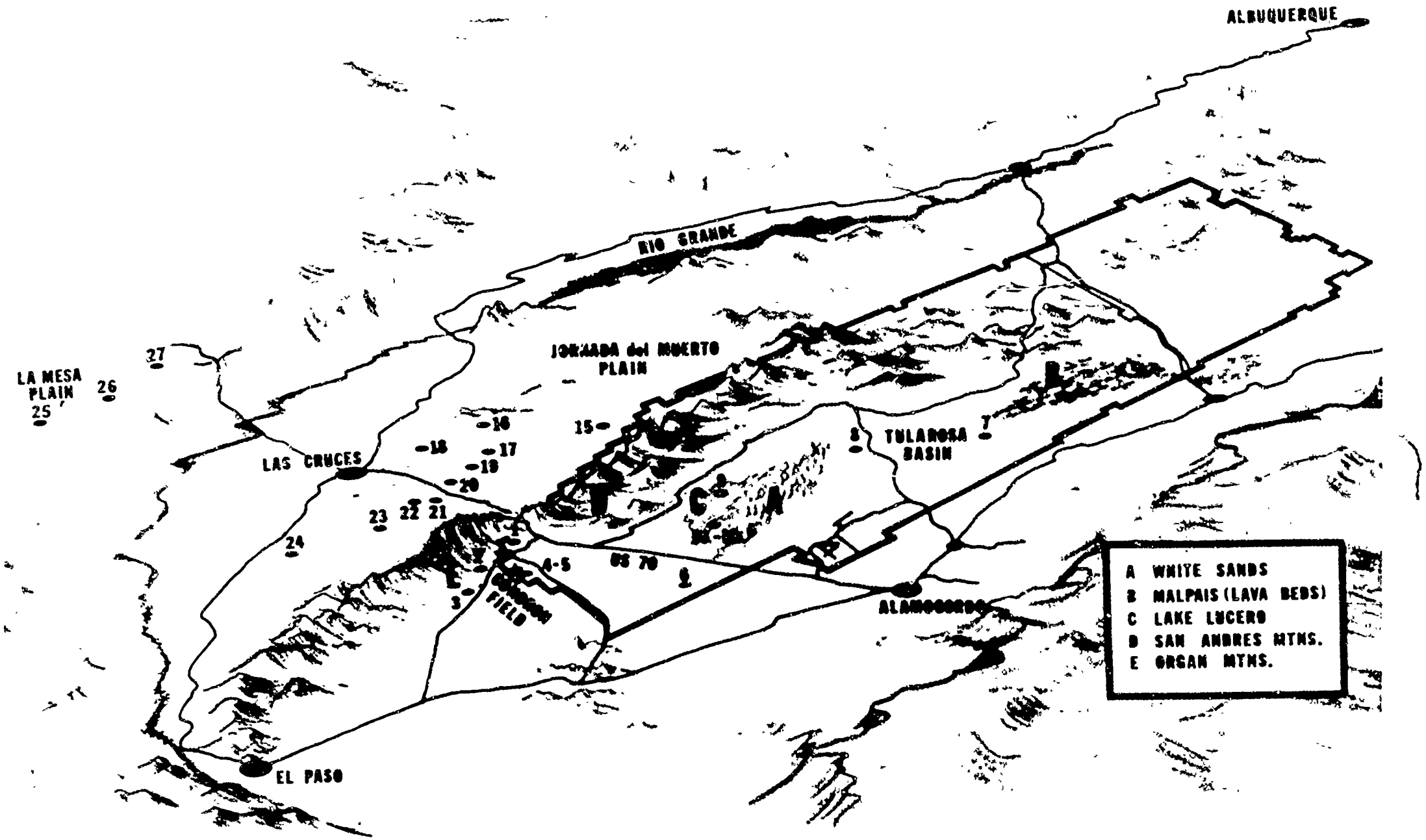

Fig.6 NUMBER AND LOCATION OF SOIL SAMPLES, SOUTH CENTRAL NEW MEXICO (SEE PAGES 32 TO 34 FOR REFERENCE LIST)

necessary to obtain samples of these "dusty" soils for subsequent size and mineralogical analysis. The sites selected for soil sampling were governed by the dustiness potential of the soil and the prevailing winds. For our purpose a soil is said to be dusty if the soil consists of an adequate supply of dust size particles, if the soil has a low moisture content so that particles are easily separated, and if there is a mechanism, of natural or human origin, to agitate the soil and generate a dust plume.

A second factor contributing to the selection of the sampling locations was the prevailing winds. During the greater part of the year the strong winds in the troposphere over the Tularosa Basin are out of the southwest. Therefore, in addition to samples from the Basin, samples were taken west and southwest of the sampler, hence, the choice of samples from the Jornada del Muerto and the La Mesa Plain (see Figure 6). Farther to the west are the playas which have been observed to be sources of airborne dust [29] and so, because of the prevailing southwesterly winds, may prove to be prime sources of local airborne dust. Recourse to the work of Kerr and Langer [30] and Güven and Kerr [31] yielded mineralogical data on playas considered to be representative of the 66 principal playas of the Southwest [32]. During summer the prevailing wind at the surface is southeasterly. Therefore, several samples to the southeast of the sampler were included. Northeasterly surface winds at the sampler are uncommon, but samples to the northeast of the sampler were included because of the special character of the deposit sampled.

On the basis of soil dustiness and prevailing winds, 27 sites were selected as representative of areas, large and small, which might contribute significant amounts of 5 to 100 micron diameter dust to the atmosphere over White Sands Missile Range under the agency of human and atmospheric factors. The various sites are indicated by number in Figure 6. Table III gives the latitude, longitude, and a brief description of each of the sites. Liter samples were taken from the top 2 1/2 to 5 centimeters of soil.

The 27 samples were sent to the Concrete Division, U. S. Army Engineer Waterways Experiment Station, Jackson, Mississippi for mineralogical and hydrometer analyses. The mineralogical data from their subsequent report are summarized in Table IV. The Munsell soil color and color name [33] appear in Table V, the color referring to that fraction of the soil which passed through U. S. Standard Sieve Series No. 140 (105 microns).

Summarizing these data with respect to the minerals tested for in Part I, it is seen that quartz is the most common mineral in the

TABLE III

SOILS SAMPLES REFERENCE LIST FOR FIGURE 6*

Map No.	Latitude	Longitude	Brief site description
1	32°23'N	106°29'W	Sampler, alluvial fan deposit, northeast slope of the Organ Mtns.
2	32°19'N	106°25'W	Soledad, wind-scoured alluvium perched on an alluvial fan deposit, east slope of the Organ Mtns.
3	32°14'N	106°23'W	Coe Lake, basically lacustrine deposit, ephemeral lake east of the Organ Mtns.
4	32°20'N	106°24'W	Condron Field, intermixed eolian and stream and sheet wash alluvium deposit, adjacent to an ephemeral lake east of the Organ Mtns.
5	32°21'N	106°24'W	Davies Tank, lacustrine-stream wash alluvium deposit, ephemeral lake one kilometer northeast of Condron Field.
6	32°42'N	106°12'W	Red Beds, reddish eolian dunes, five kilometers south of the White Sands National Monument and at the northern edge of an extensive area of such dunes.
7	33°15'N	106°15'W	Minnow, lacustrine deposit, ephemeral lake north of the White Sands dunes and south of the Malpais lava beds.
8	33°07'N	106°20'W	Salt, eolian dune, north of ephemeral Lake Lucero.
9	32°41'N	106°25'W	Lucero 1, lacustrine deposit, west edge of Lake Lucero.
10	32°41'N	106°24'W	Lucero 2, lacustrine deposit, center of the southern extension of Lake Lucero.
11	32°40'N	106°24'W	Lucero 3, lacustrine deposit, southern "shore" of Lake Lucero.

TABLE III (continued)

Map No.	Latitude	Longitude	Brief site description
12	32°40'N	106°24'W	Lucero 4, eolian dune, southern edge of Lake Lucero.
13	32°40'N	106°21'W	Lucero 5, eolian dune, southeast of Lake Lucero.
14	32°40'N	106°22'W	Lucero 6, lacustrine deposit, southeast of Lake Lucero.
15	32°38'N	106°41'W	Jornada 1, alluvial-fan piedmont sand dune deposit, west of the San Andres Mountains.
16	32°32'N	106°44'W	Jornada 2, basin-floor deposit, west of the San Andres Mountains.
17	32°31'N	106°43'W	Jornada 3, basin-floor deposit, west of the San Andres Mountains.
18	32°29'N	106°45'W	Jornada 4, alluvial-fan piedmont deposit, east of the Dona Ana Mountains.
19	32°29'N	106°43'W	Jornada 5, alluvial-fan piedmont deposit, west of the San Andres Mountains.
20	32°25'N	106°41'W	Jornada 6, alluvial-fan piedmont deposit, west of the Organ Mountains.
21	32°23'N	106°42'W	Jornada 7, alluvial-fan piedmont deposit, west of the Organ Mountains.
22	32°22'N	106°42'W	Jornada 8, alluvial-fan piedmont deposit, west of the Organ Mountains.
23	32°15'N	106°39'W	Jornada 9, alluvial-fan piedmont deposit, west of the Organ Mountains.
24	32°09'N	106°37'W	Rio Grande 1, basin-floor deposit, southwest of the Organ Mountains.

TABLE III (continued)

Map No.	Latitude	Longitude	Brief site description
25	32°06'N	106°52'W	Rio Grande 2, basin-floor deposit, west of the Rio Grande River on the La Mesa Plain.
26	32°13'N	106°51'W	Rio Grande 3, basin-floor deposit, west of the Rio Grande River on the La Mesa Plain.
27	32°17'N	106°54'W	Rio Grande 4, basin-floor deposit, west of the Rio Grande River on the La Mesa Plain.

*Most or all of the sampled horizons probably contained an eolian component.

TABLE IV

MINERALOGIC COMPOSITION OF SOILS SAMPLES

SAMPLE	QU	FE	AM	MI	MA	IL	CA	DO	GY	HA	SY	KG	MO	CM	ML	CV
	NONCLAY											CLAY				
1	A	A	M	M	R	-	-	-	-	-	-	R	-	-	-	-
2	A	A	M	M	R	-	-	-	-	-	-	M	-	-	-	-
3	M	M	-	R	T	-	C	-	-	-	-	R	R	-	-	-
4	A	C	R	-	R	-	A	-	-	-	-	R	R	R	-	-
5	A	A	-	M	R	-	M	-	-	-	-	R	R	-	-	-
6	A	C	-	-	R	-	M	-	M	( )	-	R	( )	R	-	-
7	A	C	-	-	R	-	M	-	-	-	-	R	T	R	-	-
8	C	T	T	-	R	-	R	-	A	-	-	T	-	T	-	C
9	C	M	R	R	R	-	A	(R)	A	M	(R)	R	C	C	C	-
10	M	M	( )	-	T	T	M	-	C	C	-	R	-	R	-	R
11	R	R	R	-	T	T	T	-	A	M	-	R	R	R	-	-
12	M	M	R	-	R	-	C	-	A	C	-	R	-	R	-	R
13	R	R	( )	-	R	-	R	-	A	-	-	T	-	R	-	-
14	C	M	-	T	T	-	A	R	-	-	-	R	R	R	-	-
15	A	C	-	-	R	-	R	-	-	-	-	R	R	R	-	-
16	A	C	-	-	R	-	M	-	-	-	-	R	T	R	-	-
17	A	M	-	-	R	-	C	-	-	-	-	R	T	R	-	-
18	A	A	R	-	R	-	-	-	-	-	-	R	R	R	R	-
19	C	M	T	( )	R	-	C	-	-	-	-	R	-	( )	-	C
20	A	M	-	M	R	-	-	-	-	-	-	R	T	-	-	-
21	A	C	-	-	R	-	-	R	A	-	-	R	-	T	-	R
22	A	M	-	-	R	-	A	-	-	-	-	R	T	T	-	-
23	A	C	( )	-	R	T	-	-	-	-	-	R	-	R	-	-
24	C	C	-	-	R	-	C	( )	-	-	-	R	R	R	-	-
25	A	C	-	-	R	-	T	-	-	-	-	R	T	R	-	-
26	A	M	-	-	R	-	R	-	-	-	-	R	T	R	-	-
27	A	C	-	-	R	-	M	-	-	-	-	R	T	T	-	-

A - ABUNDANT OR MAJOR MINERAL IN SAMPLE
C - COMMON OR SECONDARY MINERAL IN SAMPLE
M - MINOR MINERAL IN SAMPLE
R - RARE MINERAL IN SAMPLE
T - TRACE MINERAL IN SAMPLE
( ) - SUSPECTED OR UNCONFIRMED MINERAL IN SAMPLE
- - MINERAL NOT DETECTED IN SAMPLE

QU = QUARTZ
FE = FELDSPAR
AM = AMPHIBOLE
MI = MICA
MA = MAGNETITE
IL = ILMENITE
CA = CALCITE
DO = DOLOMITE
GY = GYPSUM
HA = HALITE
SY = SYLVITE
KG = KAOLIN GROUP
MO = MONTMORILLONITE
CM = CLAY MICA
ML = MIXED LAYERED
CV = CHLORITE OR VERMICULITE

TABLE V

MUNSELL SOIL COLOR

SAMPLE	SOIL COLOR	COLOR NAME
1	10.0YR 5.0/3.0	BROWN
2	10.0YR 5.0/3.0	BROWN
3	10.0YR 4.5/3.0	BROWN
4	10.0YR 5.5/3.0	PALE BROWN
5	10.0YR 4.5/3.0	BROWN
6	10.0YR 6.0/3.5	LIGHT YELLOWISH BROWN
7	10.0YR 6.5/3.0	VERY PALE BROWN
8	7.5YR 7.5/4.0	PINK
9	10.0YR 6.0/3.0	PALE BROWN
10	10.0YR 7.0/2.0	LIGHT GRAY
11	10.0YR 8.0/2.0	WHITE
12	10.0YR 5.5/3.0	PALE BROWN
13	10.0YR 8.0/2.0	WHITE
14	10.0YR 7.0/2.0	LIGHT GRAY
15	7.5YR 5.0/4.0	BROWN
16	7.5YR 5.5/4.0	LIGHT BROWN
17	7.5YR 6.0/4.0	LIGHT BROWN
18	10.0YR 5.5/3.5	LIGHT YELLOWISH BROWN
19	10.0YR 7.0/3.0	VERY PALE BROWN
20	7.5YR 4.5/4.0	BROWN
21	7.5YR 5.0/4.0	BROWN
22	10.0YR 6.0/3.5	LIGHT YELLOWISH BROWN
23	7.5YR 4.5/4.0	BROWN
24	MISSING	
25	7.5YR 5.0/4.0	BROWN
26	7.5YR 5.5/4.0	LIGHT BROWN
27	5.0YR 4.5/6.0	YELLOWISH RED

area soils, gypsum is common in and around Lake Lucero, the clays kaolinite and illite are generally locally rare, and calcite runs the gamut from not detected to being the major mineral. These data are in general agreement with data of Kerr and Langer [30, p. 61] who analyzed the crustal constituents of playas of the Mojave Desert of southern California and with data of Güven and Kerr [31] on Great Basin playa clays which included the Animas Playa of southwestern New Mexico. These minerals plus selected minerals noted in Part III will now be discussed in a little more detail in reference to source areas.

Quartz

The 27 local samples indicate that the alluvial-eolian dune deposits so common to this area are predominantly quartz. On the basis of the x-ray analysis of 27 samples from 16 representative Mojave playas, Kerr and Langer [30] state that although a number of minerals are present, the granular fraction, i.e., greater than 10 microns in least dimension, is predominantly quartz and feldspar. The quartz-laden local soils are generally quite porous and where the water table is sufficiently deep would tend to dry out rapidly even after heavy rains, thus providing a ready source of airborne dust particles even when playas are flooded. The vegetation which tops many of these dunes restricts the movement of the dunes, per se, but is not extensive enough to afford sufficient protection to the loose fine grains when the wind is strong, when the wind shifts, or when mountain waves and thunderstorm downdrafts blast down from above.

Gypsum

The primary surface deposit of gypsum in southern New Mexico, if not in the world, is the 1250 square kilometers which encompass the Lake Lucero-Alkali Flats-White Sands area located 35 to 75 kilometers north northeast of the sampler within the confines of the Tularosa Basin. Bedded gypsum in the San Andres Mountains, subjected to erosion and solution following Tertiary uplift [34], has concentrated in playas at the lowest parts of the Basin near the eastern foot of the San Andres Mountains. Predominantly southwesterly winds have scoured the gypsum particles from Lake Lucero and the Alkali Flats and deposited them in the 96 percent pure gypsum dunes to the northeast.*

The primary source of airborne gypsum over the Tularosa Basin is felt to be Lake Lucero and the southern portion of the Flats, not the area of the dunes. Within this region the water table is

*for various theories on the origin of the gypsum deposits see Vandiver [37, 395-397].

generally within a few feet of the ground surface [25, p. 105, 35, or more recently, 36]. The saline water ascends to the surface by capillary action and evaporates, leaving an alkali crust consisting of small crystals of gypsum and resultant anhydrous powders, and other soluble salts, such as sodium chloride, which would tend to be more easily redissolved by rainwater and surface runoff. After infrequent rains much of this area may be flooded, but this does not preclude the areas acting as a source for airborne solid particles since it is known that whitecaps and wavelets entrain air to form bubbles which, upon bursting, produce airborne droplets [5, p. 80]. Subsequent evaporation in the normally very dry atmosphere over the Flats could reduce the droplets to a number of airborne salt particles. Intense evaporation over the Flats soon renders the flooded portions dry, but covered with saline dust and crystals.

In the area of the dunes neither the dunes, per se, nor the interdune areas are generally considered to be a good source of airborne dust over the Basin. The grains of the dunes are too large to be airborne except in the case of exceptionally strong winds, or when a moderate wind blows normal to the slip-face, where the finest particles are deposited. In the interdune areas of the active dune belt, the water table is shallow [35], and thus could contribute gypsum particles to the surface via capillary action. However, in contrast to the open expanse of the Flats, these areas are surrounded by dunes which act as wind breaks, thus generally leaving the interdune areas as sinks, rather than sources, of airborne particles. Changes of wind direction and/or speed could allow these sinks to act as sources depending on the dune orientation and location with respect to the interdune area.

A small portion of the airborne particles of gypsum may result from the mechanical disintegration of the large selenite* crystals west of the Flats.

In contrast to the precipitates which dominate the deposits of the southern part of the Flats, the northern part furnishes the material for the quartz dunes into which the gypsum dunes gradate on the northern end of the White Sands National Monument. Also, in the surface materials of the precipitate area the ratio of chlorides to sulfates increases toward the north [37, p. 393].

With the exception of the aforementioned deposit, surface deposits of gypsum are not common in the Southwest. Gypsum dunes do occur near Mesquite Dry Lake northwest of Jean, Nevada [28, p. 83] but the area is not large. Moreover, gypsum is not a common constituent of the playas to the west of the sampler. Kerr and Langer [30]

*crystalline form of gypsum

reported gypsum in only 8 out of the 27 samples, and even then it was present only as a trace in five of the samples. Out of nine samples from five widely separated playas Güven and Kerr [31] reported gypsum in only the sample from the Upper Sevier, Utah.

Kaolinite-Illite

The kaolin group represents three distinct species, namely kaolinte, nacrite, and dickite, with kaolinite characterizing the majority of kaolins [38, pp. 29-30]. Therefore, based on the data of Table IV, it may not be justifiably concluded that kaolinite is more common than illite. The data of Kerr and Langer [30] support the generally accepted fact that illite and montmorillonite are the characteristic clays of the soils of arid regions. In fact, they state that these two clay minerals consititute the major portion of the clay size, i.e., one to five microns in diameter, though for the bulk samples the two minerals were present in only trace amounts. If the same were true for the local samples, then clay minerals would constitute the bulk of the clay-size particles, which would account for such high concentrations of illite and kaolinite despite the small amounts present in total sample. In prairie soils both illite and kaolinite are usually present [38, p. 340], with illite being slightly more abundant. Thus, it would appear that of the two clay minerals, illite and kaolinite, illite predominates in the soils of the Southwest. However, kaolinite concentrations are generally greater than illite concentrations in our samples. Perhaps the source regions were predominantly kaolinite; or perhaps kaolinite is more common in the 5 to 100 micron soil fraction than illite, even though illite constitutes the bulk of the sub 5 micron fraction; or perhaps, as suggested by Mason [39, p. 556], kaolinite is the most stable of all the clay minerals.

An interesting aside is the observation of Jacobs and Ewing [40] that illite was the most abundant mineral in a surface-water sample from the Caribbean Sea north of Colombia.

Carbonates

As noted in Part I, the term 'carbonates' includes the minerals calcite, dolomite, and aragonite. Of the three, dolomite and calcite are the most common. According to Feth et al. [41], "in the intermontane areas of the West, alkaline-earth carbonates are a major constituent of the prevailing pedocal soils ... ." Locally, calcite was detected in all but six of the twenty-seven samples and was a major mineral in four samples, one from Condron Field, two from Lake Lucero, and one west of the Organ Mountains. In the playa study of Kerr and Langer [30], calcite, dolomite, and aragonite were

present in that order of occurrence. Calcite was the major mineral in one sample, a secondary mineral in another sample. In the remainder of the samples calcite, aragonite and dolomite were either not present or present only as minor, rare, or trace minerals. The Animas Playa of southwestern New Mexico is reported to have a low saline content with calcite the chief saline mineral [31]. In many soils along the mountain slopes of the Southwest, the carbonate content increases with depth below the surface. Thus, landscape dissection could expose layers with successively higher carbonate content.

Other Minerals

Magnetic

Locally, magnetite was present in all samples while ilmenite was reported as a trace mineral in three samples. However neither of these minerals was reported by Kerr and Langer.

Mirabilite-Thenardite

Mirabilite is hydrated sodium sulfate ($Na_2SO_4.10H_2O$); thenardite is anhydrous sodium sulfate (Na_2SO_4). Neither mineral was detected in the analysis of the 27 local soil samples. However, according to Wells [42] sodium sulfate is a constituent of surface salts and lake deposits in many areas of the Southwest. In particular, Wells has cited the area between the San Andres Mountains and the gypsum dunes as a source for sodium sulfate. Thenardite was detected in seven of the Kerr and Langer samples, but only the sample from the Soda Playa, California contained more than a trace amount. Güven and Kerr detected thenardite only in certain samples from the Deep Springs Playa, California.

The presence of mirabilite or thenardite at a given source is dependent on temperature, moisture, and the amount of sodium chloride present [42]. Thus thenardite on a normally dry playa may transform to mirabilite at times of high water table or abundant rainfall. Conceivably, source mirabilite could become thenardite in atmospheric transport in the normally arid Southwest. This problem will be examined in more detail in a later report.

Halite

Halite, i.e., sodium chloride, was a secondary or minor mineral in the four local samples from Lake Lucero. Kerr and Langer [30] found halite as the major mineral in three samples, a secondary mineral in two others, and a minor mineral in four samples. Halite was detected in seven of the nine Güven and Kerr [31] samples.

Exposed 'salt' areas are also known east of El Paso [43]. Thus salt sources exist at least to the south, west, and north of the sampler. Oceanic sources exist to the southeast (Gulf of Mexico) and southwest (Pacific Ocean).

WIND-DUST RELATION

The removal of soil particles from the earth-air interface into the atmosphere for subsequent translocation is a complicated process. The purpose of this section is not to present the many facets of the problem of wind erosion of soil particles from a land surface (see Hilst and Nickola [44] for a summary), but to gain some insight into the complexity of the problem.

The transfer of dust from a soil surface into the atmosphere is basically a function of an agent of natural or human origin acting upon dust-size particles.

Particle Size

Local soils have relatively low amounts of sub 100 micron diameter particles as indicated in Table VI, which was derived from the gradation curves supplied with 9 of the 27 samples analyzed by the U. S. Army Waterways Experiment Station. Samples 1 and 8 display the results of eolian ablation coupled with a lack of stream deposit influx of fine particles or lee-side sheltering.

TABLE VI

WEIGHT PERCENTAGE OF SUB 100 MICRON PARTICLES IN SELECTED SOIL SAMPLES

Sample	Percent finer than 100 microns diameter (by weight)
1. Sampler	7
2. Soledad	19
4. Condron Field	23
5. Davies Tank	17 1/2
6. Red Beds	21
8. Salt	7 1/2
9. Lake Lucero 1	23
18. Jornada 4	33
21. Jornada 7	28

The playa samples analyzed by Güven and Kerr [31] show that particles of diameter less than 100 microns constitute nearly 90 percent of the weight of the sample. The argillic playa samples of Kerr and Langer [30] show that 33 to 99 percent of the weight of the samples is composed of particles of diameter less than 80 microns. Thus, the playas contain an abundance of fine particles, but this does not necessarily imply a good source of airborne dust. For example, Hafer [45] considers soils of more than one percent by weight of sub 75 micron diameter particles to be dusty when subjected to vehicular traffic.

Generally, soils in this area are not of high moisture content. The loosely consolidated, highly permeable soils permit relatively rapid percolation of the infrequent rain to the water table or perched water table far beneath. At the sampling site the water table is about 100 meters below the ground surface. In addition, low humidity, intense surface heating, and moderate winds combine to relieve the soils of their moisture by evaporation, the rate of which is some ten times that of the incident precipitation.

Certain soils, such as from the playas, contain a high percentage of the fine clay particles. These particles may be so agglomerated and present such a smooth surface that they may not be dislodged, even in the presence of gale force winds [44; 22, p. 45; 46]. Agglomeration may be a particularly important factor in certain areas of the Southwest where the water table, or perched water table, is near the surface.

The effect of roughness elements on eolian ablation is difficult to determine. On the one hand they serve to reduce the wind speed and provide lee-side sheltering and lee-side sinks; on the other hand they generate turbulence elements which enhance the vertical transfer of momentum [44].

Dislodging Agents

The agent responsible for the entrainment of particles into the atmosphere from the ground surface may do so by acting upon loose particles or by breaking a surface crust to expose loose particles. The agent may be human or natural. An example of the former would be vehicular traffic which, in addition to the mechanical breakup of the surface, thus exposing many particles to wind erosion, serves to mechanically fracture the grains to finer particles.

Wind is perhaps the logical choice for the atmospheric agent acting upon the soil, taking many forms such as dust devils,

thunderstorm downdrafts, mountain waves, and state-wide duststorms. The wind serves both to erode and translocate the particles. Its effectiveness will depend, among other things, upon the speed, direction, angle of attack, and gustiness. Strong winds are not the sole natural agents. Twomey [47] has shown that large numbers of cloud nuclei are released from the soil when it is heated by radiation in dry conditions.

With even these few factors in mind, it is no wonder that the pickup speed of the wind is not unique for a given grain size [22,45]. Nonetheless, it has been possible in the field and in the laboratory to investigate the relationship. Clements' University of California group [22]constructed a portable blower and, in the field, subjected six different types of desert surface to varying wind speeds. Their results may be summarized as follows:

(1) Sand dunes, 1.2 meters in height, crests fixed by vegetation, fine quartz sand. At a wind speed of 5.8 meters per second some very fine material was carried in suspension.

(2) Desert flat. At a wind speed of 8 meters per second, there was minor movement of dust-size material in the form of a series of very small eddies.

(3) Dry wash. Similar to desert flat.

(4) Desert pavement (nascent area on an alluvial fan). No movement observed until a speed of 8.7 meters per second had been reached.

(5) Alluvial fan, pronounced crust which, if broken, could supply abundant material for wind transport. Movement of surface material first noted at a wind speed of 15 meters per second.

(6) Playa, salt-clay-silt crust. First movement at a speed of 9.5 meters per second. "The undisturbed surface of a playa is very stable. The finer material available for transportation is protected by a highly cemented surface crust. Winds in excess of 33 miles per hour (14.8 meters per second) would be required to raise a dust or sandstorm on a dry lake of this type."

A similar study by Fedorovich and Nakodeyev (cited by Chu, et al. [48]) shows that a wind of one meter per second may pick up sub 100 micron diameter particles.

On the basis of these data it is seen that it is at best difficult to generalize in regard to critical pickup speeds, especially when no mention has yet been made of the effects of wind direction (including the angle of attack) and of direction changes.

Among the primary atmospheric factors responsible for the translocation of surface dust in this area are evaporation, thunderstorms, and mountain waves. Each will be briefly discussed as it applies to this area.

Evaporation

The effect of evaporation is twofold: (1) it aids in the rapid drying of the porous soils and (2) it aids in maintaining the Lake Lucero-Alkali Flats area as a source of airborne gypsum. The rate of evaporation is primarily governed by the dryness of the air, the speed of the wind, and the temperature of the water. With the exception of Vandiver [37, p. 392] who mentions 710 millimeters of water evaporated during a July, data on evaporation over the Flats are lacking. However, data are available for the Jornada Experimental Range [49, p. 83], which is located about 30 kilometers west southwest of Lake Lucero. These data are summarized in the histogram of Figure 7. Evaporation is at a peak in May and June, though the monthly mean wind speed peak is in April and the maximum monthly temperature is in June and July.

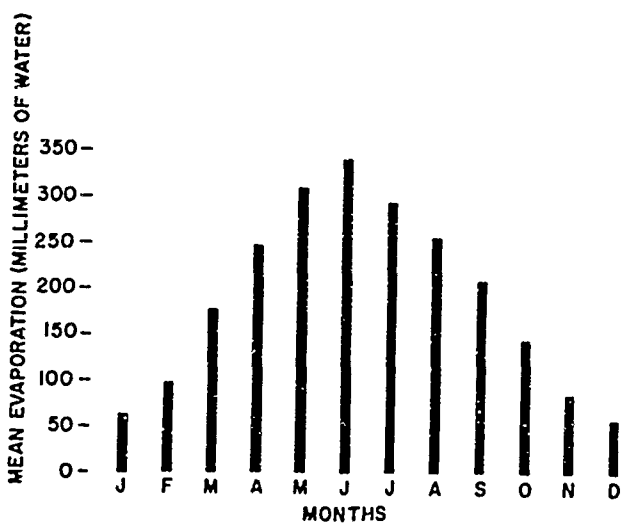

Fig. 7. Monthly Mean Evaporation, Jornada Experimental Range, New Mexico (22 years of record)

Thunderstorms

In this area of generally sparse vegetation, thunderstorms, especially of the dry type, are effective in sweeping large quantities of surface dust aloft. An exceptional storm of this type has been photographed and described by Elser [50]. Warn [51] graphically depicts the circulation in and around a thunderstorm in which strong downdrafts (12 to 20 meters per second) strike the surface obliquely, dislodge the dust which is then transported to great heights by means of strong updrafts. The cause of the downdraft in such dry thunderstorms has been discussed by Krumm [52].

Mountain Waves

Mountain waves result from strong westerly flow across the north-south oriented Organ-San Andres Mountain chain, and consequently are most common over the Tularosa Basin during winter and spring. In those cases where the trough of the mountain wave reaches the surface to the east of the mountains, the resultant force acts obliquely on the surface. At Condron Field, surface easterly flow has been observed a short distance west of the surface impingement of the wave*. A similar effect is believed to occur over the Alkali Flats, which have been observed to lie under the first trough to the east of the San Andres Mountains [53]. These waves may or may not be signatured by the characteristic wave clouds, depending on the availability of moisture.

METEOROLOGICAL ANALYSES

The meteorological analysis of the concentration data of Part I is divided into two sections. The first section is devoted to a description of the meteorological environment which could have accounted for nine cases of high concentration, three each of gypsum, quartz, and kaolinite. In the second section the effect of oceanic particles on the monthly variations of composite mineral concentration is discussed. Also, briefly touched upon are the apparent seasonal variation of the gypsum concentration, the sample of lowest composite concentration, and the influence of cosmic, volcanic, natural combustion, and industrial dust on the observed concentrations. The local wind data used in this study were obtained at the wind sites shown in Figure 8.

*Reported by John N. Reitzel in a private communication dated 1 February 1965.

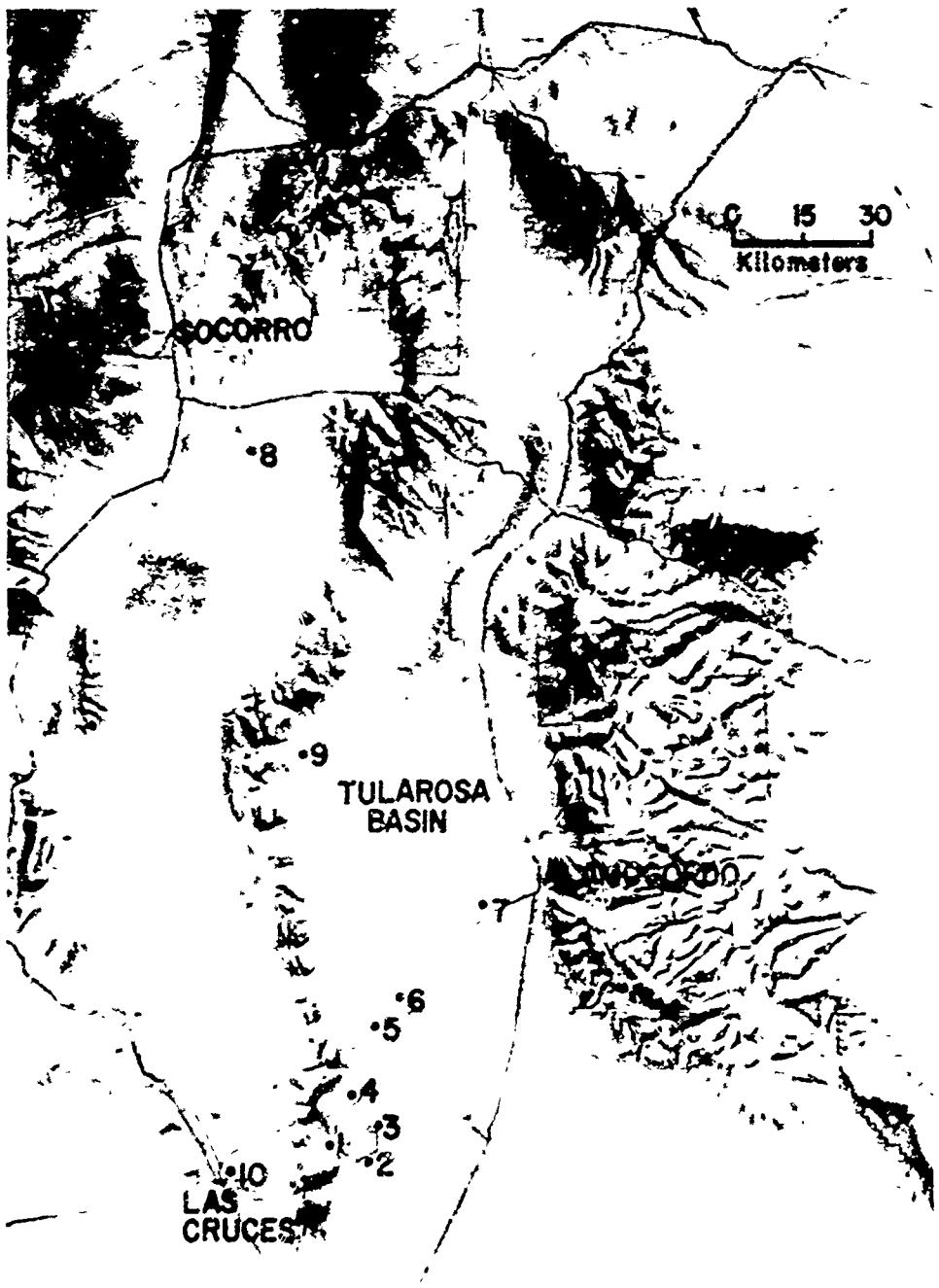

Fig. 8. Number and Location of Wind Sites, South-Central New Mexico (See Page 54 For Reference List)

Before discussing the data of Part I, it is necessary to reemphasize the meaning and significance of the term "particle concentration" as used in this text. Particle concentration refers to the number of particles of a given component of a mixture per one thousand total particles. In the case of our atmospheric dust samples, the mixture consists of an identified fraction and an unidentified fraction, the former consisting of several sub units, i.e., quartz, gypsum, kaolinite, illite, and carbonates. If the mass concentration (mass per unit volume) and the number concentration (number of particles per unit volume) of both the identified and unidentified fractions were to decrease by the same percentage, then the particle concentration of each fraction would remain unchanged, even though there would be less dust in the air. By the same token, a decrease in the particle concentration of the identified fraction signifies an increase in the particle concentration of the unidentified fraction. By extending this reasoning, a decrease in the gypsum particle concentration would represent a combination of three factors: (1) a decrease in the mass concentration of gypsum, (2) a net increase in the mass concentration for the other identified minerals, and (3) an increase in the mass concentration of the unidentified component.

Specific Cases

The concentration data of Part I have been plotted in Figure 9, where the individual data points have been connected by straight lines as an aid to visual acceptance of the data. The straight lines are not meant to imply a linear change in concentration between two points which may be separated in time by periods of up to two weeks. It may be noted that there are apparent high individual concentrations superposed on what may be long period variations. That both the individual and long period variations may be related to source regions through the agency of atmospheric transport will become clearer in the following analyses. The data are summarized in Figures 10 and 11 by month and by particle concentration, respectively.

Gypsum

Concentrations of gypsum were generally quite low (Figure 9) in spite of the fact that the sampler is located within 50 kilometers of one of the world's largest surface deposits of gypsum. The main reason for the low concentration is that the atmospheric circulation is rarely such that particles of gypsum would be transported from the Lake Lucero area to the sampler. However, occasionally the gypsum concentration reaches a relatively high level, such as on 4-5 November 1964, 1-2 December 1964, and 9-10 August 1965. These cases illustrate three diverse manners of gypsum transport from source to sampler.

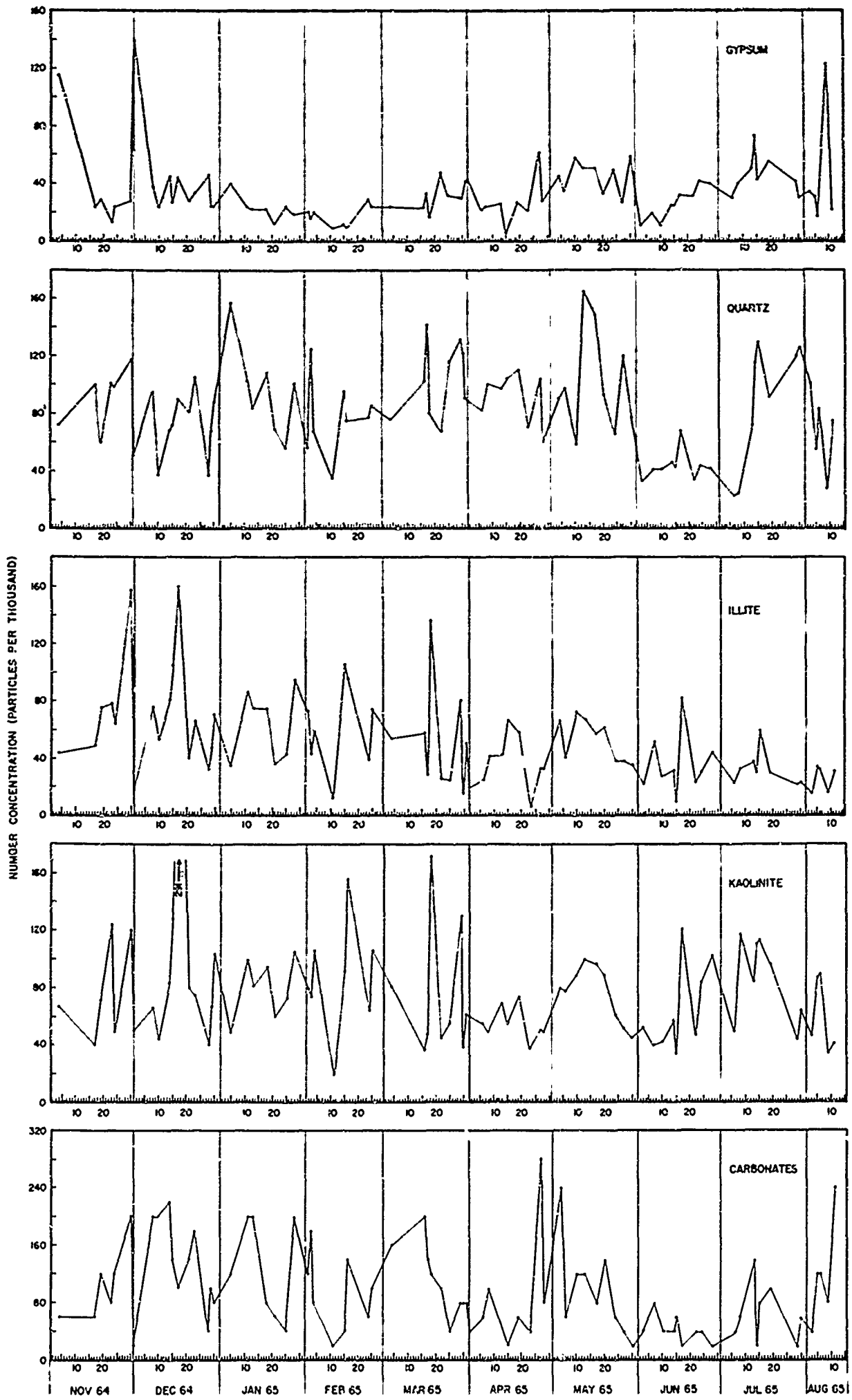

Fig 9 OBSERVED MINERAL PARTICLE CONCENTRATION, WHITE SANDS MISSILE RANGE DUST SAMPLING SITE, NEW MEXICO, NOVEMBER 1964 TO AUGUST 1965 (81 SAMPLES)

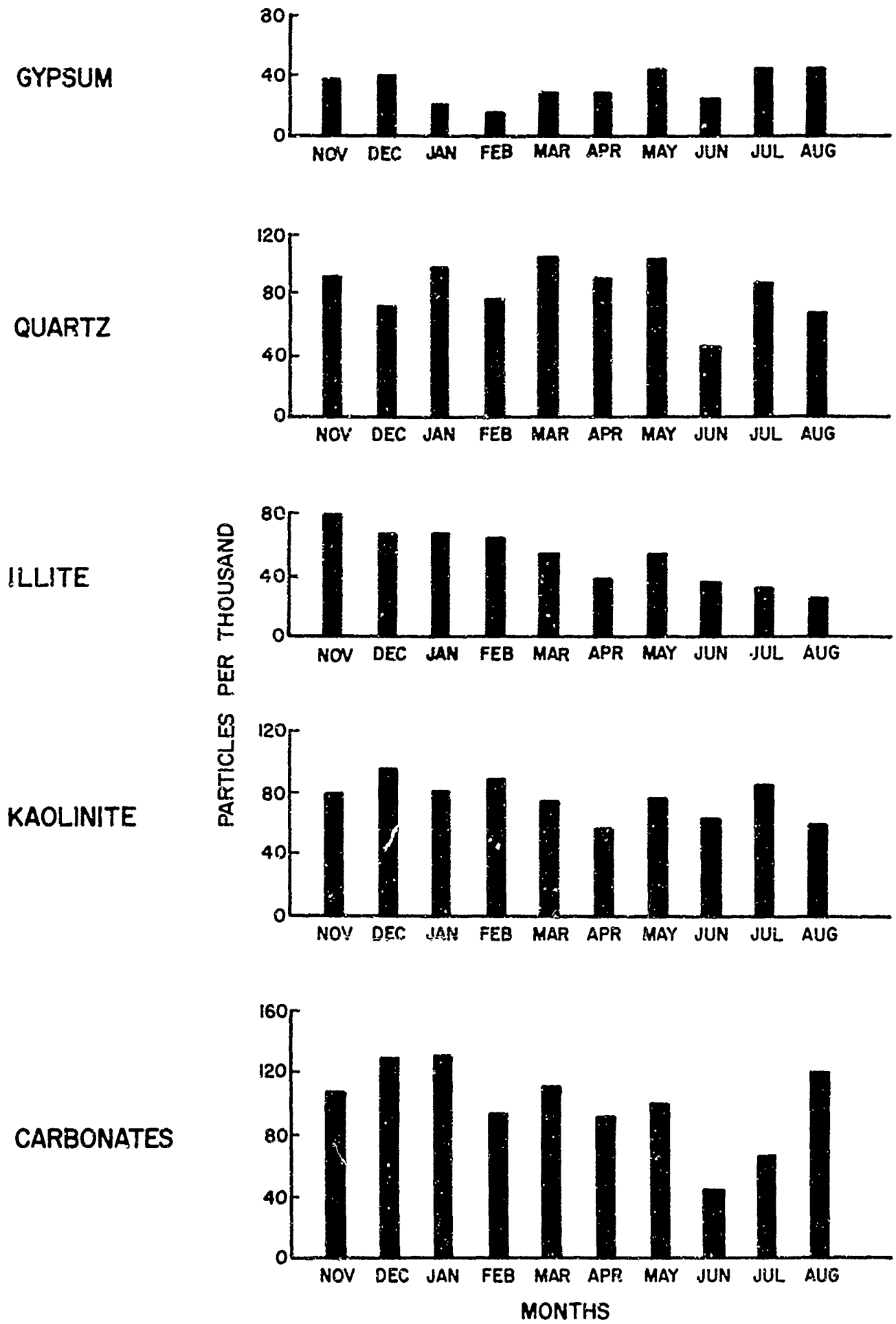

Fig. 10 MONTHLY MEAN MINERAL PARTICLE CONCENTRATIONS, WHITE SANDS MISSILE RANGE DUST SAMPLING SITE, NEW MEXICO, NOVEMBER 1964 TO AUGUST 1965 (81 SAMPLES).

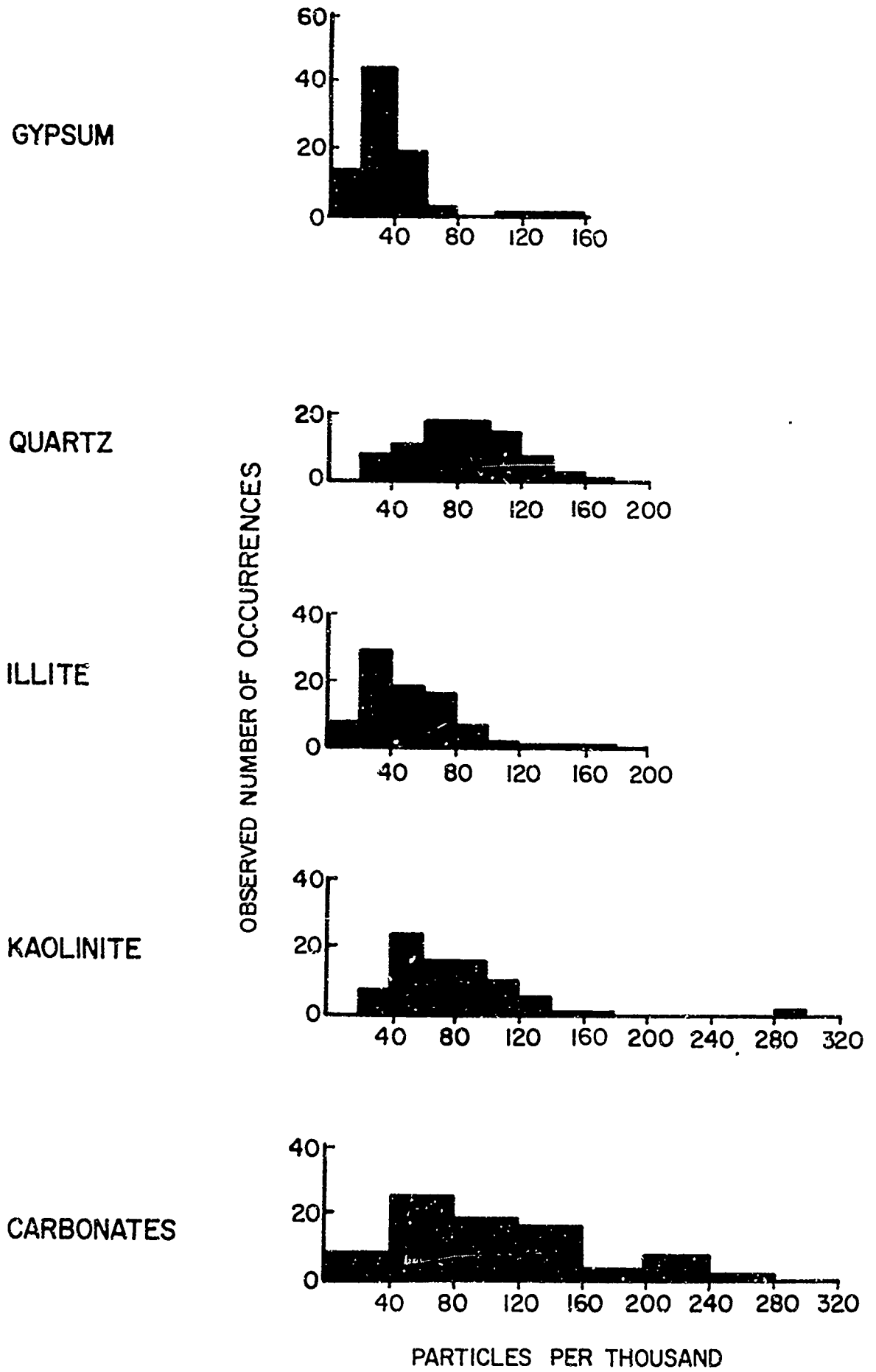

Fig. 11 NUMBER OCCURRENCE OF MINERAL PARTICLE CONCENTRATIONS, WHITE SANDS MISSILE RANGE DUST SAMPLING SITE, NEW MEXICO, NOVEMBER 1964 TO AUGUST 1965 (81 SAMPLES).

4 - 5 November 1964

Figure 12 shows the surface and 500-millibar height contour charts at times midway through and at the start of the sampling period, respectively. The surface weather map shows a high pressure area extending from the central plateau to the central plains. The dominant feature of the 500-millibar flow over the area is an eastward-moving, closed low centered over the southeast tip of New Mexico.

By virtue of the northeast winds aloft, the gypsum could be transported to the sampler if the dust could be entrained into the atmosphere from the source region. A mechanism for so doing was available and is illustrated in Figure 13. For at least 30 hours prior to 1900 MST, 4 November 1964, winds at Southeast 30 (see Table VII) were northerly at speeds up to 14 meters per second. This would allow substantial obstacle lee deposition of fine particles which were then suddenly exposed by the abrupt shift of the wind to a southerly direction at speeds up to 11 meters per second at 1900 MST and consequently entrained into the atmosphere. The surface flow remained southerly until midnight; after midnight the surface winds at all sites were light and variable. The moderate southerly winds were apparently confined to the central portion of the Basin, since at that time winds at Holloman, Jallen and the sampler were light and also supported by the fact that the quartz concentration was not high. The ground was certainly dry as attested by the lack of significant rainfall since 12 September.

At the sampler, winds were out of the northeast from 1500 MST to 1700 MST, 4 November. The wind then veered to the southwest. At 2100 MST the wind became light and variable.

Thus, the picture is one of southerly winds across the surface of the Flats, after a prolonged period of northerly flow, picking up the gypsum particles, which are then transported to the sampler by the northeast winds aloft.

1 - 2 December 1964

The highest gypsum concentration was observed in this sample, taken during a period of strong westerly winds, a condition not likely to foster such a high concentration. Aloft, an eastward-moving trough had passed over the Range by the start of the sampling period (Figure 14), resulting in northwesterly flow aloft during most of the sampling period. At the surface at 2300 MST a low pressure system was centered over the Texas-Oklahoma Panhandle (Figure 14).

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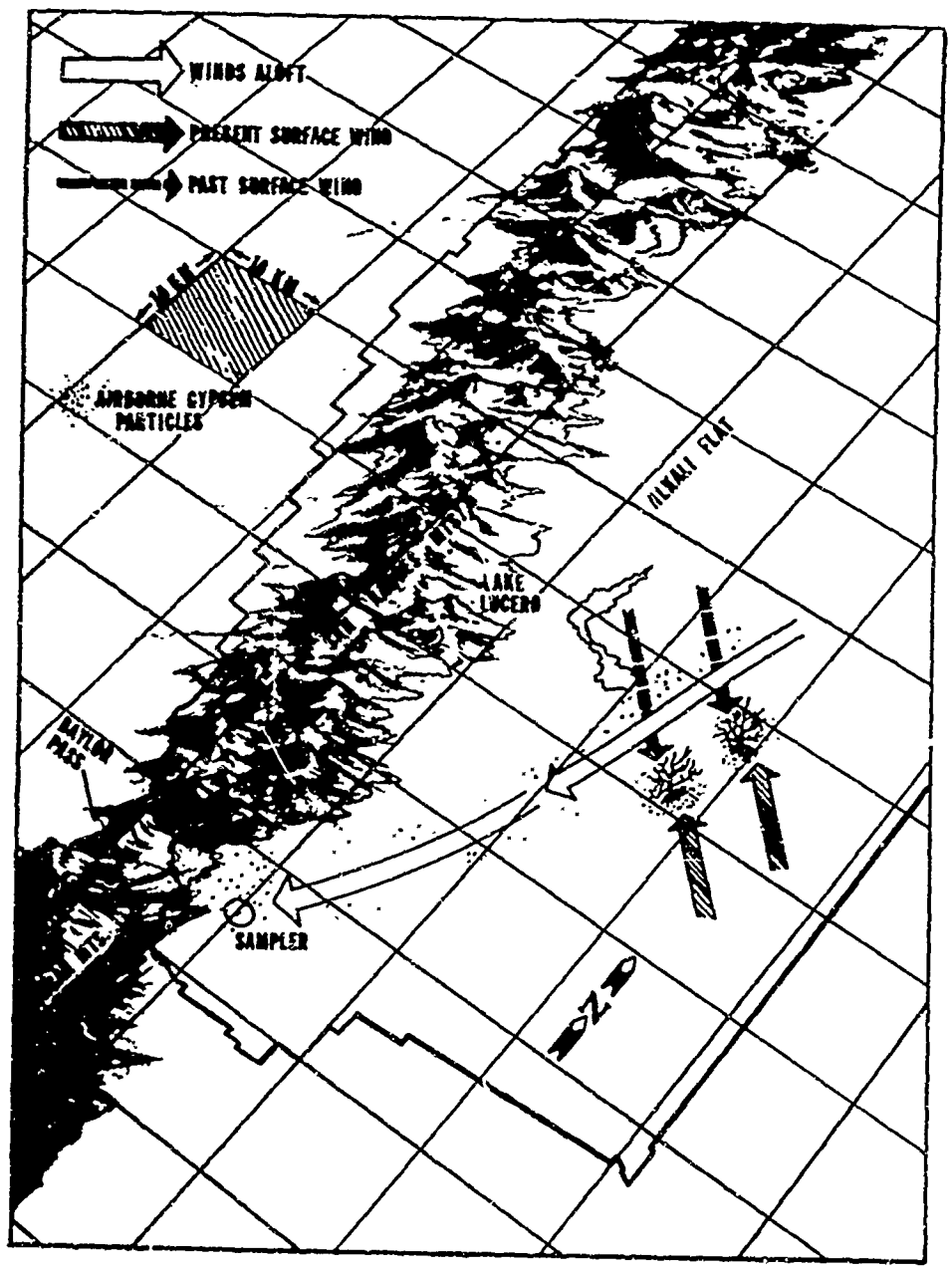
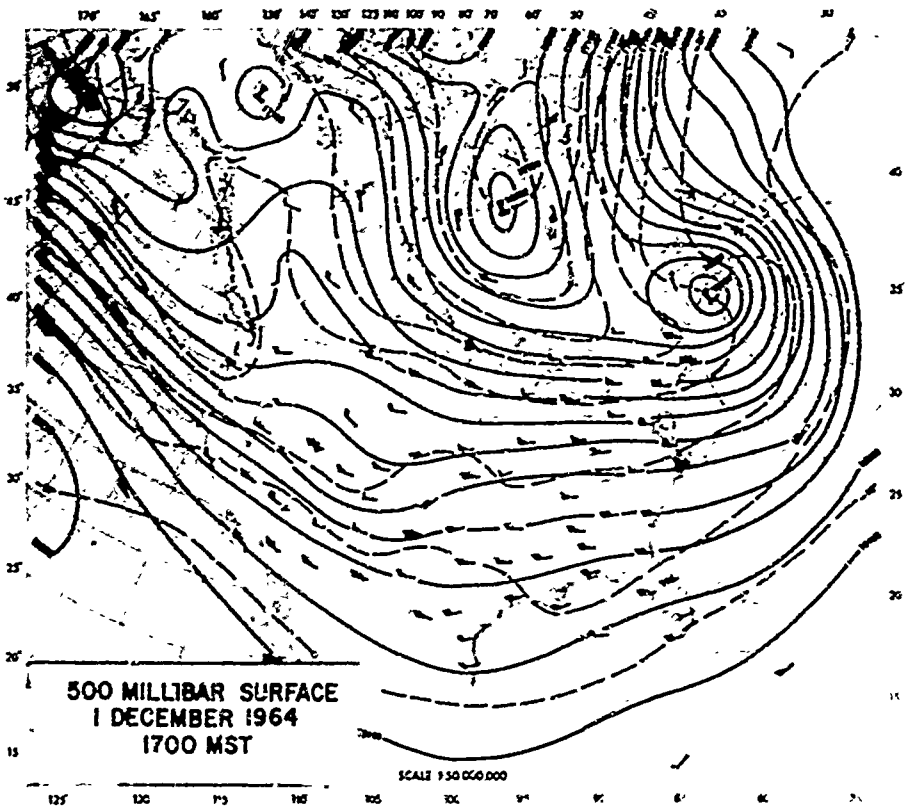


Fig. 13. Schematic Illustration of Gypsum Transport, 4 - 5 Nov 64

TABLE VII

Selected Area Wind Data Stations Reference List for Figure 8

	Station	Elevation (M MSL)	Latitude	Longitude	Surface Data	Radiosonde Data
1.	Sampler	1311	32°23'N	106°29'W	X	
2.	Condron Field	1199	32°20'N	106°24'W	X	
3.	White Sands Desert	1216	32°24'N	106°22'W	X	X
4.	Small Missile Range	1219	32°28'N	106°25'W		X
5.	Apache	1206	32°38'N	106°24'W		X
6.	Southeast 30	1220	32°40'N	106°20'W	X	
7.	Holloman	1247	32°51'N	106°05'W	X	X
8.	Stallion	1506	33°48'N	106°40'W		X
9.	Jallen	1235	33°11'N	106°29'W	X	X
10.	Las Cruces Mobil Met	1201	32°08'N	106°46'W		X



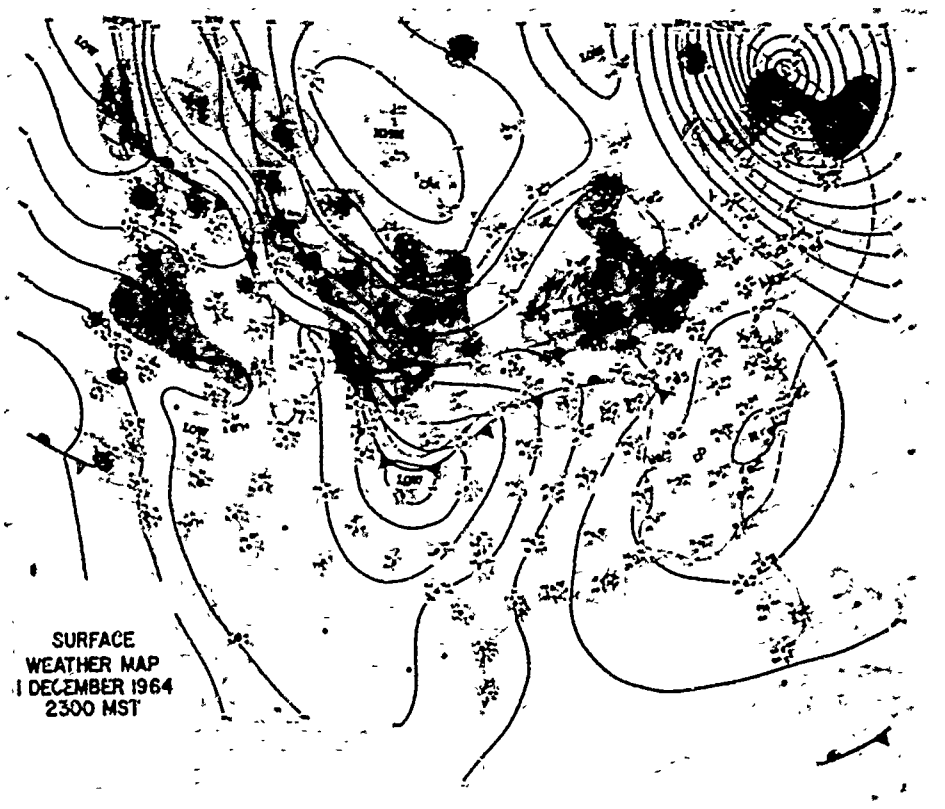


Fig. 14. Synoptic Weather Pattern Associated with Dust Sample of 1 - 2 Dec 64

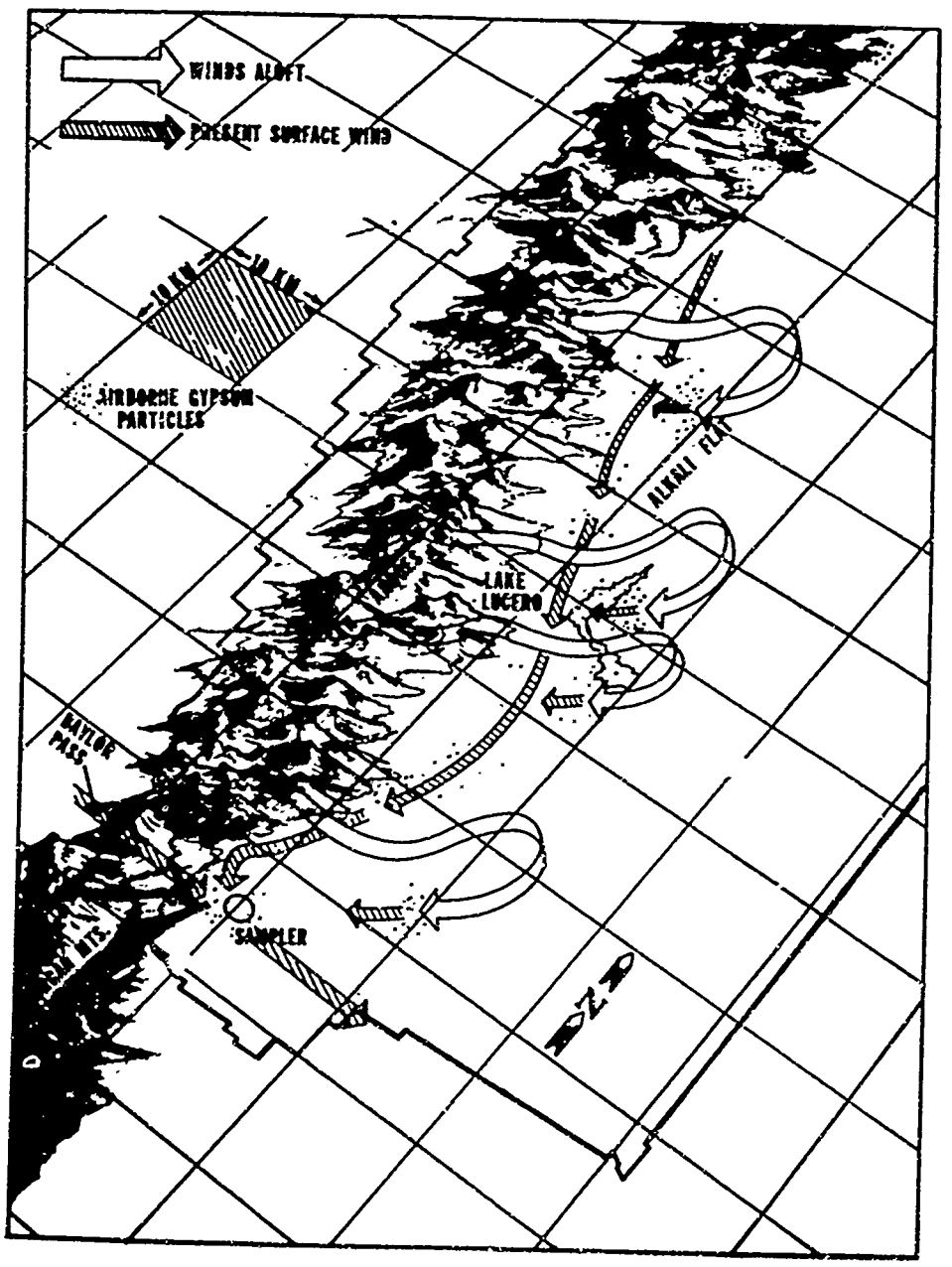


Fig. 15. Schematic Illustration of Gypsum Transport, 1 - 2 Dec 64

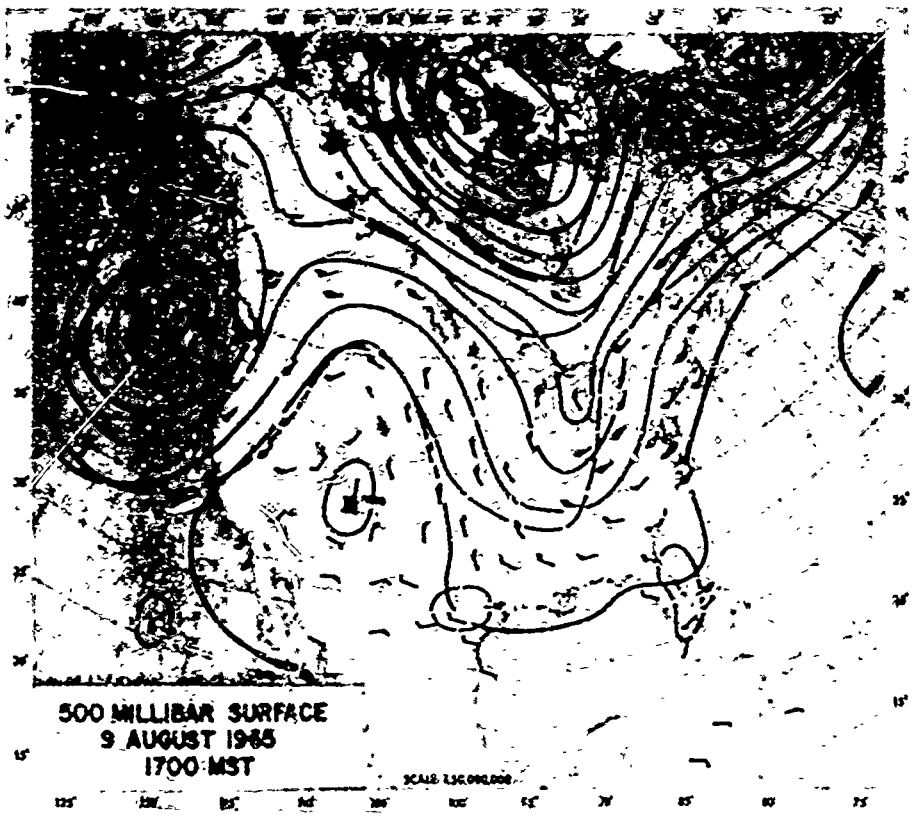
At the sampler, this combination resulted in strong westerly winds at mean hourly speeds ranging from 8 to 12 meters per second and gusts to 20 meters per second during the sampling period. This situation, coupled with 28 particles per thousand gypsum concentration of the previous day, made it difficult to account for the transport of gypsum particles from the Flats southwest to the sampler.

The flow over the basin was complex, but did resolve itself into a pattern which is illustrated in Figure 15, where the airborne dust generating mechanism is assumed to be a mountain wave, which had been signatured by wave clouds earlier on the day of the 1st. At White Sands Desert site, winds were moderate northwesterly; at Southeast 30, moderate to strong westerly and southwesterly. At Jallen, the surface winds were northerly at speeds of two meters per second or less with the exception of light westerly winds from 2100 MST to 0200 MST when the surface temperature rose by 6°C. At Holloman, winds were southeasterly until sunset, southwesterly until 0200 MST, easterly until 0600 MST, and southerly for the remaining three hours of sampling, all speeds being less than five meters per second. This indicates a shifting surface impingement of a mountain wave with White Sands Desert to the west, Southeast 30 to the east, and with Jallen and Holloman under the main stream but within the local low-circulation generated by the mountain wave and supplemente by drainage winds.

The picture is thus one of a mountain wave blasting gypsum particles from the surface and thusting a portion of them back toward the west into a channel bounded by the Organ-San Andres Mountains to the west and the mountain wave overhead. The gypsum particles were then transported toward the south in this duct and entrained into the rapidly moving westerly flow through Baylor Pass (2000 meters MSL, eight kilometers west of the sampler). The persistence of the mountain wave plus high gypsum concentrations within the duct could account for the high concentration at the sampler despite the slow southerly transport within the duct.

9 - 10 August 1965

The last example of a high gypsum concentration is one engendered by thunderstorm activity. Aloft, the western third of the United States was dominated by a slowly northeastward expanding ridge of high pressure which, at the start of the sampling period, was centered over the four corners area of Utah, Colorado, New Mexico and Arizona (Figure 16). Consequently, over the Tularosa Basin the winds aloft up to approximately 6000 meters MSL were generally light easterly during the period of sampling. The surface weather map at 2300 MST revealed weak pressure gradients over the Southwest (Figure 16).



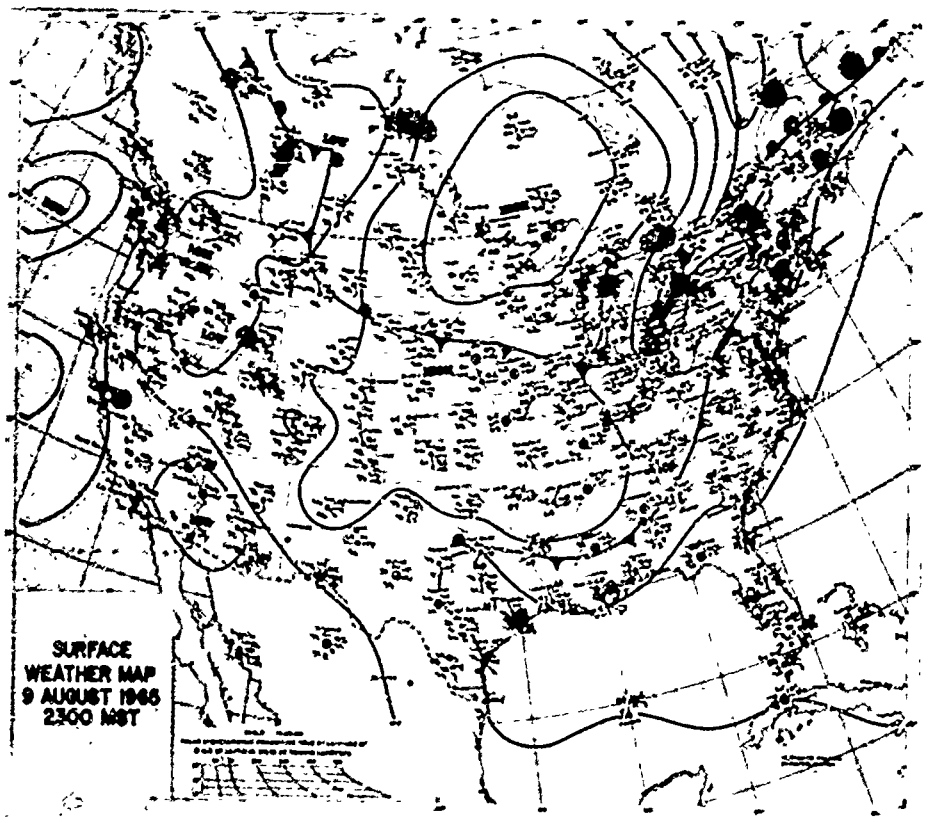


Fig. 16. Synoptic Weather Pattern Associated with Dust Sample of 9 - 10 Aug 65

Analysis of the surface wind data showed that during the afternoon of the 9th winds over the Tularosa Basin were easterly to southerly at speeds of three to five meters per second with gusts to 15 meters per second. By late afternoon thunderstorm activity had developed over the White Sands National Monument area. In response, the surface wind switched to the north and northeast around sunset at mean hourly speeds of 10 to 13 meters per second at all six Basin wind sites. Gusts in excess of 20 meters per second were reported at Holloman and Southeast 30, both located on the southern fringes of the National Monument. Such winds would be sufficient to pick up fine particles from the Flats, expecially because of the earlier southeasterly flow and also because of the lack of precipitation since early in the month. However, the main portion of the pickup was probably due to the angle of attack of the original thunderstorm downdrafts on the surface, which would provide a more efficient scourer than horizontal flow. The low concentration of quartz is evidence that the thunderstorm activity was localized over the gypsum source as far as the dust at the sampler was concerned. Otherwise, quartz concentrations would be expected to be high.

Surface winds at the sampler were out of the east until 1900 MST at which time winds became north northeasterly at speeds up to 15 meters per second. After 2100 MST and until sunrise, winds were light westerly, due primarily to local drainage off of the Organ Mountains. Over the Basin, however, winds remained northerly to northeasterly all night following the initial surge of northeasterly flow. This, coupled with the light northeasterly to southeasterly winds aloft, could account for the observed high gypsum concentration. The mechanism is schematically represented in Figure 17.

The foregoing three examples illustrate that, because of the divers nature of local winds and because of the localized source of gypsum, high gypsum concentrations at the sampler are not a function solely of the surface wind at the sampler. The circulation over the entire Basin must be considered.

Quartz

As already noted, one of the major mineral constituents of the soils of the Southwest is quartz. Hence, an a priori generalization might be that a strong wind at the sampler results in a high quartz concentration. On the basis of the limited data of 81 samples, such a generalization may not be warranted. Three cases of high quartz concentration, illustrating three different dislodging and transport mechanisms, will be discussed.

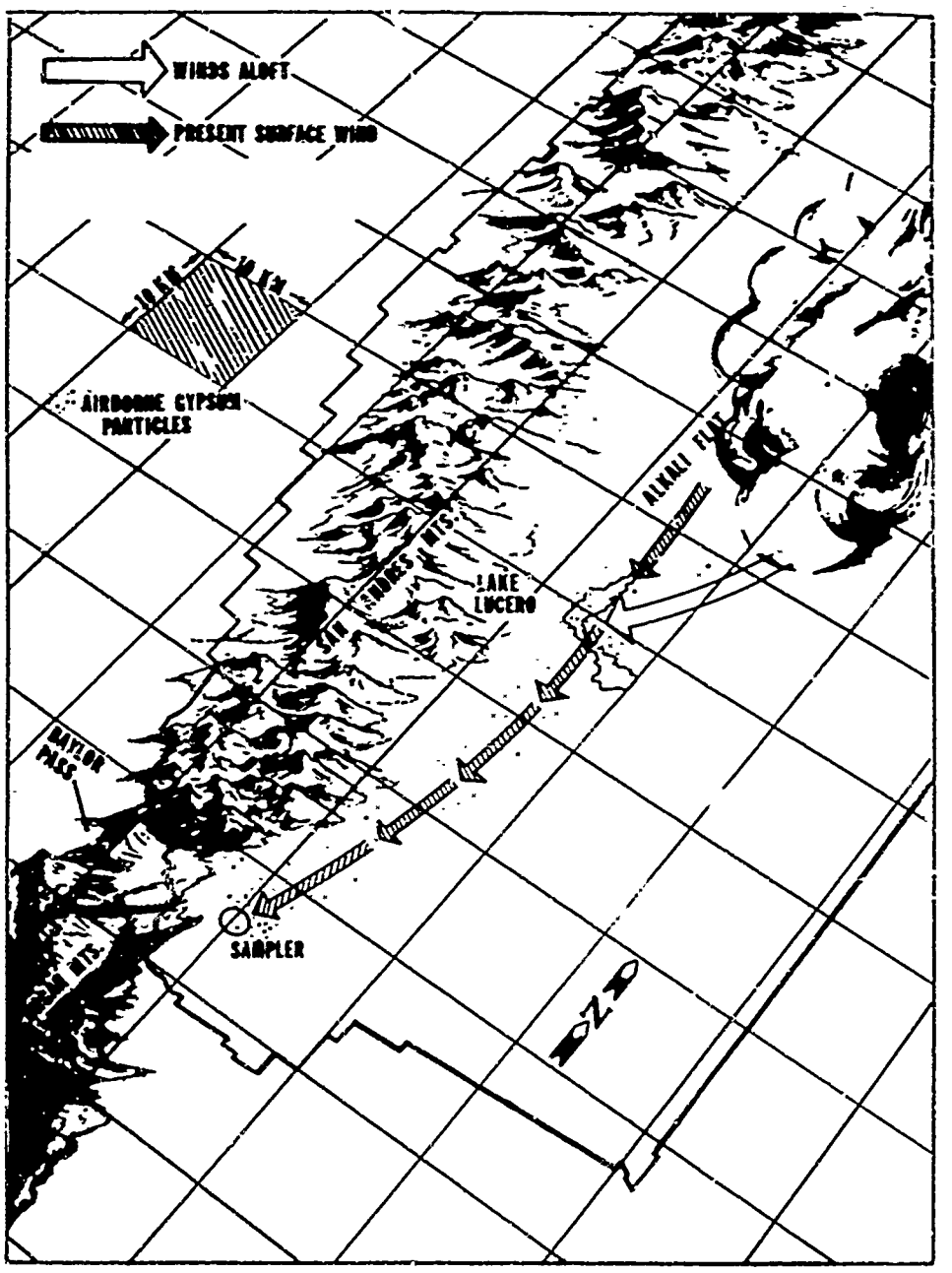


Fig. 17. Schematic Illustration of Gypsum Transport, 9 - 10 Aug 65

5 - 6 January 1965

This sample illustrates that just as particles may be deposited in the lee of small scale obstacles, so the Organ Mountains themselves may act as an obstacle with the sampler in its lee. The 500 millibar chart for 1700 MST, 5 January 1965 (Figure 18) carried a trough off the California coast. With the exception of the lowest kilometer above the floor of the Basin where winds were light and variable, the resultant flow over the Basin up to 500 millibars was southwesterly at speeds of 7 to 20 meters per second. The 2300 MST weather map (Figure 18) had a high pressure area centered over southwest Colorado and northwest New Mexico.

As was true oor the rest of the Basin, surface winds at the sampler were light and variable throughout the sampling period. Moreover, after the strong westerly winds at the sampler on the 1st of January, the winds at the surface over the Range had generally been less than seven meters per second inclusive of gusts. Also it had been 2 1/2 weeks since the last measurable general rain over the Basin, southwestern New Mexico, and southern Arizona, so soils were probably dry. Over the Basin up to 500 millibars winds had been generally southwesterly from the 27th of December through the 7th of January at speeds up to 38 meters per second. This would have allowed quartz to be entrained into the atmosphere by the moderate to strong southwesterly winds acting on the dry soils to the southwest of the Tularosa Basin. The southwesterly winds aloft then transported the particles to the obstacle lee presented by the Organ Mountains. Thus, the Basin with its light surface wind speeds could act as a sink for the transient quartz particles.

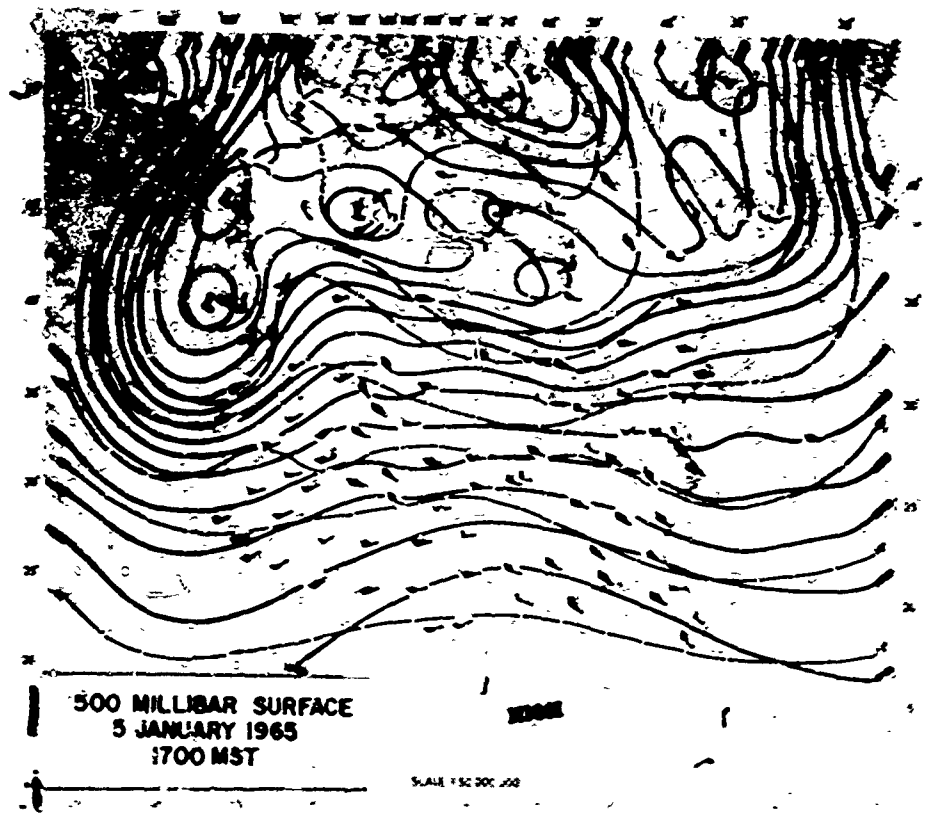
13 - 14 May 1965

The highest quartz concentration was observed in this sample.

Winds aloft veered from southwest to northwest during the sampling period as a closed low moved eastward across Colorado (Fig. 19). The 2300 MST weather map (Fig. 19) carried low pressure areas over eastern Colorado, north central Mexico, and southern Nevada.

During the sampling period, winds at the sampler were westerly to northwesterly at gradually diminishing speeds which ranged from 15 to 3 meters per second with gusts to 22 meters per second. This was generally the picture over the entire Basin - veering westerly winds at decreasing speeds.

A clue to the high concentration is given by the prevailing winds at the sampler on the two previous days, which had been southeast and east southeast, respectively. The same was true over the Basin floor



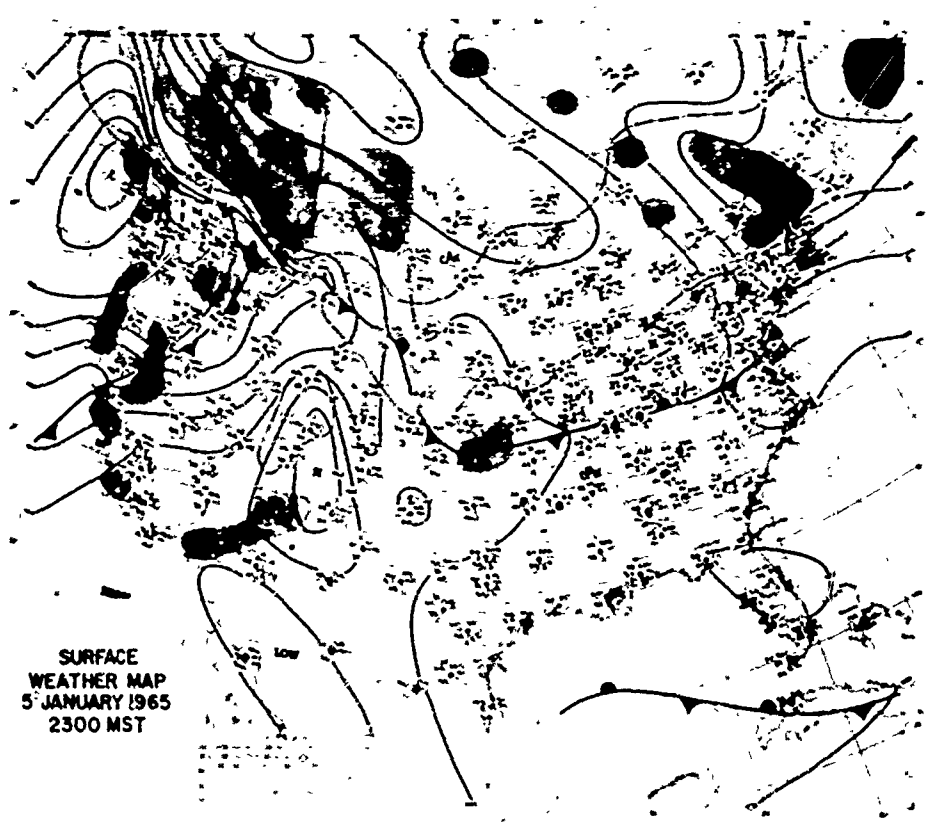
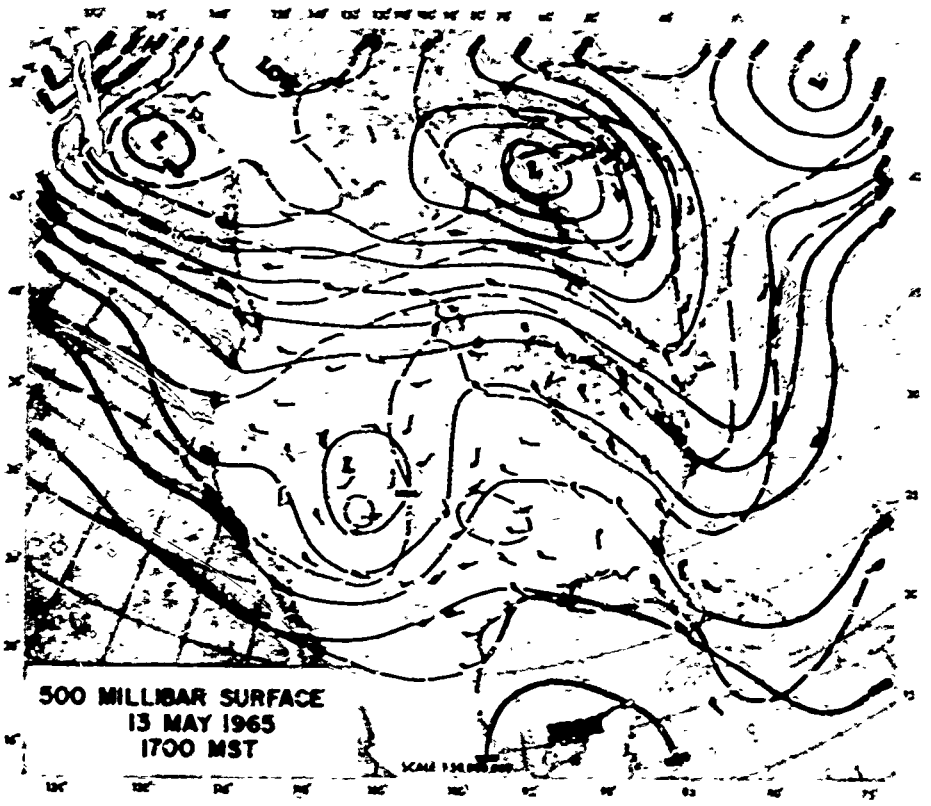


Fig. 18. Synoptic Weather Pattern Associated with Dust Sample of 5 - 6 Jan 65



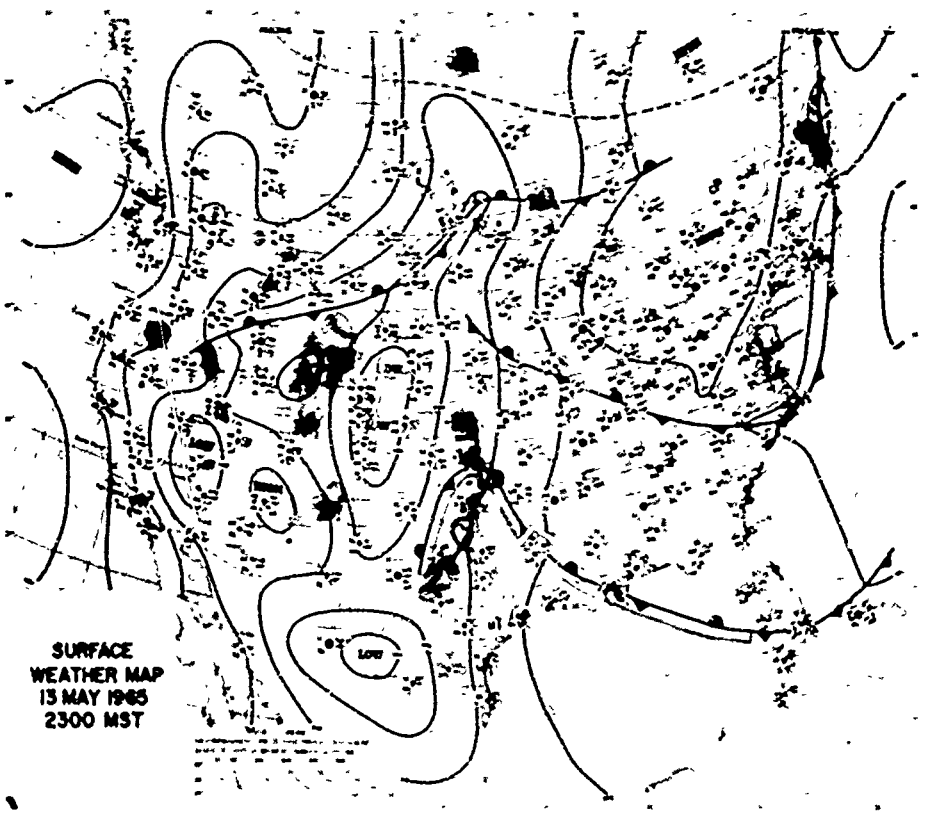
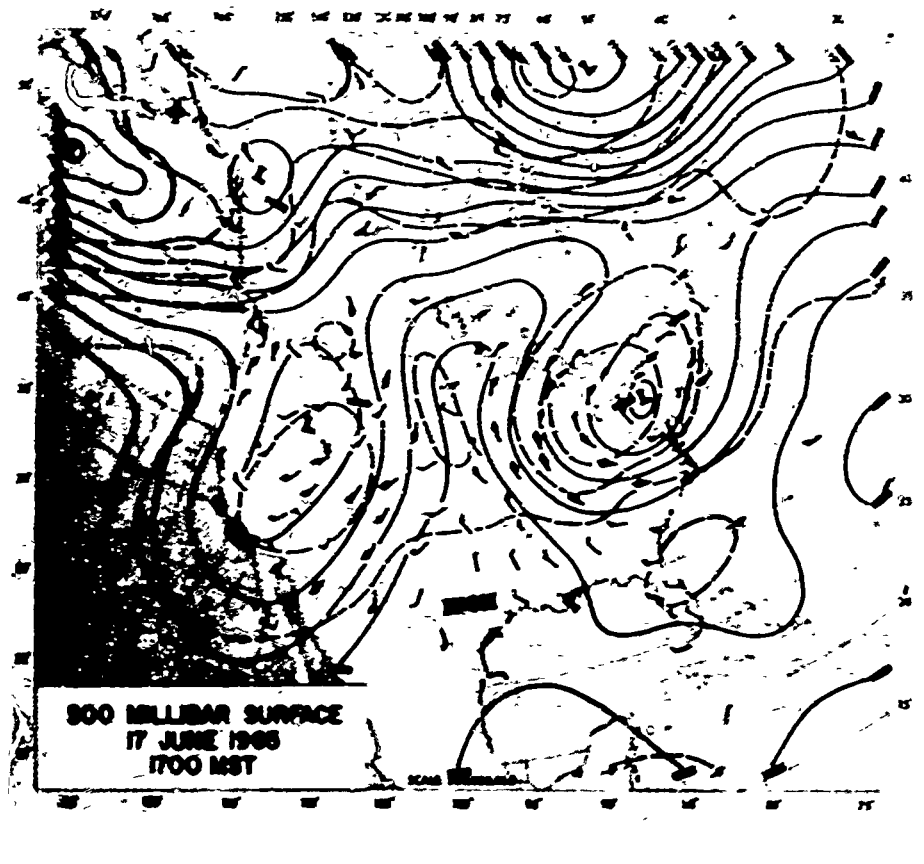


Fig. 19. Synoptic Weather Pattern Associated with Dust Sample of 13 - 14 May 65



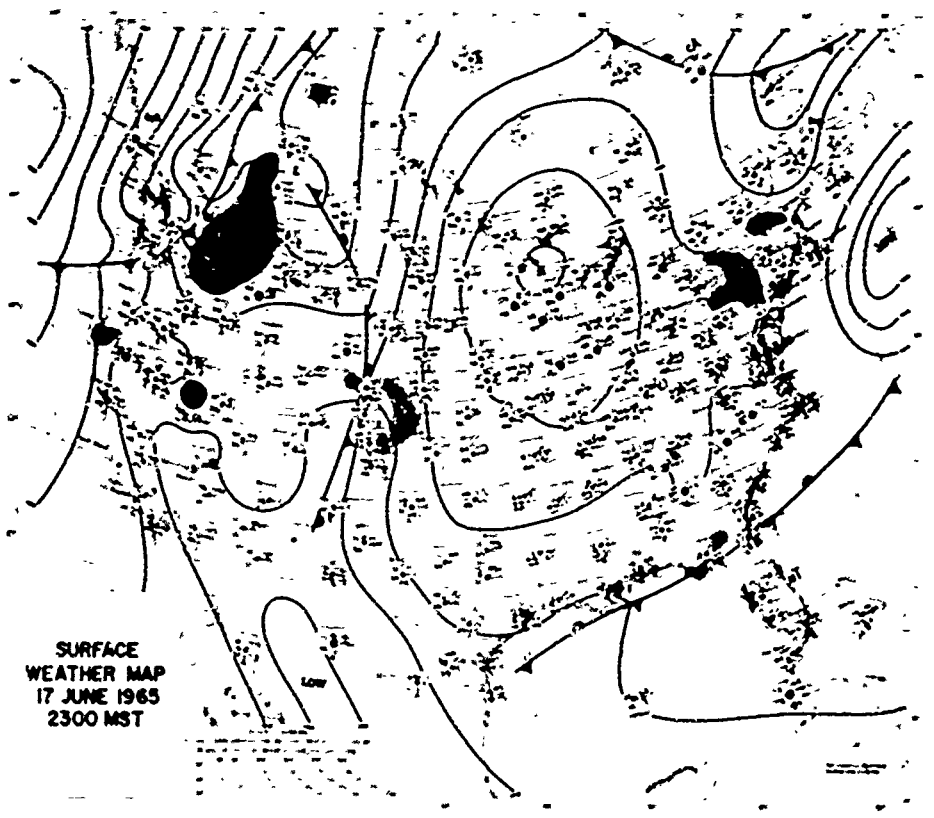


Fig. 20. Synoptic Weather Pattern Associated with Dust Sample of 17 - 18 June 65

as revealed by analysis of Southeast 30 data which showed moderate southerly to southeasterly winds at the surface during the two preceding afternoons.

Thus, quartz particles would have been deposited on the northwest side of obstacles during the 11th and 12th. As the westerly flow developed at the surface in response to the closed low aloft, these particles became vulnerable. Moreover, as the wind speeds decreased, low-level particle mass concentrations would increase. These two factors, primarily the former, could account for the high concentration of quartz.

17 - 18 June 1965

Perhaps the best example of the combined effect of frontal passage and thunderstorm downdraft on quartz concentration occurred during the sample of 17 - 18 June 1965 when the quartz concentration rose to 68 particles per thousand. Though this is far below the mean of 85 particles per thousand for the 81 samples, it was the highest concentration observed during June and it occurred despite a high kaolinite concentration associated with frontal passage from the east.

Winds aloft over the Basin within 3000 meters of the surface during the sampling period were southeasterly at speeds up to 13 meters per second. The 2300 MST surface weather map (Figure 20) revealed that the southwestern edge of a high pressure area centered over northern Wisconsin had pushed across the Basin.

Frontal passage was marked by the passage of a thunderstorm dust wall, such as the one described by Elser [50], at the sampler two hours after the sampling had begun. The wall moved northwestward across the Basin at about 30 kilometers per hour. At the sampler it was accompanied by visibilities of five kilometers in blowing dust.

Thus, concomitant with the kaolinite associated with the cold frontal passage from the east was quartz resulting from thunderstorm downdraft pickup of local exposed soils.

Because of the ubiquitous distribution of quartz in the soils of the area, knowledge of the flow over the entire Basin is not as important as was the case with localized gypsum, but the flow still needs to be considered. More important is the availability of mechanisms to pick up the dust, such as strong surface winds to the southwest coupled with obstacle lee deposition into the sampler, low-level wind shifts, and a thunderstorm generated dust wall.

Kaolinite

Kaolinite, though only a rare constituent of the area soils, is relatively common in the local atmospheric aerosol. At times the kaolinite concentration rises to high levels such as in the samples of 17 - 18 December 1964, 16 - 17 February 1965, and 18 - 19 March 1965. In contrast to gypsum and quartz, however, the situations under which the high concentrations occurred were remarkable for their similarity as will be noted in the following discussion.

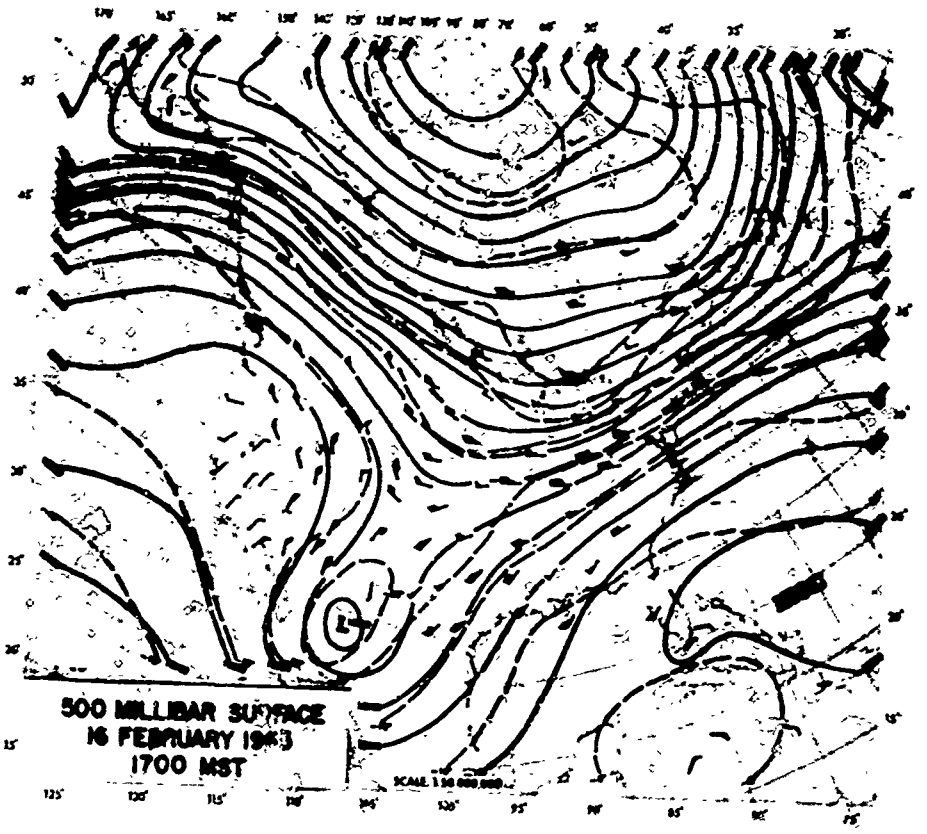
17 - 18 December 1964

The highest concentration of kaolinite was observed in this sample. At 500 millibars (Figure 21), there was a trough off the California coast and a ridge over the Great Plateau. At the surface (Figure 21), a cold front associated with a mass of frigid air centered over eastern Kansas passed over the Basin from the east late in the afternoon of the 17th.

The cold front reached Southeast 30 at about 1800 MST and was marked by southerly surface winds at 5 to 10 meters per second with gusts to 13 meters per second. At the sampler the wind switched to the southeast shortly before midnight and remained light southeasterly to calm for the remainder of the sampling period. Winds aloft backed from northwesterly to southeasterly as the cold high moved in.

It is suggested that the high kaolinite concentration was due to the entrainment of kaolinite particles into the Arctic air mass as it swept across the exposed soils of the western Great Plains. It was then this kaolinite-laden sector of the anticyclone which was sampled.

It is interesting to note that Mason [39] has suggested kaolinite crystals as an important constituent of atmospheric ice nuclei, because sleet and snow did occur on the 18th followed by 70 hours of fog which reduced the visibility at the sampler to less than 1.6 kilometers on the 19th through the 23rd. The band of fog extended roughly from the Socorro-Corona, New Mexico line on the north to 160 kilometers south of Ciudad Juarez, Mexico; and from Alamogordo, New Mexico on the east to Deming, New Mexico on the west. At El Paso, Texas there were 31 hours on the 19-21-22-23 when visibility was restricted to 0.4 kilometer or less by fog. This exceeds the total number of hours of said visibility restriction by fog and/or ground fog for the entire period from October 1953 to 19 December 1964. Atmospheric stagnation, i.e., restricted natural ventilation, coupled with the high concentration of potential condensation nuclei, and sufficient moisture are suggested as major contributing factors to the record-breaking fog. Note that the illite concentration was also at its highest level.



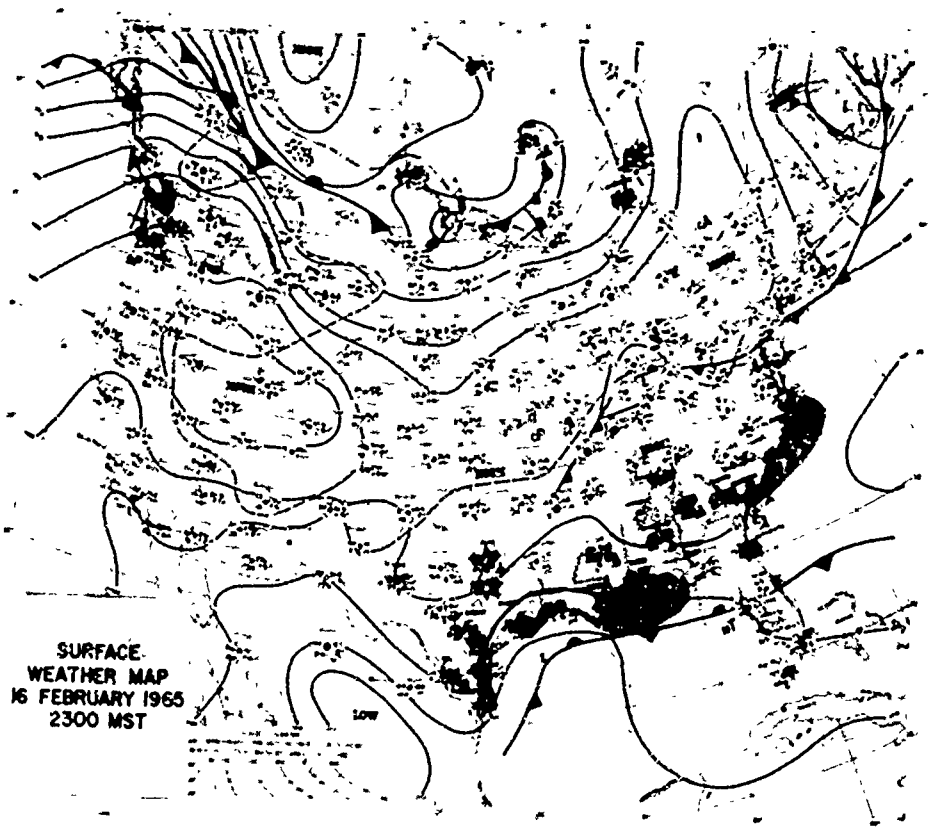


Fig. 22. Synoptic Weather Pattern Associated with Dust Sample of 16 - 17 Feb 65

16 - 17 February 1965

Once again a high concentration of kaolinite may be related to the passage of a cold front from the east, though this may not be evident from a glance at the 2300 MST weather map (Figure 22), where the nearest front is southeast of Brownsville, Texas. The winds aloft over the Basin veered from northwesterly at the start of the sampling period to northeasterly at the close the following morning as the result of the eastward movement of a closed low which at 17 MST, 16 February, was centered 500 kilometers southwest of El Paso, Texas (Figure 22).

Analysis of available weather data from the several sites across the Basin revealed that a cold front had passed across the Tularosa Basin from the east early on the morning of the 16th, too late to raise the kaolinite concentration markedly in that sample, though it was a respectable 92 particles per thousand. The influx of kaolinite particles continued as the air mass continued to flow across the Basin on the heels of the northeasterly flow aloft. Once again, winds at the sampler did not help to clarify the picture; they were light and variable from 0200 MST on the 16th through 1000 MST on the 17th. During the sampling period winds across the Basin floor were light to moderate northerly through easterly in contrast to the southeasterly flow of the 17 - 18 December kaolinite sample.

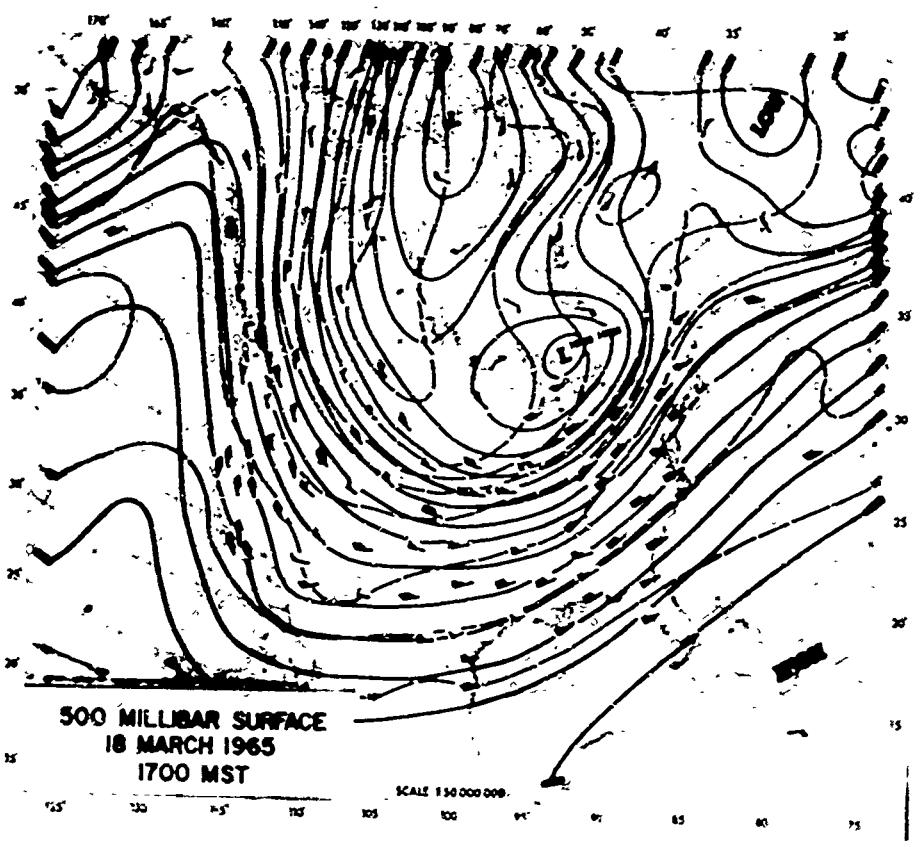
Thus, this case is similar to that of 17 December in that the kaolinite concentration rose with cold front passage from the east, the kaolinite probably once again originating from the exposed lands of the western Great Plains.

18 - 19 March 1965

Cold front passage from the east is once again responsible for a high concentration of kaolinite. The 500-millibar chart had a trough extending from the Great Lakes to the northern Gulf of California (Figure 23) which resulted in westerly winds across the Basin for the entire sampling period. At the surface (Figure 23) a cold front passed the sampler at about sunrise on the 18th, too late to raise the kaolinite concentration for that sample. Advection of kaolinite continued over the entire Basin throughout the sampling period on the heels of moderate to strong low-level southerly to southeasterly flow at speeds of 5 to 10 meters per second with gusts to 15 meters per second.

Others

Other high concentrations, such as those occurring in the samples of 30 November 1964, 29 March 1965, and 17 June 1965, were likewise



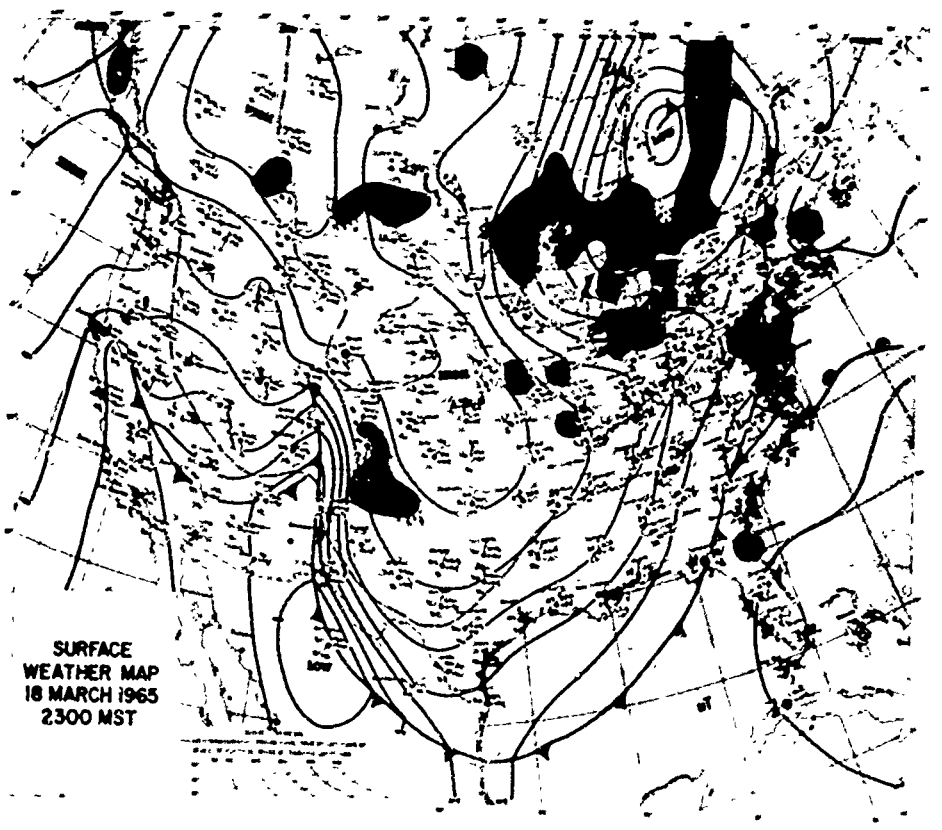


Fig. 23. Synoptic Weather Pattern Associated with Dust Sample of 18 - 19 Mar 65

dependent on cold front passage from the east (Figures 24, 25, and 20, respectively). In all six cases the ground was relatively dry from the Panhandle of Oklahoma and Texas southwest across southeastern New Mexico, with only light amounts of precipitation reported during the two or three day period preceding the passage of the cold front at the sampler. Moreover, there was virtually no snow cover over these areas during this same period. Evidence that the western Great Plains may be the source region for the kaolinite is provided by the sample of 27 - 28 April 1965, when the kaolinite concentration following cold front passage from the east reached only 51 particles per thousand. In this case moderate rains had soaked the Panhandle and southeastern New Mexico during the day of the 26th. Resultant particle agglomeration and soil saturation may have prevented the wind erosion of the clay fraction of the soil.

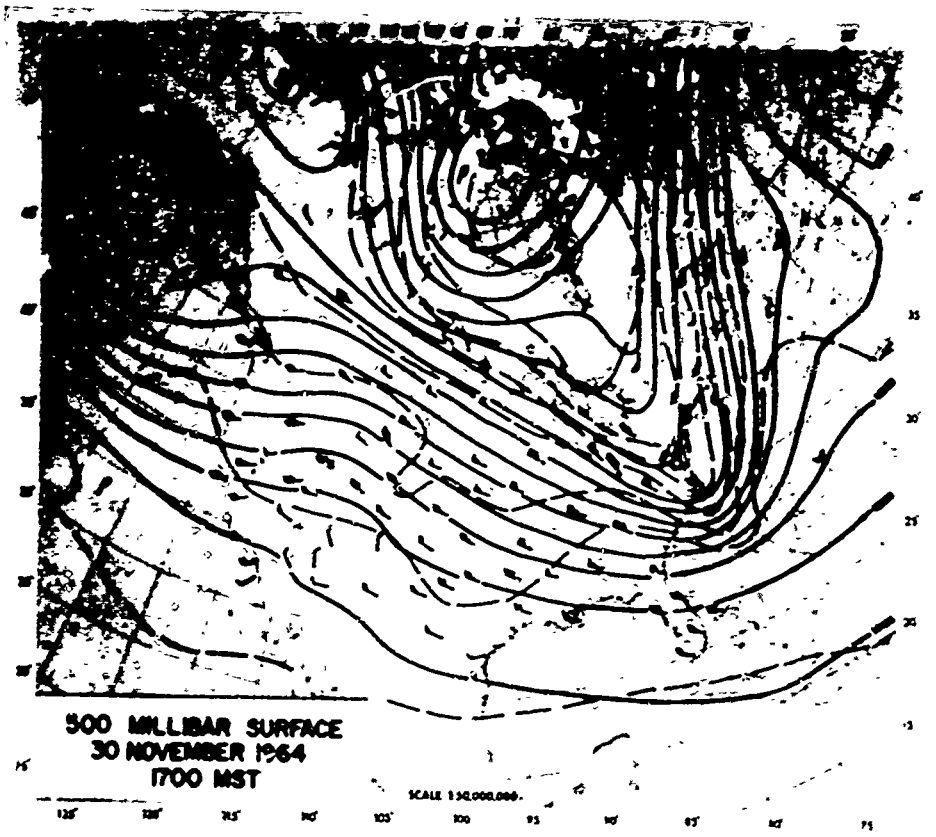
Kaolinite influxes over the Tularosa Basin are apparently confined to cold front passage from the east (as distinguished from frontal passages from the north and west or no frontal passage at all) if the soils of west Texas and southeast New Mexico are free of snow cover or if there has been insufficient rain over the area to agglomerate the soil particles or saturate the soils. As the source region is cut off, kaolinite concentrations drop rapidly, no doubt influenced also by the light winds generally associated with the anticyclones.

Illite

The word kaolinite in the preceding discussion could just as well have been replaced by the word illite, so similar are the concentration trends of the two minerals. The concentration is generally lower for illite than for kaolinite, but the peak kaolinite concentrations are also peak illite concentrations. Therefore, high illite concentrations seem also to be dependent on cold front passage from the east under the same restrictions as for kaolinite.

Carbonates

The carbonate concentrations present an enigma, in that no correlations have been found between carbonate concentrations and meteorological elements or between high carbonate concentrations and high concentrations of the other minerals. The carbonate component of local soils varies widely from sample to sample and so perhaps does the carbonate component of the transient particle fraction. In any case, no further discussion of the carbonate concentration will be made at this time.



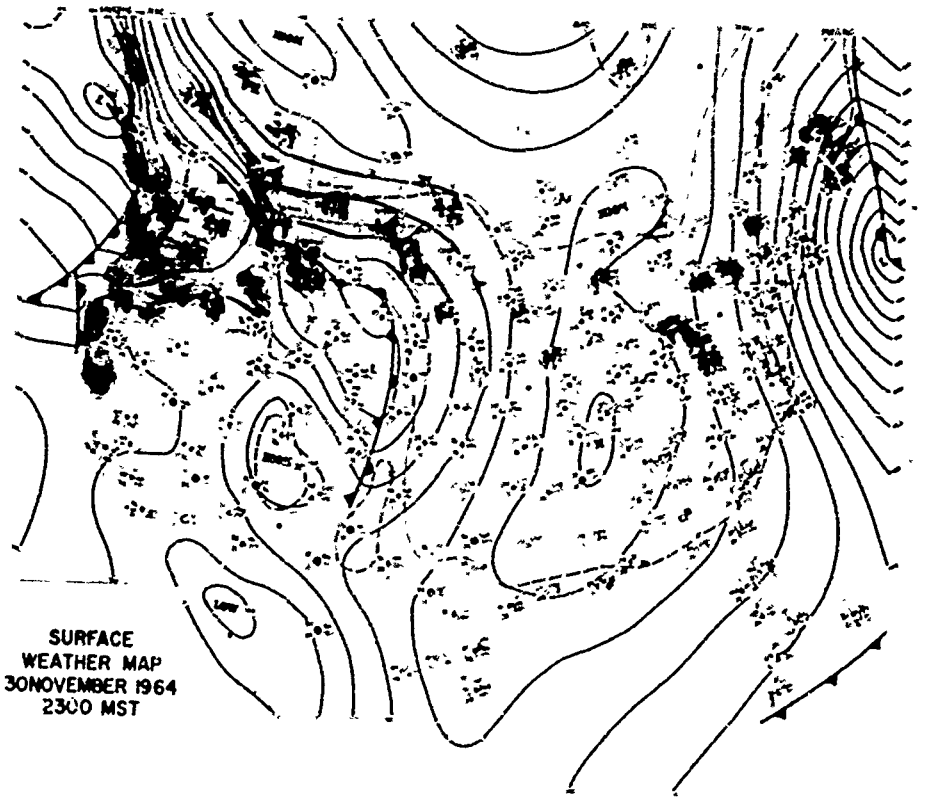
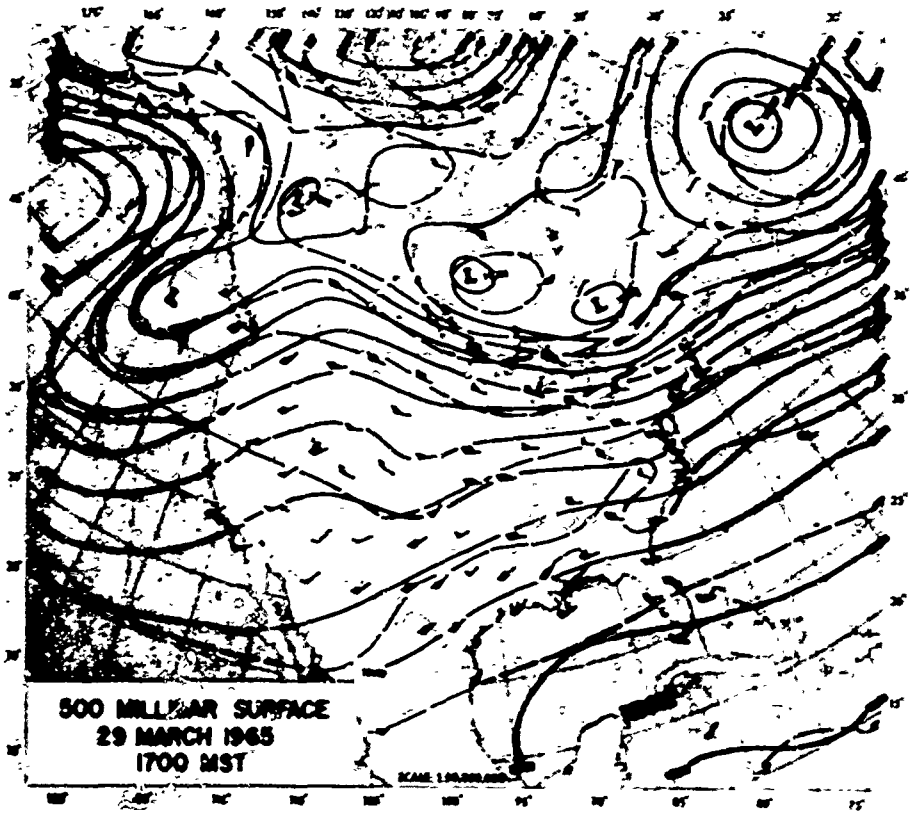


Fig. 24. Synoptic Weather Pattern Associated with Dust Sample of 30 Nov 64 - 1 Dec 64



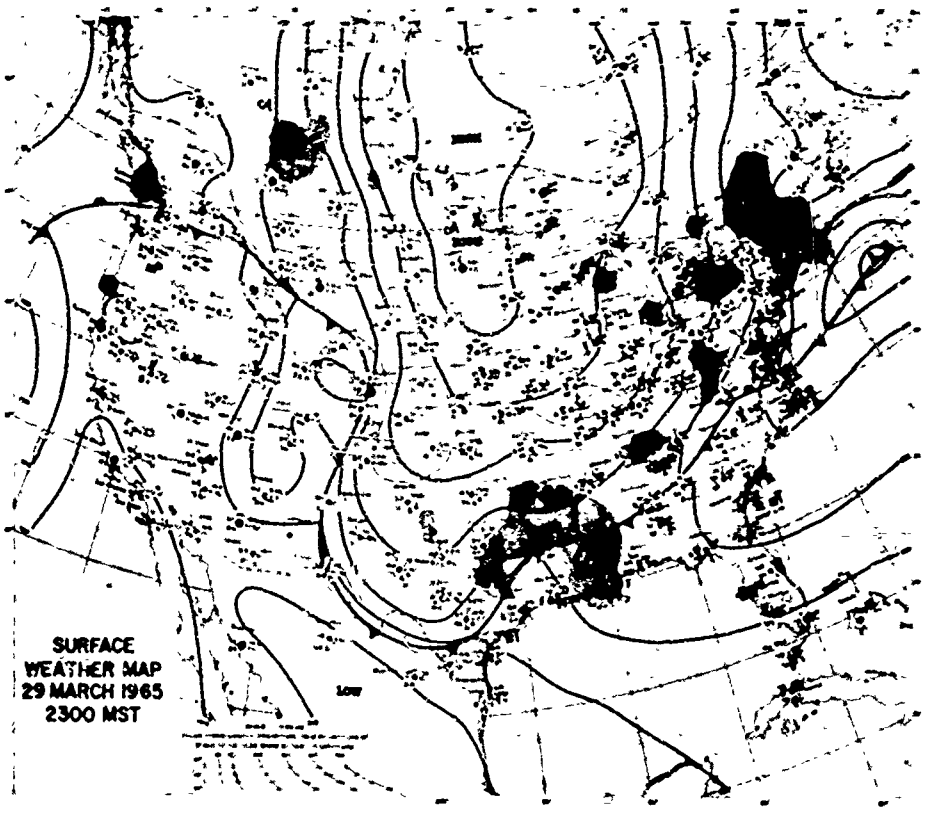


Fig. 25. Synoptic Weather Pattern Associated with Dust Sample of 29 - 30 Mar 65

General Features

Examination of Figure 9 reveals an apparent periodicity in the occurrence of maxima and minima in the concentrations of the five components. This was made more evident by calculating and plotting running-mean, 11-sample concentrations* of the five components (Figure 26). It seemed that the cause of the maxima and minima might lie in the unidentified fraction. Therefore, the concentration of the identified fraction (the sum of the concentrations of gypsum, quartz, illite, kaolinite, and carbonates) was plotted (Figure 27). The influence of the unidentified fraction was established by calculating and plotting a running 11-sample mean of the summed mineral concentration (Figure 28). The maxima and minima points evident in Figure 28 suggest that they are related to real phenomena. This section will be devoted to a physical explanation of these extremes. It should be noted that the features of this curve, which are to be discussed in this section, are the same irrespective of whether carbonates are included.

The minima represent net influxes of unidentified particles which could be eolian dust from the land, oceanic salts, cosmic dust, volcanic dust, dusts of natural combustion, and industrial dust. If, as suggested by Green and Lane [54, p. 414] and Fletcher [55, p. 96], sea salt is the predominant constituent of atmospheric nuclei greater than one micron in diameter, and if such nuclei could penetrate inland as far as the Tularosa Basin, then, based on considerations of wind and rain, one might, a priori, expect seasonal increases in such oceanic particles over the Basin which would be reflected in the summed concentrations as minima. The two prime sources for oceanic particles over this area might be the Gulf of Mexico and the Pacific Ocean.

Both sources are equidistant from the sampler, the Pacific Ocean being 1000 kilometers to the southwest and the Gulf of Mexico 1000 kilometers to the southeast at the nearest. Thus, assuming sea-salt-laden air moving toward the northeast at 10 meters per second from the nearest Pacific source and toward the northwest at 10 meters per second for the nearest Gulf of Mexico source in an unobstructed straight line, it would require only 28 hours to reach the Basin. Would gravitational settling reduce the concentration of sea-salt particles by a significant amount in this overland path? Interpolating from Fournier d'Albe's data [56] on the 'half-life' of airborne particles where Fournier d'Albe uses the modified Stokes' Law and assumes spherical particles of the density of dry salt and a mixing height of only one kilometer, it may be seen that it requires

*Several types of smoothing, i.e., running-mean and binomial, over various time and sample intervals were used, but all revealed the same general features as shown in Figures 26 and 28.

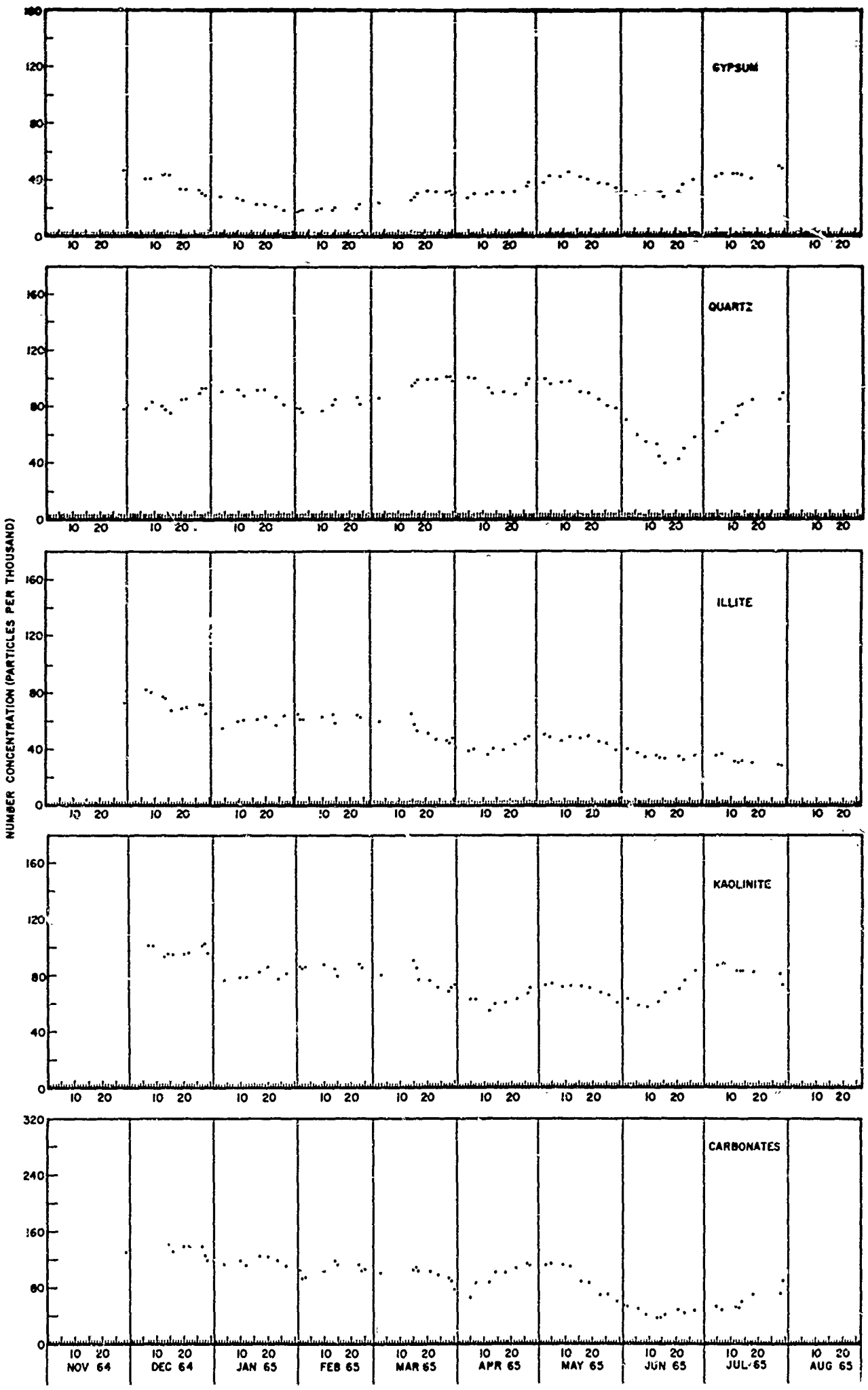


Fig 26 ELEVEN SAMPLE RUNNING MEAN MINERAL PARTICLE CONCENTRATIONS, WHITE SANDS MISSILE RANGE DUST SAMPLING SITE, NEW MEXICO, NOVEMBER 1964 TO AUGUST 1965

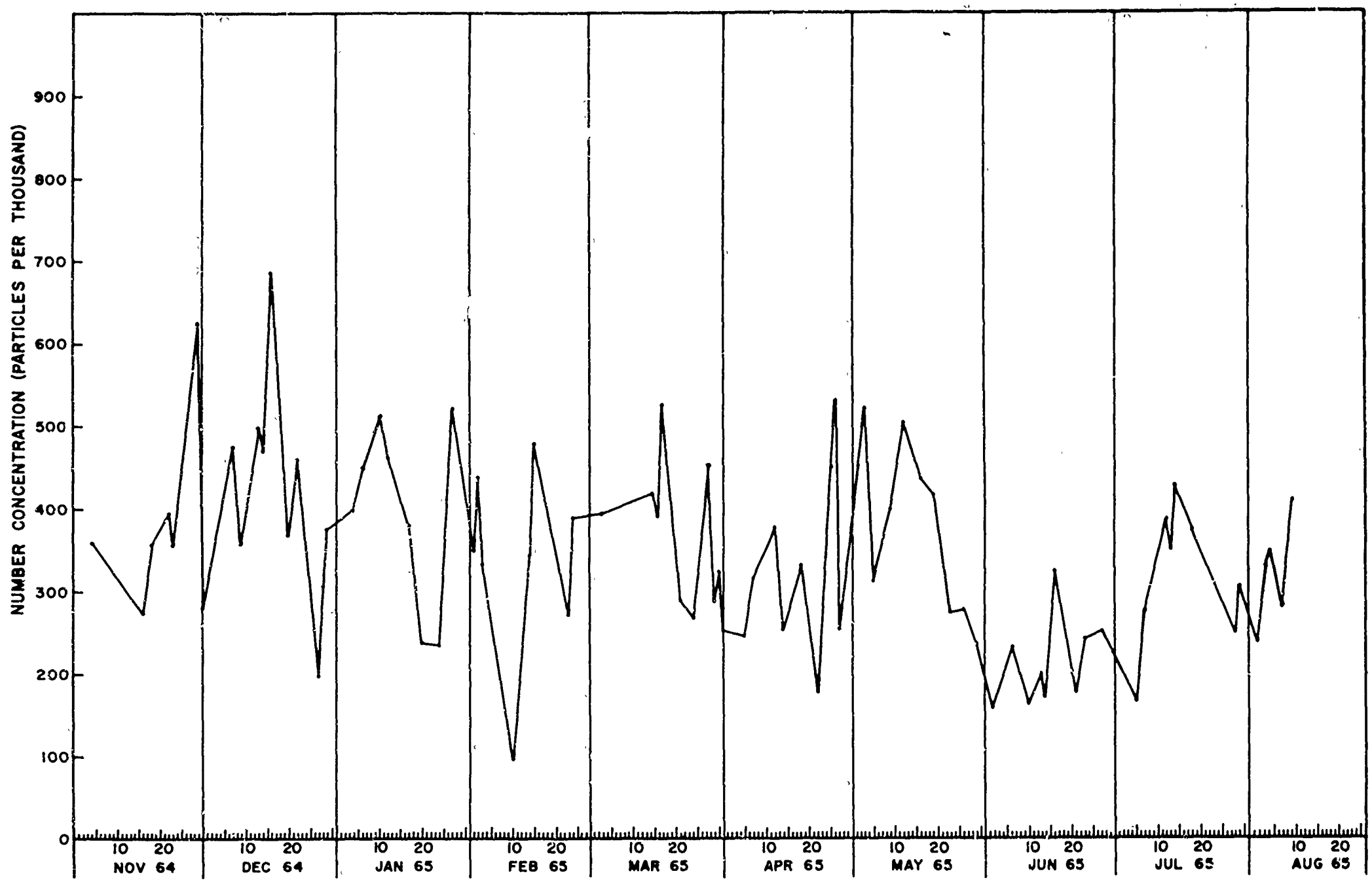


Fig. 27 SUMMED MINERAL PARTICLE CONCENTRATION, WHITE SANDS MISSILE RANGE DUST SAMPLING SITE, NEW MEXICO, NOVEMBER 1964 TO AUGUST 1965.

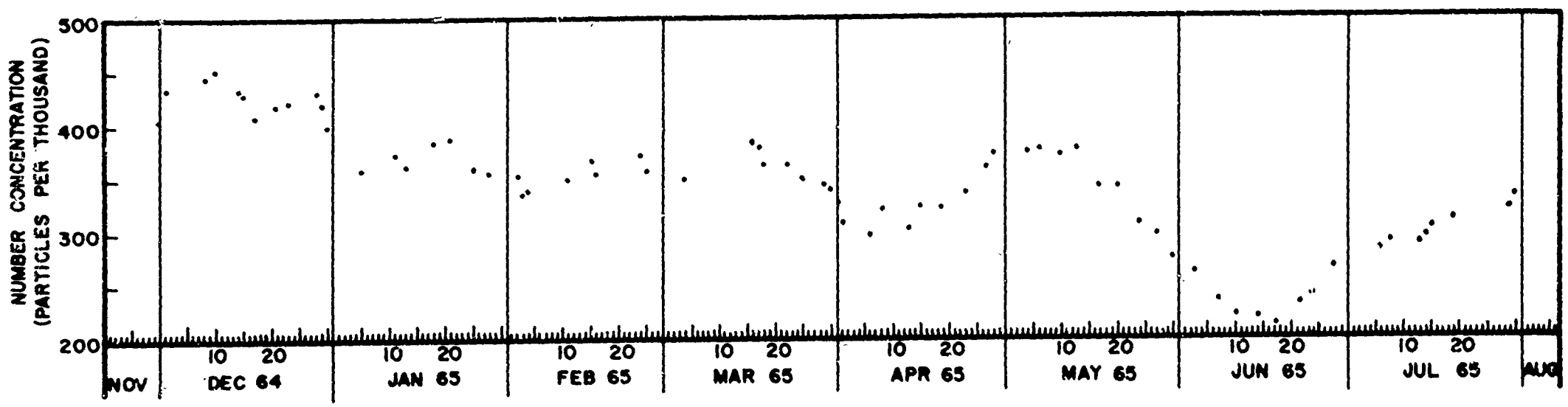


Fig.28 ELEVEN SAMPLE RUNNING MEAN OF SUMMED MINERAL CONCENTRATIONS, WHITE SANDS DUST SAMPLING SITE, NEW MEXICO, NOVEMBER 1964 TO AUGUST 1965.

about eight days for the concentration of particles of 5 micron diameter to be reduced by a factor of two and two days for 10 micron diameter particles. Thus, even for winds of 10 meters per second, sea-salt particles from both sources may penetrate the Tularosa Basin in significant amounts in the size range of particles identified in Part I.

Let us consider the main features of Figure 28 under the supposition that the identified fraction represents eolian dust from the surface of the earth and the unidentified fraction represents oceanic salts.

November 1964

Over southern New Mexico and Arizona precipitation was generally light during the first three weeks of the month, with no precipitation reported during the last week. At the sampler only 0.8 millimeter of precipitation was recorded. Therefore, exposed surface soils were dry and susceptible to wind erosion throughout the month. This is partially attested to by the high kaolinite content following passage of a cold front from the east on the 21st.

At the sampler, westerly surface winds averaged in excess of six meters per second on five days, the 11th, 13th, 14th, 18th, and 27th, with blowing dust reported only on the 11th.

Synoptically, the month may be split in half. For the first half of November a 700-millibar upper-air trough held sway over the Pacific States and the Plateau allowing the intermittent influence of Pacific maritime air masses over the Tularosa Basin where winds aloft were generally out of the southwest. By the 19th a strong ridge covered the West Coast and adjacent ocean areas. This blocking ridge broke down a few days later, but the long wave trough remained over the Mississippi Valley, resulting in northwesterly flow over the Basin. This served to block penetrations of oceanic air from the southwest and to allow polar continental air to sweep in from the north. Thus, oceanic particles could account for the low concentrations observed prior to the formation of the blocking ridge.

December 1964

The highest composite concentrations were observed during December, thereby implying blocking of oceanic sources until perhaps the end of the month when concentrations began to drop rapidly.

Precipitation was generally light throughout the month over southern New Mexico and Arizona, occurring over New Mexico on the

2nd, 3rd, 4th, and 18th and over Arizona on the 18th and 28th. At the sampler, however, 18.5 millimeters of rain were recorded from the 2nd through the 4th and 94 millimeters of snow on the 18th.

Prevailing surface winds at the sampler were once again out of the west with the speeds averaging in excess of six meters per second on the 2nd, 3rd, 24th, 28th, and 29th. Blowing dust was reported on the 24th. Fog blanketed the Basin from the 18th through the 23rd.

During the first week of December the upper air flow over the Southwest was dominated by a mean 700-millibar ridge over the West Coast. The ridge, which continued through the third week though decreasing in amplitude, blocked Pacific storms from this area. Cold continental air was thus able to penetrate the Basin four times during this period. By the 27th a long wave trough had formed over the West Coast and adjacent Pacific Ocean. This allowed a Pacific maritime air mass to pass the sampler from the west for the first time since late November.

The high concentrations of the first three weeks are accounted for by the predominance of continental air over the area. Then, as incursions of Pacific air began during the last week, the concentrations dropped.

January 1965

The summed concentrations observed in January were much lower than in December, the peak concentration occurring in the middle of the month.

Precipitation over southwest New Mexico and southeastern Arizona was much below normal with amounts generally less than six millimeters and occurring on the 6th - 8th and 20th - 22nd. At the sampler 18.3 millimeters were recorded during the former period and 5.3 millimeters during the latter period, all as rain.

Westerly surface winds in excess of six meters per second at the sampler were limited to the 7th, 8th, 24th, 25th, and 31st. Fog was reported on the 21st and blowing dust on the 25th.

The Pacific Coast trough of late December held sway through the first eight days of January allowing two passages of Pacific maritime air masses over the sampler during this period. The subsequent blocking ridge over the Pacific Coast permitted weak incursions of polar continental air during the middle of the month. Over the last week of January the mean ridge over the Pacific Coast intensified, shifted westward, and gradually weakened, allowing an incursion of Pacific maritime air over the Basin on the 25th.

Thus, the observed composite concentration pattern of January may be accounted for by penetrations of Pacific maritime air during the first and last weeks, with blocking of the oceanic source allowing concentrations to rise during midmonth.

February 1965

With the exception of the day of lowest composite concentration for the period of record, which will be discussed separately, the composite concentration pattern was characterized by a gradual increase in concentration as the month progressed.

Precipitation was light and confined mainly to the first two weeks of the month over southwestern New Mexico and southern Arizona, with amounts in excess of 10 millimeters over southern Arizona during the first week. At the sampler, 26.4 millimeters were recorded from the 6th through the 10th.

Surface winds at the sampler were in excess of six meters per second on the 1st, 6th, 9th, 10th, 23rd, and 28th, with the prevailing direction being west. Snow was reported on the 10th and blowing dust on the 23rd.

The mean 700-millibar contours for February revealed a ridge centered on the 130th Meridian which would make it difficult for Pacific maritime air to penetrate the Tularosa Basin. As a result, polar continental air dominated the Basin and could have allowed the concentration of the identified fraction to increase as the maritime sources were blocked.

March 1965

Sampling difficulties resulted in only one sample being taken in the first two weeks and therefore the discussion will center on the decrease in summed concentration which occurred during the latter half of the month.

Light showers, of 6 to 18 millimeters, over southwestern New Mexico and southern Arizona were confined to the second week of March. At the sampler only five millimeters of precipitation were reported through the 12th and none for the remainder of the month.

Sampler winds exceeded six meters per second on the 2nd, 8th, 12th, 16th, 17th, 22nd, 23rd, 24th, and 25th. Blowing dust reduced visibility only on the 16th and 17th. The prevailing wind direction for the month was west, but on five days the prevailing direction was southeast.

The West Coast ridge at 700 millibars persisted through the first week of March with resultant northwesterly flow over the Basin. The appearance of a closed low over California during the second week produced strong westerly to southwesterly flow over the Basin, but no frontal passage from the west. Despite the strength and direction of the winds, it should be noted that the over-water trajectory was short. During the third week the ridge reestablished off the California coast with consequent strong northwesterly winds over the sampler. As the ridge shifted westward during the last week, a trough moved over California resulting in strong southwesterly flow, with a history of a long over-water trajectory, over White Sands. However, there were no accompanying frontal passages from the west.

Thus, it is possible that the steady concentration decrease during the last two weeks of March may reflect an increasing influx of oceanic particles as the West Coast trough was establishing.

April 1965

The summed concentrations increased markedly during the last two weeks after the relatively low values of the first two weeks.

Precipitation was light over southwestern New Mexico and southeastern Arizona, occurring on the 1st, 2nd, 9th, 10th, and 25th. At the sampler, light amounts of rain were recorded on the 2nd and 26th for a total for the month of six millimeters.

Westerly surface winds in excess of six meters per second at the sampler occurred on the 5th, 9th, 10th, 11th, 14th, 17th, and 18th, with blowing dust on the 4th, 7th, 9th, and 10th.

A deep trough was established along the California coast during the first two weeks. This system spawned four frontal assaults of maritime air over the sampler. By the 14th, the upper-air vortex over southern California began to move northward causing winds to veer to the west and speeds to diminish over White Sands.

The low concentrations of the first two weeks are attributed to the strong southwesterly flow which allowed at least three Pacific maritime air masses to cross the Basin. That the concentration did not exhibit a decrease during this period may be due to the strong surface winds and blowing dust of the first two weeks which would tend to increase the concentration of the identified fraction, thus countering the effect of sea-salt particle influx. During the last two weeks the oceanic source was cut off, thereby allowing the identified component to increase though the strong surface winds were not in evidence.

Part of the increase may be attributed to gusty northeast winds on the 22nd and southeast winds on the 27th which would disrupt the obstacle lee deposition of the prior prevailing westerly flow at the surface.

May 1965

May marked the beginning of the long descent to the low concentrations of mid-June.

Precipitation over southern Arizona and southwestern New Mexico was extremely light during the month. At the sampler, the only noteworthy precipitation occurred on the 16th with 7.4 millimeters.

Sampler winds in excess of six meters per second occurred on the 5th, 6th, 7th, 13th, 24th, and 25th, with blowing dust reported on the 17th and the 30th. The prevailing direction on all but eight days was again westerly.

The concentration decrese in May may be linked to the 700-millibar trough over the Southwest which persisted through virtually the entire month, giving moderate southwesterly flow over the Basin. This continuous tapping of the oceanic salt source could have forced the concentration of the identified fraction to continually lower values as the month progressed.

June 1965

The fall in total concentration which began in May reached its nadir in mid-June. The last two weeks were marked by a sharp rise in total concentration.

Southern Arizona and southwestern New Mexico remained generally dry, though 6 to 18 millimeters of rain were reported during the third week. At the sampler precipitation totaled 33.5 millimeters, the rain falling during three periods - 9th to 10th, 18th to 23rd, and 28th to 29th.

Surface winds in excess of six meters per second at the sampler occurred on the 3rd, 4th, 9th and 15th, with blowing dust, associated with thunderstorm activity, reported on the 17th and 23rd. During the first 15 days thunder or distant lightning was reported on only one day, whereas during the last 15 days one or the other was reported on eight days.

The West Coast trough of May persisted through June, although its intensity was gradually weakening as the Bermuda high began encroaching over the Tularosa Basin from the southeast about midmonth.

Thus, southwesterly winds continued to feed in oceanic particles until midmonth when the flow in the low levels began to shift to the southeast. As this happened, the tapping of the Gulf source of oceanic particles began. That the composite concentration rose after midmonth indicated that either the Gulf of Mexico was not as pregnant a source of oceanic particles as the Pacific or there was some mechanism contributing to the rise of the identified fraction. With the generally low mean surface wind speeds of June it did not seem likely that a continual influx of oceanic particles would result in an increase in the concentration of the identified fraction. However, the onset of the thunderstorm season in mid-June provided a mechanism for thrusting land source dust into the atmosphere by means of the downdrafts previously discussed. Moreover, the rain would leach out at least some of the hygroscopic salts. Therefore, a plausible picture would be a continual influx of oceanic salt particles through the month, with a midmonth onset of the thunderstorm season causing an increase in the identified fraction.

July 1965

July featured a continued but more gradual increase in the identified fraction over that observed during the latter half of June.

Scattered showers occurred over southern Arizona, southwestern New Mexico, and the Rio Grande Valley almost every day with more rainfall being recorded during the last half of the month. At the sampler, 6.8 millimeters less rain fell than during June, but it occurred on 16 days, 5 more than in June. Moreover, thunder or distant lightning was recorded on all but seven days of July.

The highest mean wind speed for a calendar day at the sampler occurred on the 19th and was only four meters per second. No blowing dust was reported during the month.

The Bermuda high continued to move westward, thus establishing low-level southeasterly flow over the Basin for virtually the entire month. Once again thunderstorm activity may account for the rise in concentration of the identified fraction despite the continued influx of oceanic particles. The slope decrease noted above might be attributed to an increased influx of oceanic particles, a decreased effect of thunderstorm downdrafts, or a combination of both.

August 1965

Conclusions in regard to August are necessarily incomplete inasmuch as only five samples were taken, and those were within the first 12 days of the month. However, one feature worthy of note is the

sharp decrease in the quartz concentration (See Figure 9). This may be due to the "lull" in thunderstorm activity over the Basin which occurred in the first half of the month. From the 3rd through the 12th, there was no measurable precipitation at the sampler.

Special Case I

Lowest Composite Concentration, 11 - 12 February

The lowest total concentration for the period of sampling occurred on 11 - 12 February when only 96 particles per thousand were identified. This was probably the result of two factors. First, precipitation had occurred over the Basin on each of the five preceding days, the total for the sampler site being 26.4 millimeters. Light rains were reported over southwestern New Mexico and southern Arizona. This resulted in a local soaking of the surface soil dust sources and probable scavenging of the transient atmospheric dust particles by the precipitation. The second factor was the flow of air aloft from the Pacific Ocean. By the afternoon of the 6th, a 500-millibar trough had moved over the west coast of the United States, resulting in 50-knot southwesterly winds over El Paso at 500 millibars. This strong southwesterly flow persisted over El Paso from that time until the start of the sampling on the 11th. This continued strong flow from the Pacific could have resulted in a marked influx of sea-salt particles which, coupled with the dampening effect of the precipitation on the land sources, could have given the resultant concentration.

Special Case II

Gypsum

Figure 26 illustrates the seasonal variation in the concentration of gypsum. Maxima are noted in mid-May and mid-July with minima in mid-February, early June, and early August. The seemingly spurious, but in reality real, peak concentrations observed superposed on the seasonal variation on several days are attributable to specific synoptic situations as discussed previously.

The mid-February minimum is felt to be due to a combination of the lowest temperature of the season, general rains over the Basin from the 6th through the 10th, and light winds from the 9th through the 21st at the surface. The low temperatures would tend to inhibit

evaporation; the rains would redissolve at least a portion of the exposed salts; and the light winds would preclude eolian pickup of the gypsum particles.

The mid-May maximum is probably a result of increased mountain wave activity coupled with an evaporation rate which was much higher than in April. Normally the surface wind speeds over the Tularosa Basin are higher in April than in May. However, in 1965 the reverse was true, both at the sampling site and at Southeast 30.

Evaporation remained high during June, but winds were decreasing from May. Therefore, until the onset of the thunderstorm season there was no convenient mechanism for the atmosphere to pick up the exposed gypsum particles. Thunderstorm activity may thus account for the July maximum.

Extraterrestrial Influence

Is it possible that the minima of Figure 27 represent the influx of extraterrestrial dust? There is some evidence that the minima do, but first some background material.

The term extraterrestrial dust will refer to micrometeorites and cosmic dust, both of microscopic size. Micrometeorites are particles which have been chemically altered by melting and oxidation in their passage through the atmosphere or which have been ablated from the surfaces of incoming meteoroids. Cosmic dust is dust which, because of its small size, passes through the earth's atmosphere practically unaltered. At incidence on the earth's atmosphere, these particles of cosmic dust, which constitute a more or less constant flux of particles into the atmosphere, span a limited range of diameters from 1 to 1000 microns. Because of their nature as ablation, melting, and oxidation products, meteoroids serve as secondary sources of fine particles, even though much larger than 1000 microns originally.

If a sufficient amount of extraterrestrial dust were to penetrate the atmosphere to the sampler, then the observed concentrations of minerals would be reduced.

The extraterrestrial dust which reaches the surface of the earth consists of spherule and angular particles. According to Öpik (cited by Junge [57]), the dominant fraction of these particles with diameters less than 20 microns is angular. The angular particles are difficult to distinguish from the terrestrial component and so cannot be ruled out as a contributing factor to the observed concentrations. However, spherule particles were probably negligible

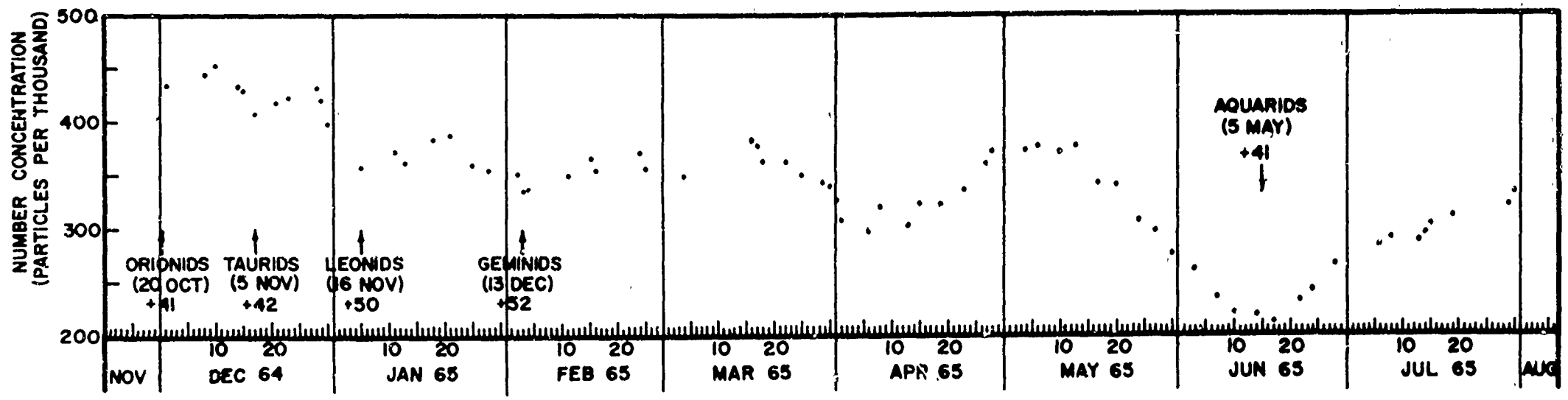


Fig.29 ELEVEN SAMPLE RUNNING MEAN OF SUMMED MINERAL CONCENTRATIONS, WHITE SANDS DUST SAMPLING SITE, NEW MEXICO, NOVEMBER 1964 TO AUGUST 1965.

because out of 450,000 particles examined, only one could possibly have been properly classed as a spherule.

Meteor showers impinge on the earth's atmosphere at much higher geocentric velocities than do the interplanetary dust particles, thereby lowering substantially the upper limit of diameter of particles surviving the fall through the atmosphere. Also, only for the more dense showers will the number concentrations of meteoritic material exceed that in the dust envelope.

Kaolinite, aragonite, and illite have yet to be observed in meteorites [58]. Calcite has been recorded only once in meteorites; dolomite has been reported as an accessory mineral in certain carbonaceous chondrites; gypsum was found in a carbonaceous chondrite, but may have been contamination; and quartz has been identified in small amounts in calcium-rich achondrites, Therefore, it seems likely that no extraterrestrial particles were identified as gypsum, quartz, kaolinite, illite or carbonates. As noted, however, they may have been present in the sample and thus served to reduce the individual concentrations.

Meteor showers which could have influenced the observed data were: Orionids, 20 October 1964; Taurids, 5 November 1964; Leonids, 16 November 1964; Geminids, 13 December 1964; and Aquarids, 5 May 1965. If one sums the daily concentrations of gypsum, quartz, kaolinite, illite, and carbonates and then plots the running eleven-sample arithmetic mean as in Figure 29, one observes minima at periods ranging from 40 to 50 days after the above dates of meteor showers. This is in excellent agreement with the data of Link (cited by Junge [57, p.27]) on the fall time of meteoritic dust for spherical particles four to five microns in diameter of both the metal and stone types.

As reported by Mason [58, p. 24], the maximum bimonthly incidence of meteorite falls occurs during May and June. This might imply that during May and June the earth crosses a region in space that contains a higher density of meteorites. This, in turn, might enhance the probability of extraterrestrial dust reaching the surface of the earth, which would lower the observed composite concentration. It is interesting to note that the lowest composite concentrations did occur during June.

Is this extraterrestrial dust in sufficient mass concentration to affect our observed mineral concentrations? Petterson [59], on the basis of data from Mauna Loa, Hawaii, estimates that the cosmic dust

content of 1000 cubic meters of air is 0.6 milligram, which is equivalent to 0.6 microgram per cubic meter, which is of sufficient magnitude to affect the observed concentrations, especially if this mass concentration were to be enhanced during times of meteor showers or meteorite falls. Note also the statement of Mason [58, p. 1] that there is no coincidence between the occurrence of meteor showers and the fall of meteorites.

Volcanic Dust

Volcanic dust could also constitute part of the unidentified fraction. This dust could result from weathering of lava outcroppings or from active volcanoes and subsequent atmospheric transport.

Volcanic outcroppings exceeding 100 square kilometers in area are located within 200 kilometers of the sampler to the southwest, northwest, and northeast. The proximity of this exposed lava suggests sources of unidentified particles which could reduce the composite concentration. Analysis of surface wind data for the mid-May to mid-June period revealed that the surface winds within a 200-kilometer radius of the sampler generally decreased as the composite concentration decreased which argues that local volcanic dust does not contribute markedly to the observed variations in composite concentration.

The possibility of an active volcano influencing the composite concentration variation is not entirely ruled out. Consider the eruption of the Agung Volcano on Bali on 17 March 1963. Optical effects therefrom were first noted in the southern United States [60] in September 1963. Twilight measurements by Volz [61] indicated a resultant seasonal variation in turbidity over Europe existent as late as the fall of 1964 (maximum) and the spring of 1965 (minimum). It is to be noted that the twilight effects of Krakatoa (27 August 1883) were observed over Europe as late as 2 1/2 years after the eruption. The main question seems to be whether significant amounts of the Bali volcanic dust could reach the sampler.

Influence of Natural Combustion

During the period from 17 May 1965 to 25 May 1965, a brush fire occurred 10 to 25 kilometers south of the sampler at the south end of the Organ Mountains. During this period the fire smoldered its way north up Boulder Canyon and then swept east down Soledad Canyon. Billowing clouds of smoke and ash marked the progress of the conflagration. Three dust samples were taken during this interval, but it is doubtful if the fire caused the drop in composite concentration of the transient dust which began about mid-May and extended on into mid-June. The sampler was insulated from the effects of the fire by an intervening 2500 meter MSL ridge, but, more important, was the fact that the configuration of the winds aloft over the Basin was not conducive to transport of transient particles from the fire area to the sampler. For the 17 - 18 May sample, winds aloft to 4000 meters above the Basin floor were northwesterly, veering to northeasterly at speeds up to 17 meters per second. During the sampling of 20-21 May, winds aloft were southwesterly to westerly at speeds less than 10 meters per second. Finally, winds aloft for the sample of 24 - 25 May were southwesterly at speeds increasing with altitude to 25 meters per second at 4000 meters above the Basin floor. On the mornings of the 19th and 20th, winds to 2500 meters above the Basin floor were southerly to southeasterly, but veered to southwesterly by afternoon. Thus, there is no strong meteorological evidence to support a net transport of air from the fire area to the sampler to account for the observed drop in composite concentration during the week of the fire.

Industrial Dust

Because the sampler is remote from the dust of industrial activity, this dust probably does not constitute a large fraction of any given sample. However, there is evidence for its occasional presence in local samples. This subject will be treated more fully in a subsequent paper.

SUMMARY

From the analysis of dust samples taken in a wide range of dustiness conditions, not exclusively duststorms, it is apparent that not all of the mineral particles in the atmospheric aerosol over White Sands Missile Range are of local origin. Of those that are, quartz and gypsum are good examples. Quartz is a ubiquitously common constituent of soils in the Southwest, but its concentration is not as high as one might expect. However, under cetain conditions its concentration may rise to high levels. Gypsum is interesting because here we have a highly localized source, but a sampler situated

with respect to it so that, because of the prevailing winds, concentrations are normally low. Once again, however, there are specific, albeit rare, conditions when the gypsum concentration at the sampler is high. That the primary source of kaolinite over White Sands lies to the east of this area may be inferred from the fact that it is not a common constituent in the Basin soils and that the kaolinite concentration increases with frontal passage from the east.

Analysis of the summed concentrations of the identified fraction leads to the conclusion that oceanic particles from the Gulf of Mexico and/or the Pacific Ocean are significant enough to influence the identified concentration. A steady inflow of air from the southwest over a period of days will gradually reduce the total concentration of the identified fraction because of a relatively steady flow of oceanic particles, coupled with a relative decrease in airborne particles of land origin due to exposed areas being swept free of such particles as the wind continues from a more or less fixed direction. Southwesterly flow over this area does not necessarily imply or dictate an abundance of oceanic particles, since a long overwater trajectory prior to entrance over the land mass of North America is apparently an additional criterion. Southeasterly flow taps the Gulf of Mexico source of oceanic particles, but the concentration of the identified fraction may increase if there is associated thunderstorm activity in the area. Even so, the summertime concentration of the identified fraction is low. At times of virtually complete blocking of the oceanic sources, the identified fraction concentrations may rise to high levels. There is some evidence for dust of extraterrestrial origin influencing the concentrations.

Thus, Part II has served to illustrate how one may relate observed atmospheric mineral concentrations to known or suspected sources of airborne dust particles by analysis of the attendent meteorological conditions. In explaining the observed concentrations of the various minerals from samples taken at the particular site selected for this investigation, it is necessary to consider not only the wind speed and direction at the sampler, but the flow within a radius of at least 1000 kilometers of the sampler. Knowledge of the mineral content of area soils and the mechanisms by which nature can thrust particles into the atmosphere, and cognizance of possible influxes of unidentified particles help to clarify certain problems.

By no means has this investigation solved the problem of the constituency of the atmosphere above White Sands Missile Range, but it has indicated that it is quite variable and may exhibit a seasonal dependence. Purporting to establish the mineral content

of the air over the Basin based on samples taken on an adjacent slope, a scant four meters above the surface, is certainly open to criticism. It must be remembered that the samples were taken at night to enhance the possibility of observing long period variations. During the day, turbulent transfer from the surface, coupled with generally stronger winds, might tend to increase the concentration of the identified component, which may be predominantly local in nature.

There is a problem in collecting and identifying microscopic meteorites because of terrestrial contamination; however, it may be possible to determine indirectly the relative variations of the influx of extraterrestrial dust in the low levels of the troposphere by determining certain composite terrestrial concentrations.

PART III

ANALYSIS OF ATMOSPHERIC PARTICULATES THROUGH INFRARED ABSORPTION SPECTROSCOPY

The grinding and mixing apparatus was a "Wig-L-Bug" amalgamator. The commercially available grinding capsules were replaced by special oversized (1.6 cm inner diameter) acid resistant stainless steel capsules. The oversized capsules allowed a more thorough mixing of the reference mineral and the KBr, easier removal of the resultant mixture from the capsule, and easier and more thorough cleaning of each capsule to prevent contamination.

The degree of grinding of the reference minerals and the degree of mixing of the KBr-reference mineral mixture were important factors influencing the quality of the infrared spectra.* The grinding time generally depended on the brittleness of the mineral, but in no case was the grinding time excessive to the point of structurally altering the mineral. An additional mixing (no ball in the grinding capsule) resulted in a breakup of the mineral power agglomerations and a more even distribution of the mineral powder in the KBr.

Then 0.15 g of the mixture was poured into a clean and dry (blank pellet tested) 13 mm inner diameter evacuable die. The die plunger was rotated several times in an alternating clockwise-counterclockwise manner with a slight downward pressure to insure an even distribution of the mixture. The die was evacuated for two minutes and, without breaking the vacuum, a force of 10^5N is applied for an additional three minutes.

The infrared absorption spectrum of the resultant 13 mm diameter pellet was recorded with a Perkin-Elmer Model 521 double beam grating spectrophotometer. Instrument settings were: slit program 800, gain 4.1, attenuator 800, suppression 6, and source amperage 1. The instrument was continuously flushed with dry nitrogen to eliminate the absorption bands of atmospheric water vapor and carbon dioxide. The spectrophotometer was calibrated to the indene absorption peaks at 3926.5, 3110.0, 2304.8, 1915.0, 1287.8, 830.5, 590.8, and 381.4 cm^{-1}, and to the water vapor absorption peak at 298.4 cm^{-1}.

Infrared spectra of 54 reference minerals (Table VIII) were obtained, but only those minerals mentioned in the text are presented in the appendix. The positions of the absorption peaks of each reference spectrum were determined from spectra recorded at expanded wave number scale.

*The grinding and mixing times are noted in the tables accompanying the reference spectra.

BACKGROUND

Infrared absorption spectroscopy has been extensively applied to the identification of minerals [62]. In this investigation microgram samples of atmospheric dust were analyzed for mineral content by this spectral analytical method in the wave number range from 4000 to 250 cm^{-1}.

This part will (1) cover reference minerals and the preparation of their characteristic infrared absorption spectra, (2) include the preparation of an alkali halide pellet of atmospheric dust, (3) present six dust spectra illustrating the identification of the sulfate minerals gypsum and mirabilite, the silicate minerals quartz and kaolinite, and the carbonate minerals calcite and dolomite, and (4) present the results of the qualitative analysis of 33 dust spectra. The infrared absorption spectra of 13 reference minerals appear in the appendix.

PROCEDURE

Reference Mineral Spectra

Reference mineral spectra are necessary for the interpretation of the infrared absorption spectra of samples of atmospheric dust for mineral content. The reference spectra define the position, strength and shape of the "fingerprint" absorption peaks.

The selection of minerals to be used as references was governed by two geological studies [26, 27] and by the independent analysis of a dust sample from the local aerosol noted in Part I. The mineral samples were obtained from several sources. Most of the samples were donated by Dr. George Switzer of the U. S. National Museum. Other sources include the U. S. Army Engineer Waterways Experiment Station, Jackson, Mississippi; the State Bureau of Mines and Mineral Resources, Socorro, New Mexico; and the Illinois State Geological Survey, Urbana, Illinois. The identity of the minerals was verified by x-ray diffraction analysis.

The pressed alkali halide pellet technique was used to prepare the reference minerals for infrared analysis. The particular alkali halide employed in this study was vacuum oven dried Harshaw Infra Red Quality potassium bromide (KBr).

The grinding and mixing apparatus was a "Wig-L-Bug" amalgamator. The commercially available grinding capsules were replaced by special oversized (1.6 cm inner diameter) acid resistant stainless steel capsules. The oversized capsules allowed a more thorough mixing of the reference mineral and the KBr, easier removal of the resultant mixture from the capsule, and easier and more thorough cleaning of each capsule to prevent contamination.

The degree of grinding of the reference minerals and the degree of mixing of the KBr-reference mineral mixture were important factors influencing the quality of the infrared spectra.* The grinding time generally depended on the brittleness of the mineral, but in no case was the grinding time excessive to the point of structurally altering the mineral. An additional mixing (no ball in the grinding capsule) resulted in a breakup of the mineral power agglomerations and a more even distribution of the mineral powder in the KBr.

Then 0.15 g of the mixture was poured into a clean and dry (blank pellet tested) 13 mm inner diameter evacuable die. The die plunger was rotated several times in an alternating clockwise-counterclockwise manner with a slight downward pressure to insure an even distribution of the mixture. The die was evacuated for two minutes and, without breaking the vacuum, a force of 10^5N is applied for an additional three minutes.

The infrared absorption spectrum of the resultant 13 mm diameter pellet was recorded with a Perkin-Elmer Model 521 double beam grating spectrophotometer. Instrument settings were: slit program 800, gain 4.1, attenuator 800, suppression 6, and source amperage 1. The instrument was continuously flushed with dry nitrogen to eliminate the absorption bands of atmospheric water vapor and carbon dioxide. The spectrophotometer was calibrated to the indene absorption peaks at 3926.5, 3110.0, 2304.8, 1915.0, 1287.8, 830.5, 590.8, and 381.4 cm^{-1}, and to the water vapor absorption peak at 298.4 cm^{-1}.

Infrared spectra of 54 reference minerals (Table VIII) were obtained, but only those minerals mentioned in the text are presented in the appendix. The positions of the absorption peaks of each reference spectrum were determined from spectra recorded at expanded wave number scale.

*The grinding and mixing times are noted in the tables accompanying the reference spectra.

TABLE VIII

Alphabetical Listing of the 54 reference minerals used in this study

Actinolite	Gypsum	Penninite
Albite	Halloysite	Periclase
Amblygonite	Hematite	Peridot
Andradite	Hornblende	Phlogopite
Anglesite	Illite	Plumbojarosite
Apatite	Kaolinite	Pyrite
Aragonite	Labradorite	Pyrolusite
Attapulgite	Lepidolite	Quartz
Augite	Magnesite	Rhodochrosite
Biotite	Malachite	Serpentine
Bytownite	Microcline	Siderite
Calcite	Mirabilite	Smithsonite
Celestite	Montmorillonite	Thenardite
Cryolite	Nacholite	Topaz
Dickite	Oligoclase	Tourmaline
Dolomite	Opal	Vermiculite
Fluorite	Orthoclase	Wollastonite
Glauberite	Pargasite	Zircon

Dust Spectra

After a portion of the dust had been removed from the membrane filter for phase microscopic investigation, the remainder of the dust on the filter could be used for the infrared portion of the analysis. To remove the dust from the membrane filter, 0.2 g KBr is placed on a clean piece of laboratory filter paper. Then the dust-laden membrane filter is placed dust side down on the halide salt and moved in a circular path over the salt several times to dislodge the dust from the membrane filter. Excessive pressure and/or rotation will ablate the surface of the membrane filter and result in unwanted absorption peaks due to the membrane filter.

The dust-KBr mixture is then placed in a clean, dry oversized capsule with no ball. The mixture is agitated for 45 to 60 minutes. Of the dust-KBr mixture 0.15 g is pressed into a

13 mm pellet following the procedure previously outlined for the reference mineral pellets. The spectrum of the pellet is recorded and the absorption peak positions determined by use of an expanded wave number scale.

INTERPRETATION OF DATA

In determining the mineral constituents of the dust, a direct absorption peak comparison technique was used, i.e., the individual dust spectra were examined for those minerals of the 54 reference minerals which could have caused the observed absorption peaks. The ensuing identifications fell into two categories termed "positive identification" and "defined identification." (The "positive identification" will be exemplified by six spectra of minerals in dust; then the criteria for the "defined identification" will be outlined.)

A "positive identification" of a given mineral in a dust spectrum was made if all the strong and medium strength absorption peaks of the corresponding reference mineral appeared in the dust spectrum with proper shape and relative strength. In the dust spectra the strong reference peaks might appear as strong, medium or weak peaks and the medium reference peaks as medium or weak peaks because of the decreased relative concentration of the individual mineral constituents in the dust pellet. Shoulders in the dust spectra might indicate overlapping of absorption peaks and, although the entire shape of the absorption peak was not discernible, the center of the peak could be determined fairly accurately.

Based on the above criteria for positive mineral identification, six minerals have been identified. The six dust spectra representing these minerals are presented in Figures 30 to 35. Each spectrum has been selected to best exemplify one particular mineral although a single dust spectrum might exhibit more than one mineral. The absorption peaks noted on Figures 30 to 35 are the strong and medium and some of the weak strength absorption peaks of the reference mineral spectra.

To facilitate the analysis of the dust spectra, the absorption peaks of the 54 reference minerals were tabulated by wave number position. This listing yielded all the minerals categorized in this study which may have caused a given absorption peak in the dust spectra.

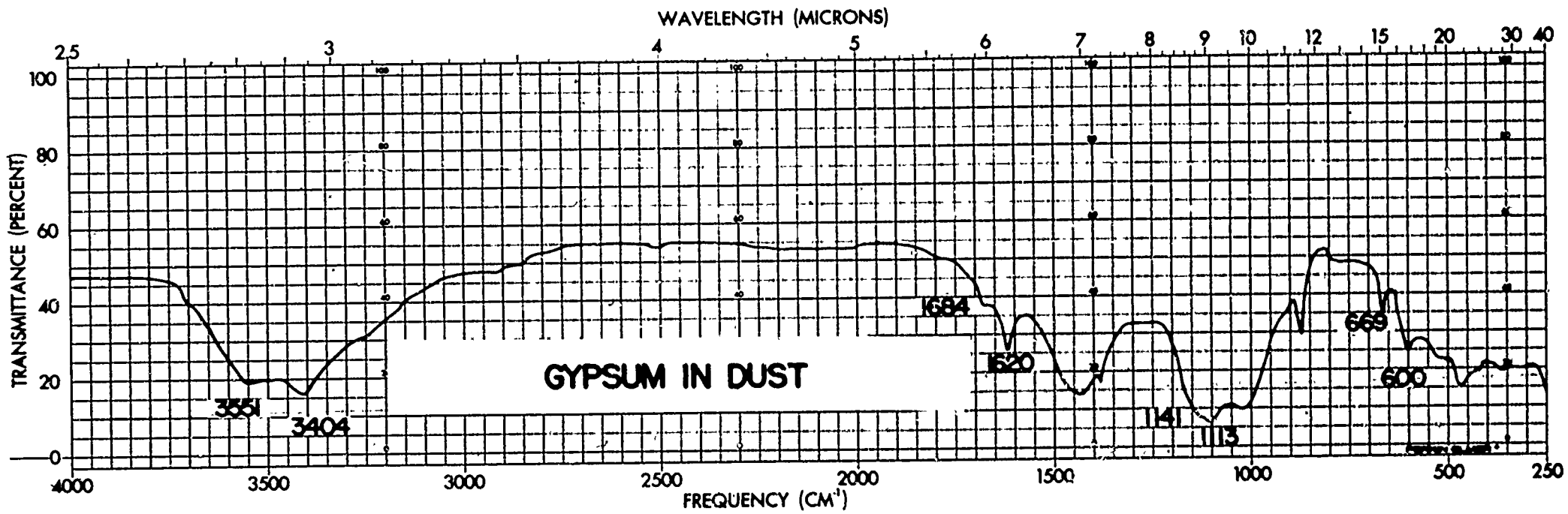


Fig. 30. Spectrum of atmospheric dust showing gypsum. Dust sample collected from 9 August 1965, 1530M, to 10 August 1965, 0830M.

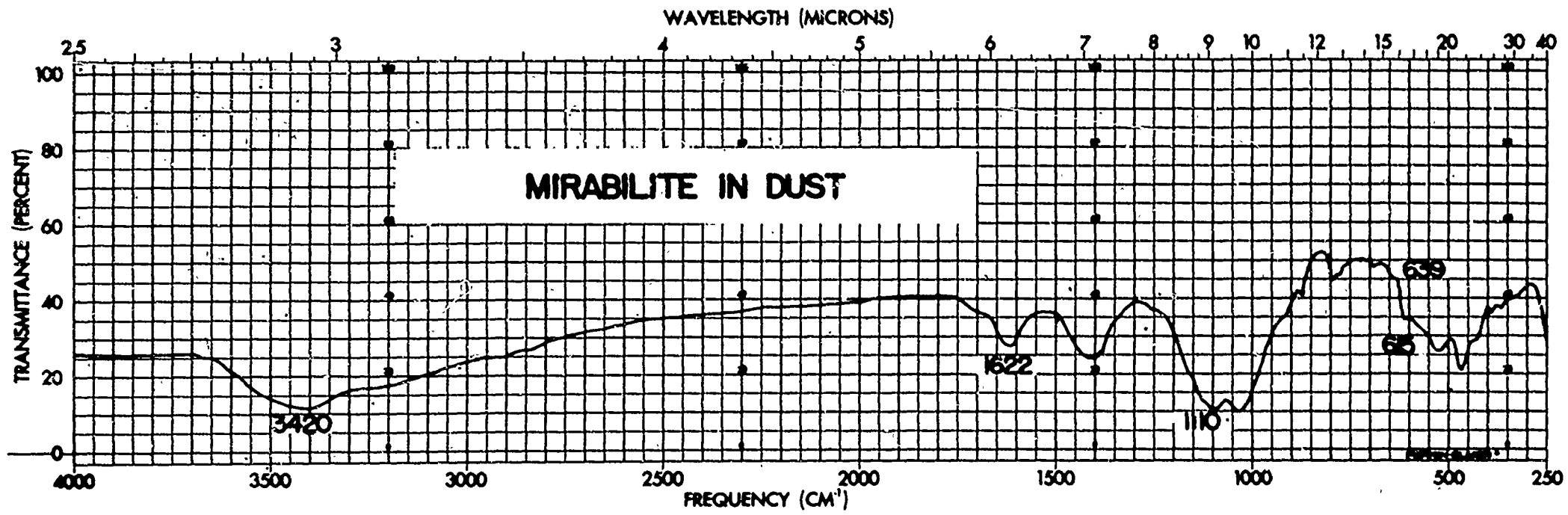


Fig. 31. Spectrum of atmospheric dust showing mirabilite. Dust sample collected from 31 March 1965, 1600M, to 1 April 1965, 0730M.

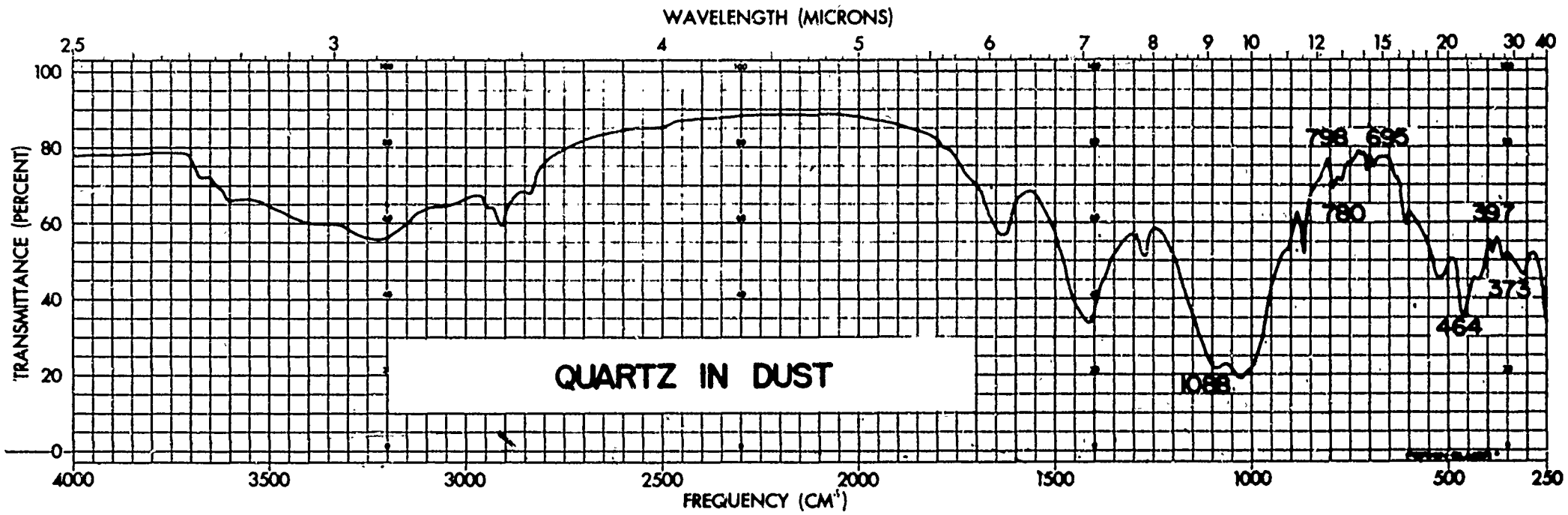


Fig. 32. Spectrum of atmospheric dust showing quartz. Dust sample collected from 15 December 1964, 1530M, to 16 December 1964, 0830M.

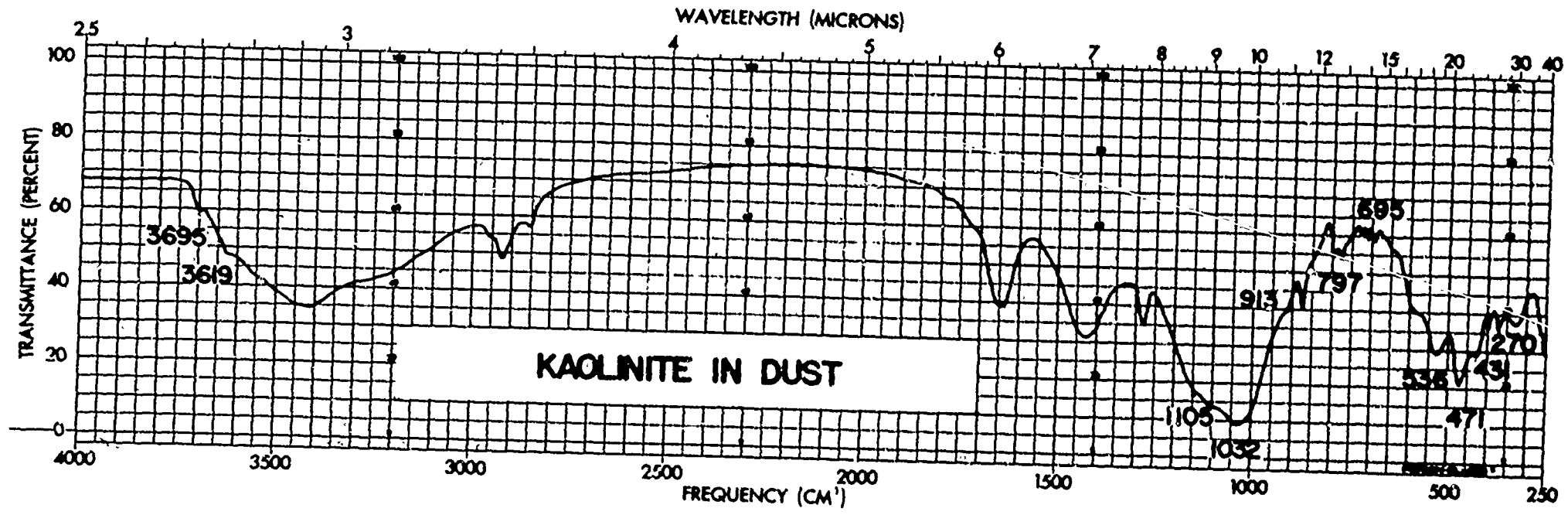


Fig. 33. Spectrum of atmospheric dust showing kaolinite. Dust sample collected from 1 October 1964, 1445M, to 2 October 1964, 0830M.

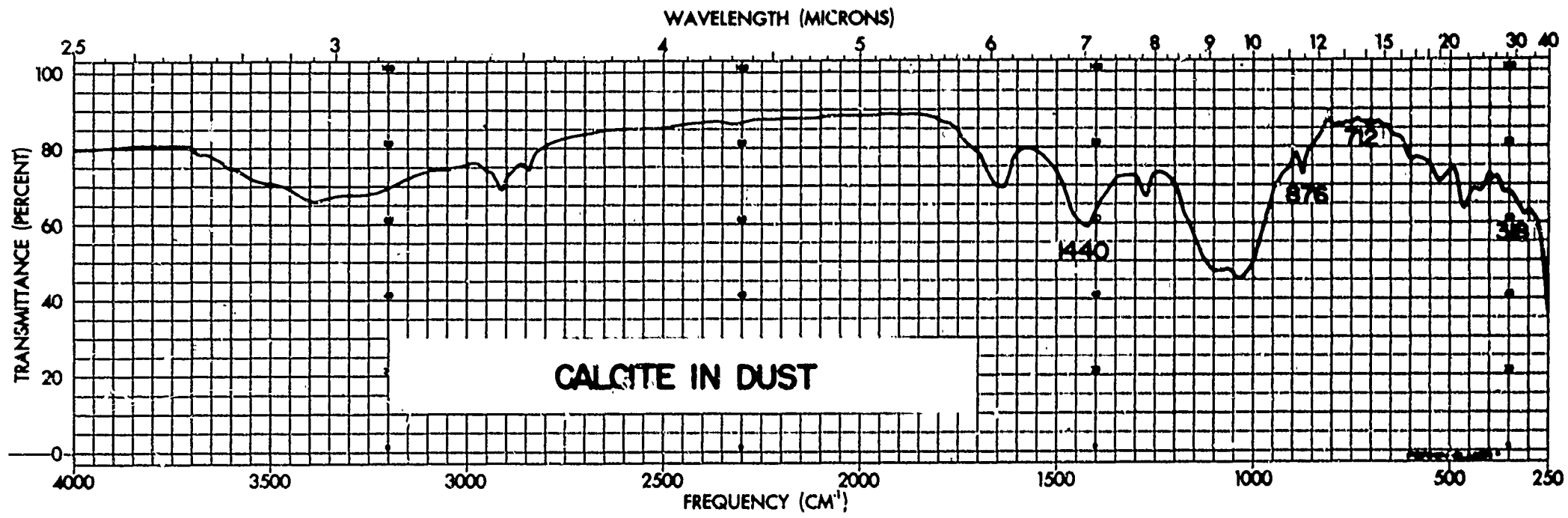


Fig. 34. Spectrum of atmospheric dust showing calcite. Dust sample collected from 8 December 1964, 1600M, to 9 December 1964, 0900M.

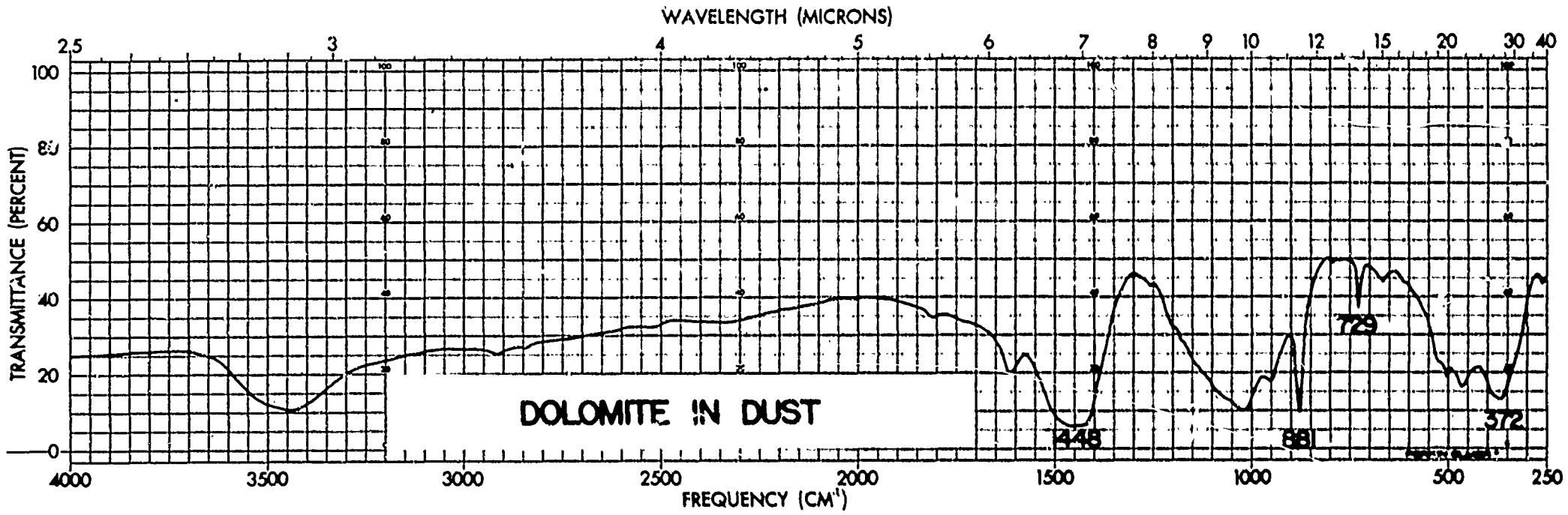


Fig. 35. Spectrum of atmospheric dust showing dolomite. Dust sample collected from 28 January 1965, 1530M, to 29 January 1965, 0800M.

In Figure 30 the sulfate family is identifiable from the strong absorption peak within the 1100 cm^{-1} to 1200 cm^{-1} range. The presence of gypsum is inferred from the doublet at 669 cm^{-1} and 600 cm^{-1}.

Figure 31 again shows the sulfate family peak. The peaks at 615 cm^{-1} and 639 cm^{-1} specify mirabilite (ten waters of crystallization) and not thenardite (zero waters of crystallization) because the 615 cm^{-1} absorption peak of mirabilite will shift to 620 cm^{-1} (thenardite) and the 639 cm^{-1} peak will vanish as waters of crystallization are lost.

Figure 32 illustrates the presence of the silicate mineral quartz. The silicate family band is evident between 1000 cm^{-1} and 1100 cm^{-1}. The particular silicate, quartz, is identified by the additional absorption bands at 798 cm^{-1}, 780 cm^{-1}, 695 cm^{-1}, 464 cm^{-1}, 397 cm^{-1} and 373 cm^{-1}.

Figure 33* illustrates the difficulties inherent in trying to identify clays in samples of atmospheric dust by infrared absorption spectroscopy alone. The kaolin group may be "positively" identified in this figure by virtue of the presence of all the strong and medium strength absorption peaks of kaolinite, dickite, and halloysite, particularly the hydroxyl bands between 3720 cm^{-1} and 3610 cm^{-1}. The individual infrared absorption patterns of these three related clay minerals, though appearing unique, are not sufficiently distinctive for identification purposes [63, 64, 65], especially in such complex mixtures as atmospheric dust, because of the overlapping of absorption bands. Weakness of the hydroxyl absorptions in the dust spectra precluded their use in distinguishing these three clays by the technique of Lyon and Tuddenham [66]. The selection of kaolinite as the clay mineral present in the dust was based on the presence of the kaolin group in the local soils (Table IV) and by its identification by dispersion staining in Part I.

In Figures 34 and 35 the carbonate family absorption peak is noted at approximately 1440 cm^{-1}. Calcite is specifically

*This sample was collected before initiation of the regular sampling program, but the spectrum thereof has been presented because it demonstrates the presence of kaolinite more clearly than the spectra of the "regular" samples.

identified by the peaks at 876 cm^{-1}, 712 cm^{-1}, and 318 cm^{-1}, with dolomite identified on the basis of the peaks at 881 cm^{-1}, 729 cm^{-1}, and 372 cm^{-1}.

In the six spectra of Figures 30 to 35 the wave number positions of the identified mineral absorption peaks match the corresponding strong and medium strength peaks of the reference spectra. In most dust spectra such positive mineral identification based on perfect matching was not possible because of masking or concentration effects. This led to the selection and judicious application of the following rules for the "defined identification" of a given mineral in a complex mixture of minerals such as airborne dust:

1. Of the medium and strong reference mineral absorption peaks, 75 percent must be present in the dust spectrum.

2. These peaks must have "subjectively proper" shape.

3. These peaks must have "proper" relative intensity.

4. The remaining 25 percent of the peaks must have been masked* or so reduced in strength by the low concentration of the mineral in the dust that they were not apparent.

On the basis of this set of criteria, 33 dust spectra were analyzed for mineral content. The results are presented in Table IX. Table IX does not cover all of the 81 samples analyzed by dispersion staining because (1) not enough dust remained on the filter after dispersion staining analysis to even attempt to prepare a pellet, (2) not enough sample was in the pellet though there appeared to be enough dust on the filter, and (3) the KBr used for the first four February dust samples was contaminated.

It may be noted from Table IX that the clay mineral illite has been identified. However, it is difficult to distinguish montmorillonite and illite in the same sample [65, 67] because

*Masking is the condition whereby one mineral has absorption peaks overlapping those of a second mineral thereby masking, or hiding, the peaks of the second mineral depending on the relative amounts of the two minerals present in the sample. As an example, in Figure 32 quartz is easily identified but, due to masking, small quantities of opal would remain hidden.

Table IX. Qualitative mineral analyses of 33 dust spectra for gypsum (G), mirabilite (M), quartz (Q), kaolinite (K), illite (I), calcite (Ca), dolomite (D). Presence of mineral indicated by an x in the appropriate column.

Dates	Time (MST)	Sulfates		Silicates			Carbonates	
		G	M	Q	K	I	Ca	D
November	1964							
13-16	1130-0830		X	X			X	
24-25	1530-0900						X	
30- 1	1430-0900		X	X	X	X	X	
December	1964							
8- 9	1600-0900						X	
10-11	1500-0930		X				X	
14-15	1500-0900		X				X	
15-16	1530-0830		X	X	X	X	X	
17-18	1500-0800		X	X	X	X	X	
23-24	1400-0800	X		X				
January	1965							
5- 6	1400-0930			X			X	
13-14	1500-0900						X	
18-19	1600-1000						X	
25-26	1500-0830			X	X		X	
28-29	1530-0800							X
February	1965							
24-25	1500-0900			X				
March	1965							
17-18	1530-0830			X				
18-19	1530-0800			X	X			
22-23	1330-0800			X				
25-26	1530-0730			X				
29-30	1530-0900			X				
31- 1	1600-0730		X	X				
April	1965							
15-16	1530-0900			X				
19-20	1530-0830			X			X	

Table IX. (continued)

Dates	Time (MST)	Sulfates		Silicates			Carbonates	
		G	M	Q	K	I	Ca	D
May	1965							
4- 5	1530-0900			X				
6- 7	1500-0730			X			X	
10-11	1600-0930			X				
20-21	1530-0900			X			X	
June	1965							
3- 4	1530-0800						X	
22-23	1600-0800	X					X	
28-29	1500-0830						X	
July	1965							
8- 9	1600-0830			X			X	
14-15	1500-0830			X			X	
August	1965							
9-10	1530-0830	X						

of the similarity of their absorption bands and because of overlapping by the kaolin group absorption bands. The choice of illite over montmorillonite rested solely on the identification of illite by dispersion staining; thus the presence of montmorillonite is not precluded.

RESULTS

In the analysis of 33 microgram samples of atmospheric dust by infrared absorption spectroscopy the minerals gypsum, mirabilite, quartz, kaolinite, illite, calcite and dolomite were identified. The reliability of these mineral identifications using a spectrophotometer spanning the range from 4000 to 250 cm^{-1} was enhanced over similar identifications possible with spectrophotometers covering only the 4000 to 665 cm^{-1} range because of the increased number of signature absorption peaks present in the extended range.

It must be emphasized that the identification of the seven minerals was based on study of the spectra of 54 selected reference minerals. Thus, the fact that seven minerals were observed certainly does not preclude the presence of minerals whose spectra were not examined. However, examination of the dust spectra revealed that most of the absorption peaks could be accounted for by adsorbed water and by the seven reference minerals.

CONCLUSIONS

The questions posed in the introduction have by no means been completely answered. However, by way of summary it may be stated that on the basis of analyses of 81 samples of the atmospheric aerosol over White Sands Missile Range from November 1964 to August 1965 significant changes in the relative mineral content of the dust therein do occur. Such changes may occur in response to thunderstorm activity, mountain waves, frontal passage, wind shifts, incursions of oceanic air, and settling of extraterrestrial particles.

Part I centered on the transient fraction of mineral dust from this aerosol. It presented the details of the application of dispersion staining microscopy to the determination of mineral concentrations, in particles per thousand total particles, for quartz, gypsum, kaolinite, illite, and carbonates. The method is quick, reliable, and requires only a small amount of sample. The resultant data reveal marked sample-to-sample variations in mineral concentration.

In Part II these variations were examined meteorologically after a discussion of the mineral content of area soils felt to be susceptible to wind ablation.

The gypsum concentration at the sampler was normally low, but on occasion was high, and exhibited a seasonal variation. The low concentrations may be attributed to the fact that the sampler is located southwest of the source and the prevailing wind is not from the northeast. Three cases of high gypsum concentrations were related to wind shift, mountain wave, and thunderstorm activity. The seasonal variation exhibits a winter minimum, a spring maximum, and an early summer minimum. By virtue of its unique source location, gypsum suggests itself as a natural tracer material for mountain waves and their resultant local circulations.

Despite being relatively common in the samples, the quartz concentration does fluctuate sharply with abrupt changes in surface wind velocity, thunderstorm activity, and mountain waves. The onset of the local summer thunderstorm season seems to be signatured by the rise in quartz concentration.

The kaolinite concentration rises markedly only with frontal passage from the east if the suspected source region is not water-soaked or snow-covered.

The summed concentrations of quartz, gypsum, kaolinite, illite and carbonates yielded indirect evidence that influxes of oceanic particles and/or extraterrestrial particles were influencing the concentrations.

Part III demonstrated the potential of infrared absorption spectroscopy for the determination of the mineral constituents of atmospheric dust. The method, based on the extension of the scanning range beyond 700 cm^{-1} and the use of reference mineral spectra allowed the identification of seven minerals in 33 samples of atmospheric dust. The method is quick, relatively easy to apply, and may be applied to extremely small samples.

The examination of the mineral content of airborne dust samples is practicable with dispersion staining microscopy and infrared absorption spectroscopy, the former for quantitative data on specific minerals and the latter for identification of various minerals present in the dust.

The site and sampling time proved to be particularly advantageous. The sampling site was well removed from the contaminating effects of industrial activity, was removed from the many dusty soils of the area, was ground based, and was at a fixed location. By sampling during the nighttime hours certain long range influences were noticed which might have been masked during the day by the net transport of particles from the ground to the atmosphere. No attempt was made to confine the sampling to duststorms, because the relative mineral concentrations therein may not be representative of common dust conditions.

A number of questions remain unanswered. Why was feldspar so conspicuous by its absence though it is a common constituent of area soils? Perhaps feldspar does not decompose into feldspar as the transient particle sizes are reached. What particles constitute the unidentified fraction? Are they mainly the volcanic ash, mirabilite, thenardite, albite, biotite, dolomite, and montmorillonite of Part III or are they rather oceanic particles or particles of unknown extraterrestrial origin? The answers to these and other allied questions are now under investigation.

ACKNOWLEDGMENTS

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APPENDIX

INFRARED ABSORPTION SPECTRA OF REFERENCE MINERALS, 4000 to 250 CM^{-1}

The appendix consists of two sections: (1) an alphabetical listing of 13 reference minerals and (2) the spectra of these reference minerals with their respective tables of wave number position, strength and shape of the absorption peaks.

Section 1

Each mineral in the listing is keyed to the source from which it was obtained by the following abbreviations:

SI = Department of Mineral Sciences, Smithsonian Institution, U. S. National Museum, Washington, D. C.

LS = Local source, i.e., samples collected by the authors on field trips and samples from the State Bureau of Mines and Mineral Resources, Socorro, N. M.

IS = Illinois State Geological Survey, Urbana, Ill.

WS = Concrete Division, U. S. Army Engineer Waterways Experiment Station, Jackson, Miss.

The column under "Catalog Number" refers to the catalog or museum number given to the mineral by the particular agency. The actual locale where the minerals naturally occur is indicated under "Locale." The minerals were verified by x-ray diffraction.* The minerals which had D spacings corresponding to the American Society for Testing Materials (ASTM) standards** are marked with a "yes." The designation

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*Analyzed by the Chemistry and Metallurgy Group, Environmental and Instrument Branch, Missile Science Division, Army Missile Test and Evaluation Directorate, White Sands Missile Range, New Mexico and by the Concrete Division, U. S. Army Engineer Waterways Experiment Station, Jackson, Mississippi.

**American Society for Testing Materials, 1960: X-ray powder data file, sets 1-13, Spec. Tech. Publ. No. 48-J, ASTM, Philadelphia, Pa.

'yes-R' indicates that the illite was received from the U. S. Army Waterways Experiment Station where it had been verified by x-ray diffraction. Opal is marked with a "no" because opal is amorphous, i. e., having no ordered crystal structure and therefore no identifiable x-ray pattern. Mirabilite and thenardite are similarly marked with a "no" because the synthetic samples thereof were carefully prepared from reagent grade sodium sulfate. Minerals which did not meet the ASTM standards were not used.

Section 2

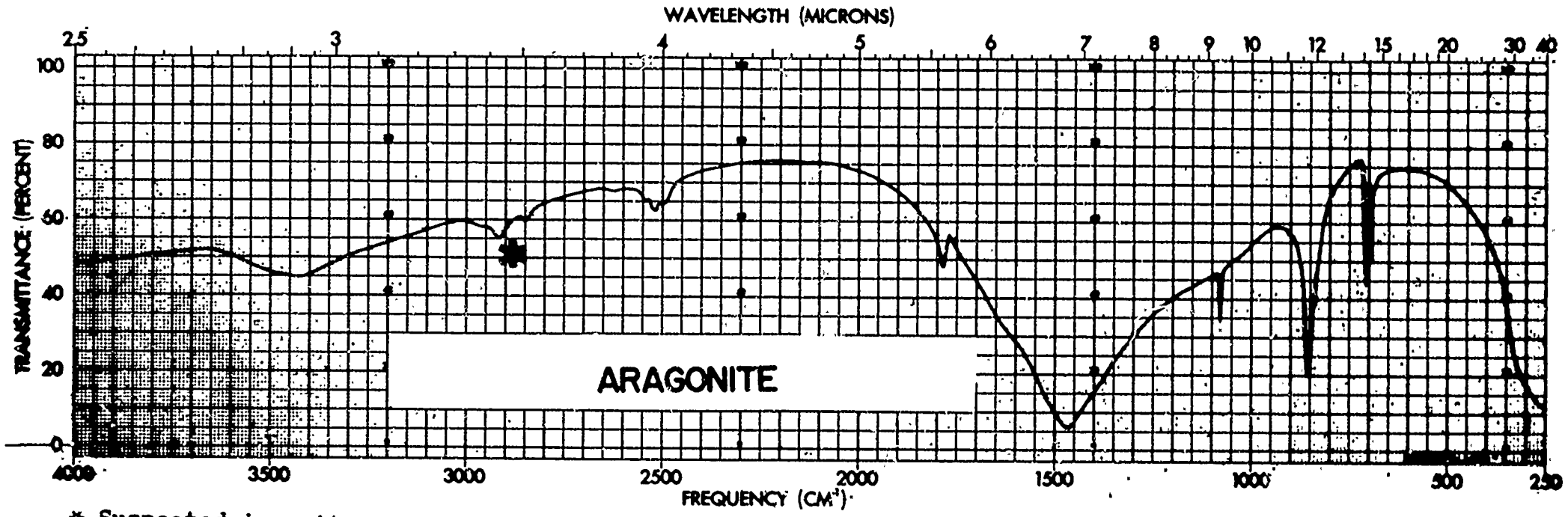
The second part of the appendix presents 13 reference mineral spectra at a one-to-one scale in alphabetical order, with the wave number (cm^{-1}), strength, and shape of each peak listed below the spectra. Due to photographic reduction, a few of the weaker peaks may not be evident.

The determination of the strength of an absorption band was based on the percent of transmittance with respect to maximum and minimum transmittance for each individual spectrum. The depth of the strongest band in a particular spectrum is considered to have a value of 100. The band with a relative depth value of 0-24 is considered to be a weak strength peak. The band with a relative depth value of 25-74 is considered to be a medium strength peak. Any band with a relative value of 75-100 is considered to be a strong peak. The peak strength is noted on the spectra as W(weak), M(medium), or S(strong). In reference to peak or band shape, four main classifications have been used: S(sharp), M(medium), B(broad), or Sh(shoulder).

APPENDIX SECTION I

LIST OF REFERENCE MINERALS

MINERAL	SOURCE	CATALOG NO.	LOCALE	VERIFIED BY X-RAY
ARAGONITE	SI	R2535	Italy, Sicily, Cianciano	Yes
CALCITE	LS	NONE	UNKNOWN	Yes
DICKITE	SI	R7593	Mexico, Chihuahua, San Juanito	Yes
DOLOMITE	IS	NF587C	United States, Illinois, Chicago outcrop	Yes
GYPSUM	LS	NONE	United States, New Mexico, Carlsbad	Yes
HALLOYSITE	SI	117151	United States, Utah, Tintic District, Dragon Mine	Yes
ILLITE	WS	NONE	United States, Nevada Test Site, Project Piledriver	Yes-R
KAOLINITE	SI	106223	England, Lanarkshire	Yes
MIRABILITE			Synthetic	No
MONTMORILLONITE	SI	90473	United States, California, San Diego County	Yes
OPAL	LS	NONE	United States, New Mexico, Radium Springs	No
QUARTZ	LS	NONE	Canada, Ottawa	Yes
THENARDITE			Synthetic	No



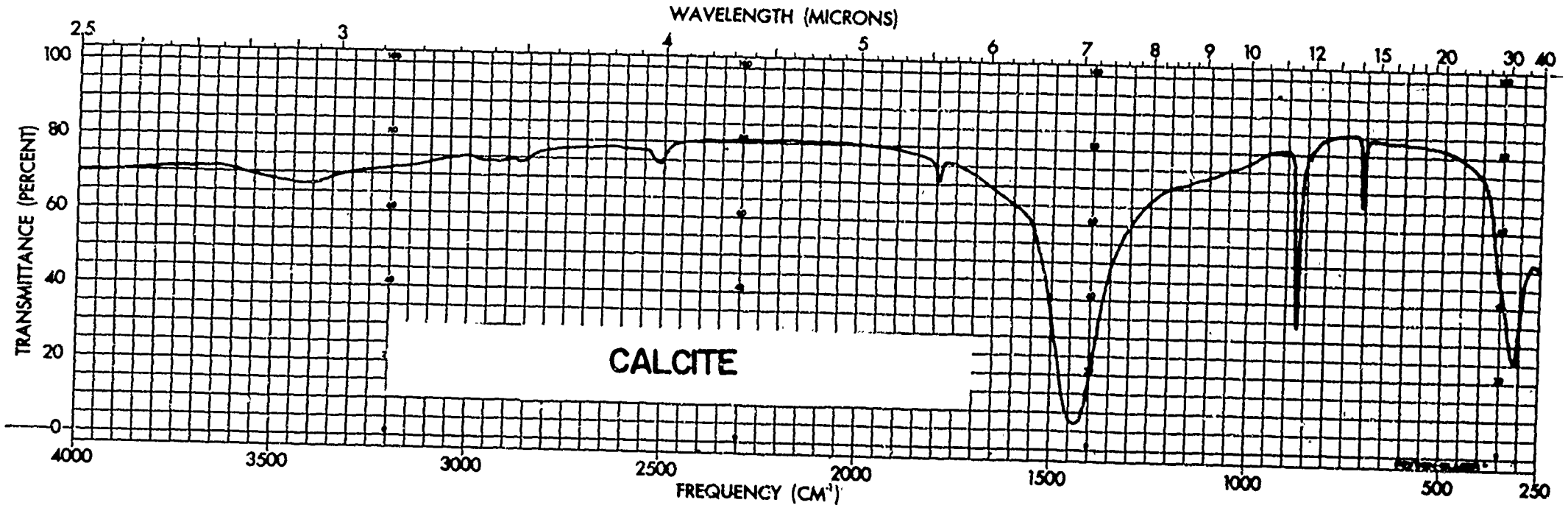
* Suspected impurity

Matrix: KBr

Grinding time: 5 min

Mixing time: 10 min

WN(cm^{-1})	ST	SH	WN(cm^{-1})	ST	SH
2545	W	M	858	S	S
2521	W	M	843	W	S
2496	W	M	713	M	S
1790	M	S	700	M	S
1472	S	B			
1082	M	S			

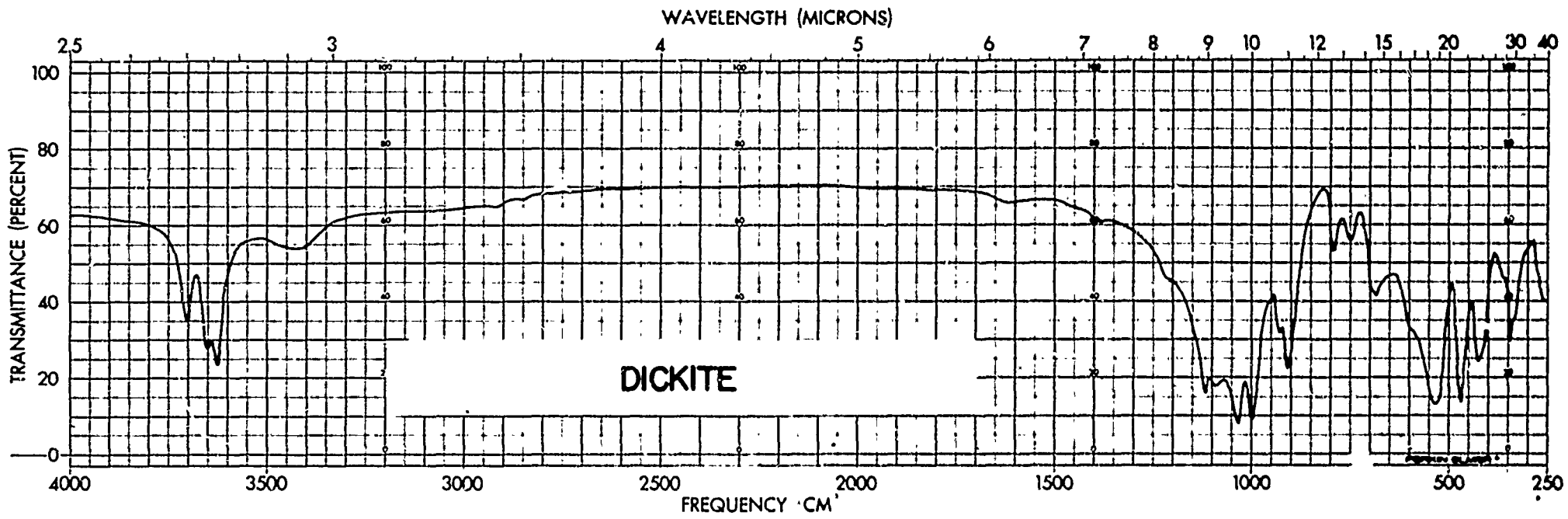


Matrix: KBr

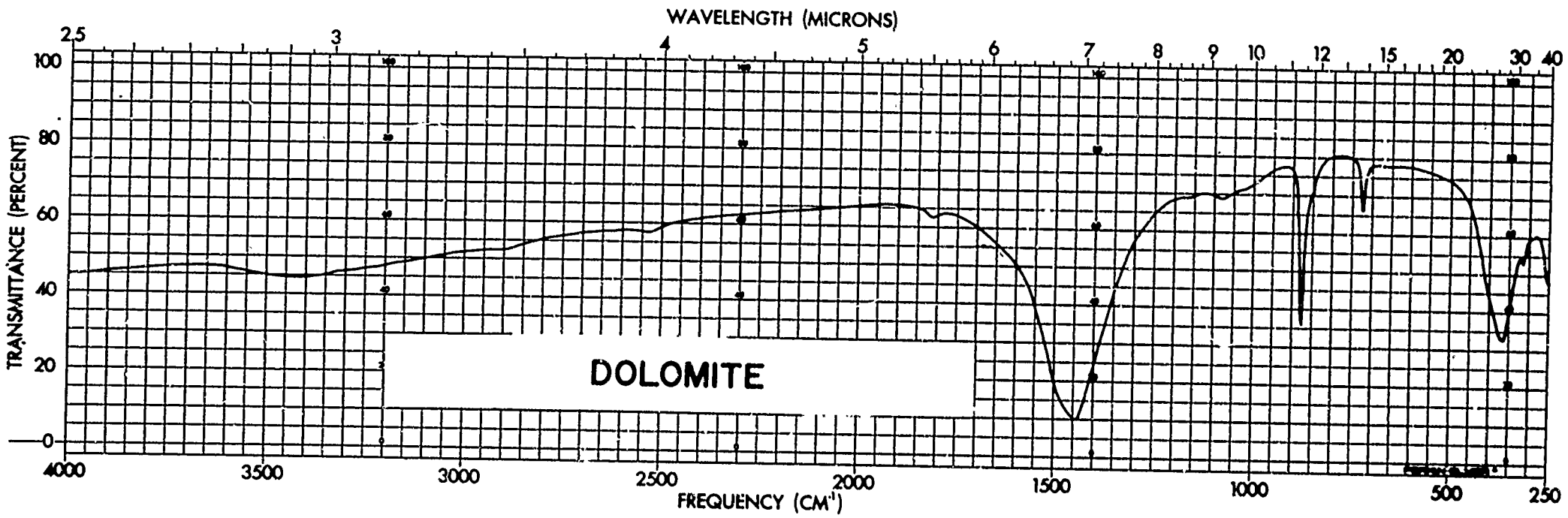
Grinding time: 10 min

Mixing time: 15 min

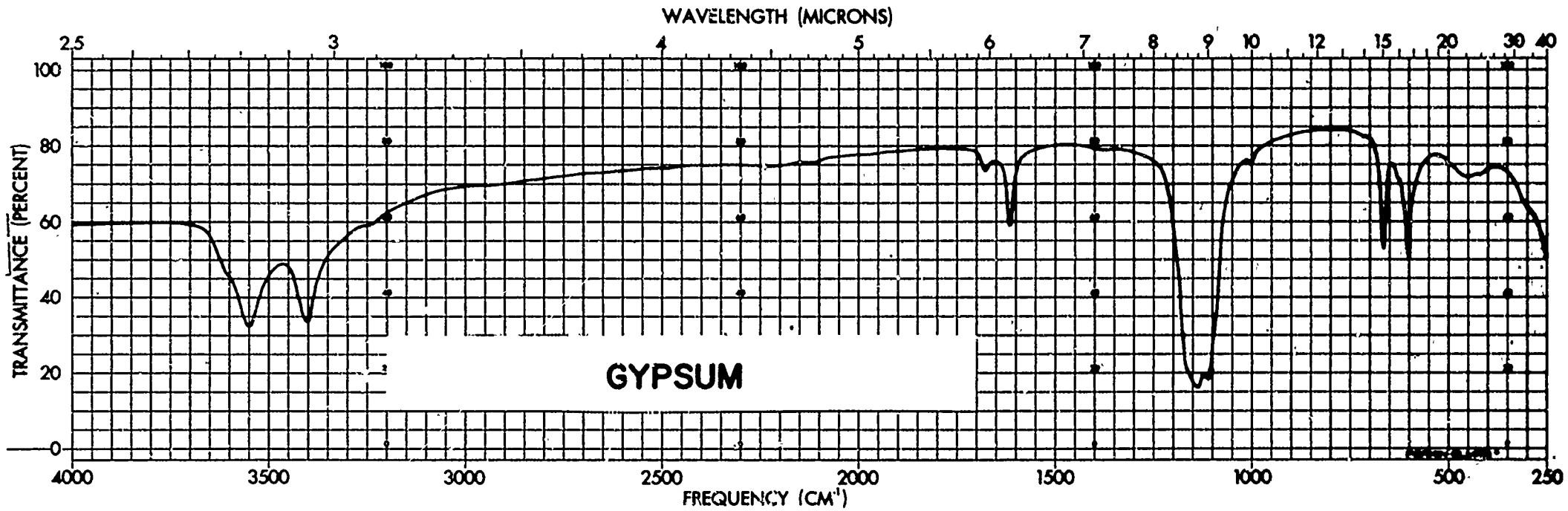
WN(cm^{-1})	ST	SH
2510	W	M
1797	W	M
1440	S	B
876	M	S
847	W	S
712	M	S
318	M	M



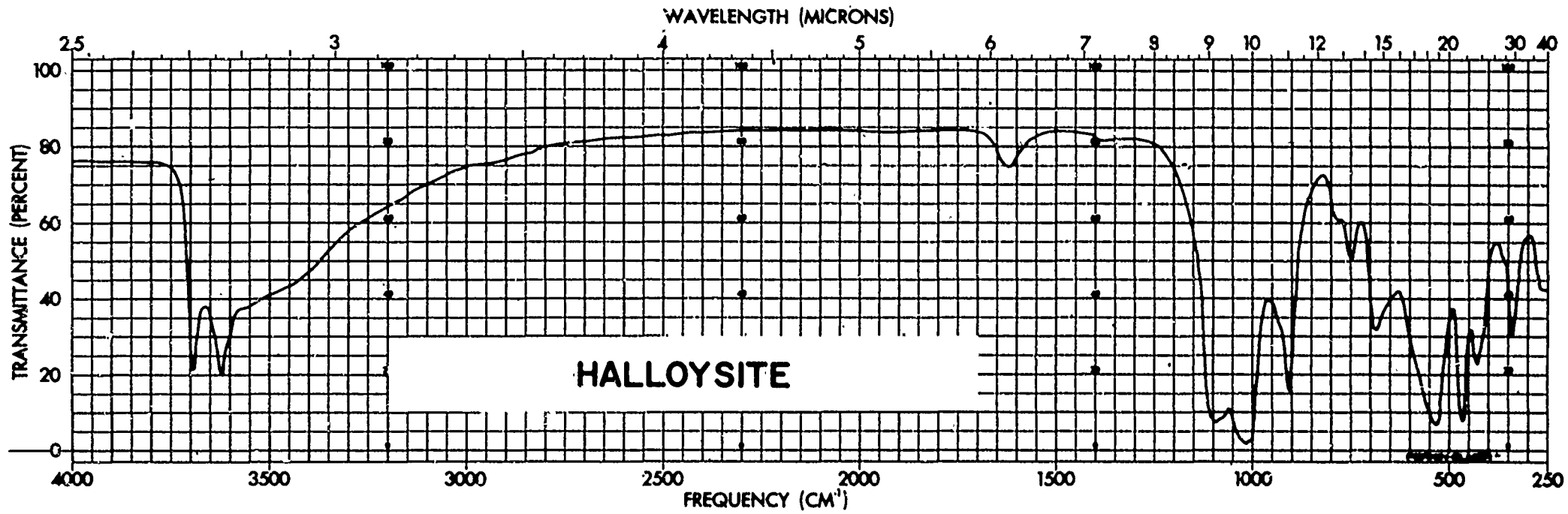
	WN(cm^{-1})	ST	SH	WN(cm^{-1})	ST	SH	WN(cm^{-1})	ST	SH
Matrix: KBr	3703	M	S	1000	S	S	537	S	M
	3649	M	S	933	W	S	471	S	S
Grinding time: 10 min	3626	M	S	911	M	S	426	M	M
	1119	M	S	796	W	S	361	W	Sh
Mixing time: 40 min	1096	M	M	752	W	M	346	M	S
	1036	S	M	690	M	M			



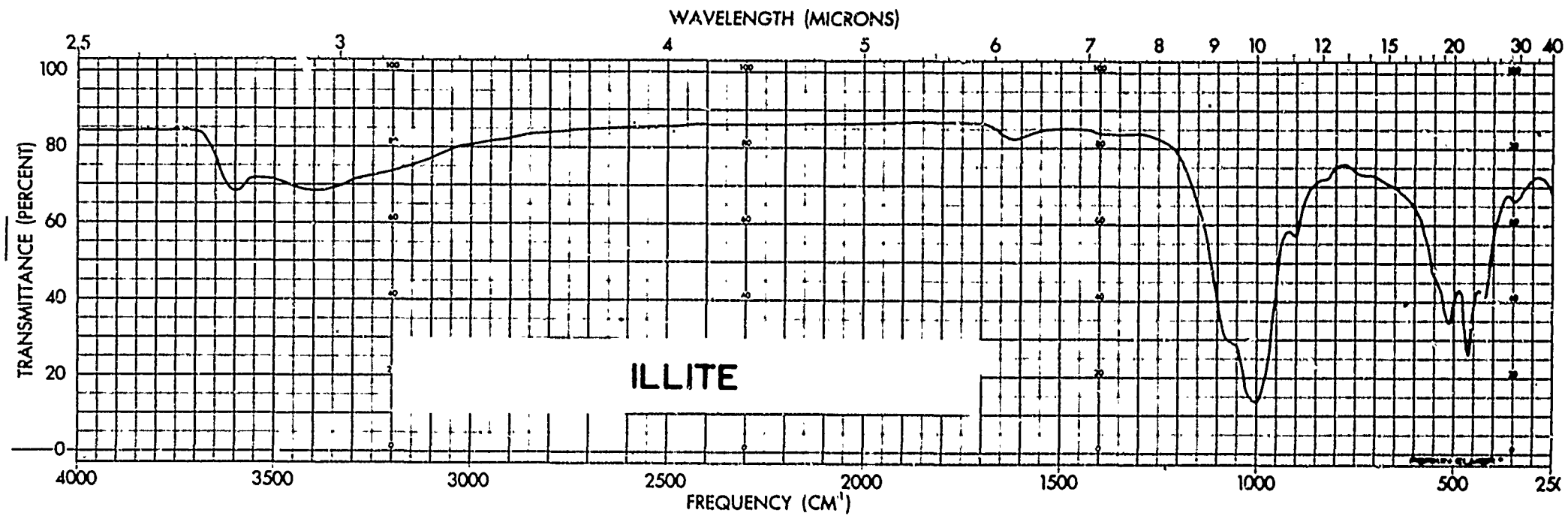
		WN(cm^{-1})	ST	SH
Matrix:	KBr	1448	S	M
		881	M	S
Grinding time:	10 min	853	W	Sh
		729	M	S
Mixing time:	25 min	372	M	M
		317	W	S



		WN(cm^{-1})	ST	SH	WN(cm^{-1})	ST	SH
Matrix:	KBr	3551	M	M	1113	S	S
		3404	M	M	1005	W	M
Grinding time:	10 min	1684	W	M	669	M	S
		1620	M	S	600	M	S
Mixing time:	20 min	1165	W	Sh	456	W	B
		1141	S	M			



		WN(cm^{-1})	ST	SH	WN(cm^{-1})	ST	SH
Matrix:	KBr	3692	M	M	754	M	M
		3619	M	S	694	M	M
Grinding time:	15 min	1624	W	M	536	S	M
		1099	S	M	472	S	M
Mixing time:	45 min	1027	S	M	433	M	M
		910	M	S	345	M	M
		786	W	Sh			

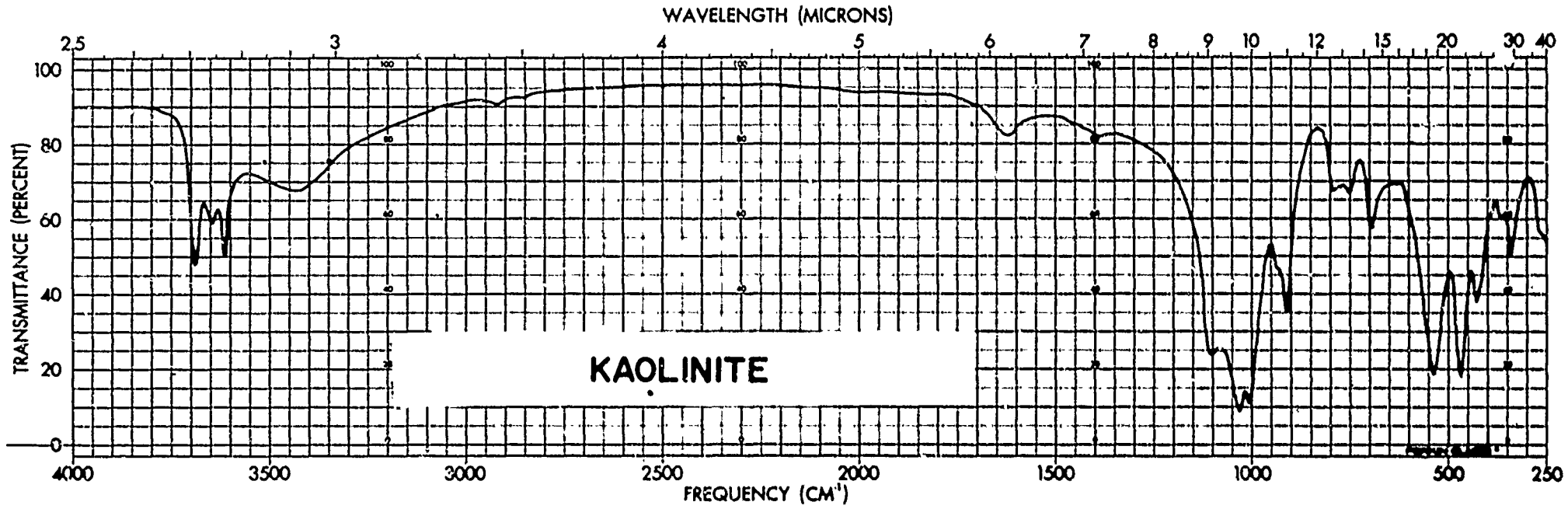


Matrix: KBr

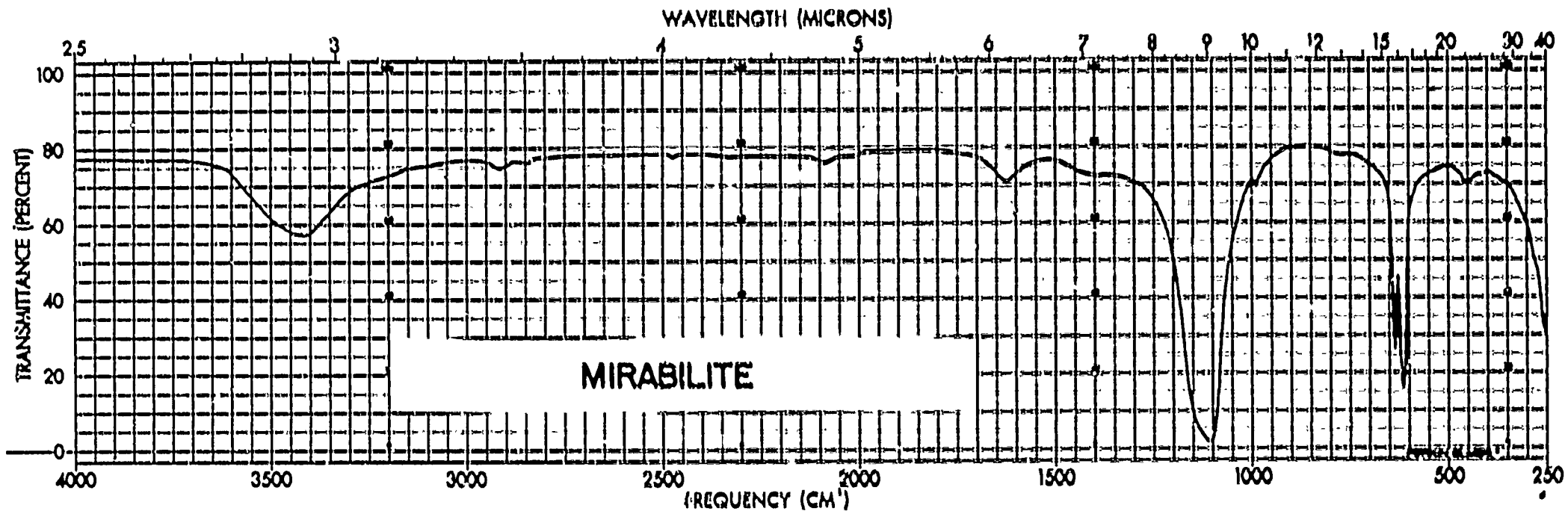
Grinding time: 10 min

Mixing time: 50 min

WN(cm^{-1})	ST	SH
3605	M	M
1072	S	Sh
1009	S	M
910	M	M
518	M	M
470	M	S
429	M	M
350	W	M



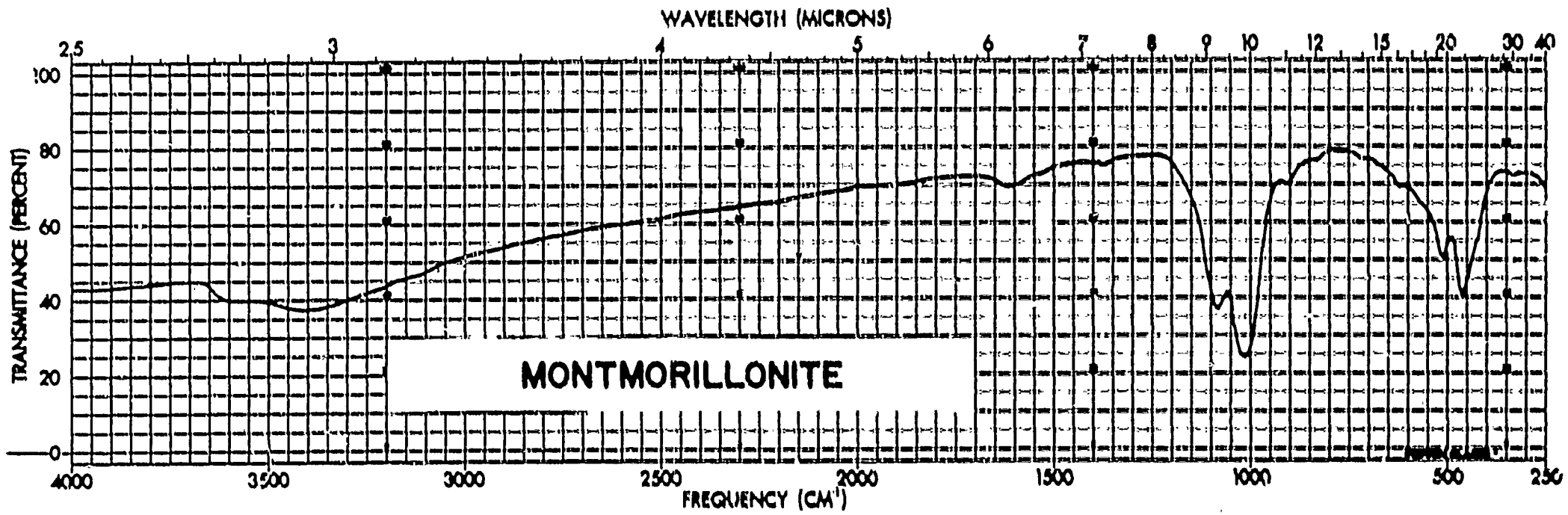
	WN(cm^{-1})	ST	SH	WN(cm^{-1})	ST	SH	WN(cm^{-1})	ST	SH
Matrix: KBr	3695	M	S	936	W	Sh	471	S	S
	3650	M	S	913	M	S	431	M	S
Grinding Time: 10 min	3619	M	S	797	M	M	399	W	Sh
	1105	S	M	754	M	M	369	W	M
Mixing time: 40 min	1032	S	S	695	M	S	346	M	S
	1007	S	S	536	S	S	270	W	Sh



	WN(cm^{-1})	ST	SH
Matrix: KBr	3420	M	B
	1622	W	M
Grinding time: 4 min	1110	S	M
	639	S	S
Mixing time: 20 min	615	S	S

Note: 992 cm^{-1} peak due to a drying effect of KBr

See: Riedmuller, G. F., and T. L. Barber, 1966: "A mineral transition in atmospheric dust transport," Rep. No. ECOM-5072, Atmospheric Sciences Lab., White Sands Missile Range, N. Mex., 9pp.

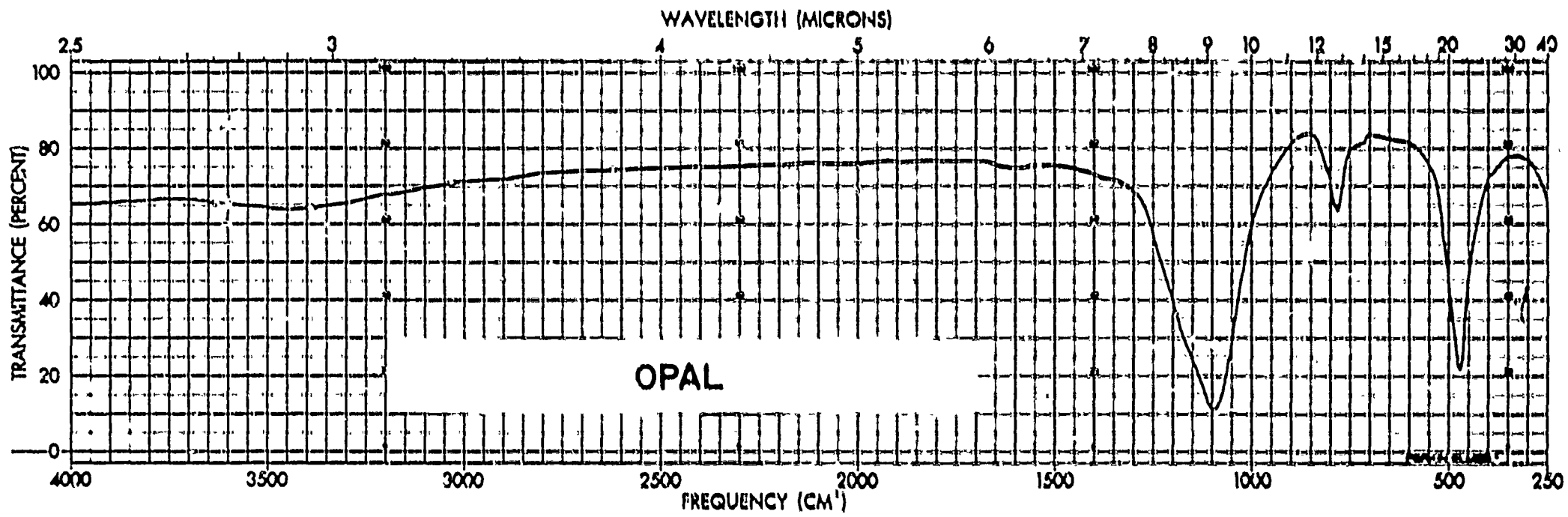


Matrix: KBr

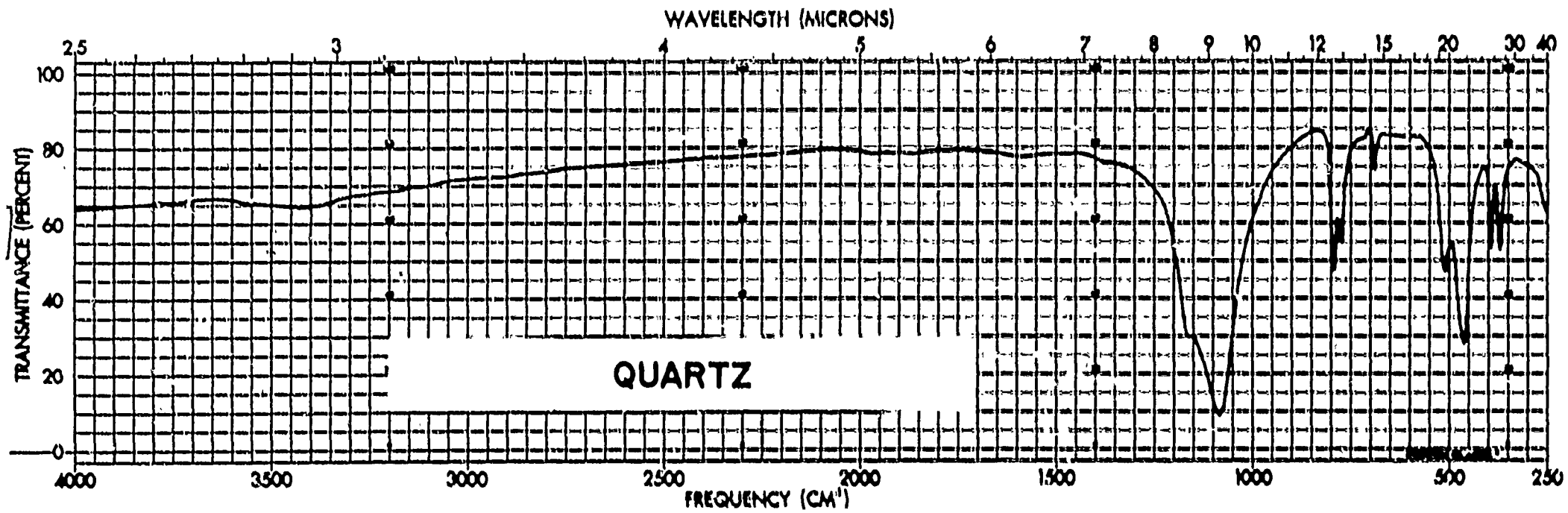
Grinding time: 10 min

Mixing time: 50 min

WN(cm^{-1})	ST	SH
3604	W	B
1090	M	M
1020	S	M
911	W	M
514	M	M
464	M	M



		WN(cm^{-1})	ST	SH
Matrix:	KBr	1104	S	M
		788	M	M
Grinding time:	5 min	477	S	M
Mixing time:	10 min			



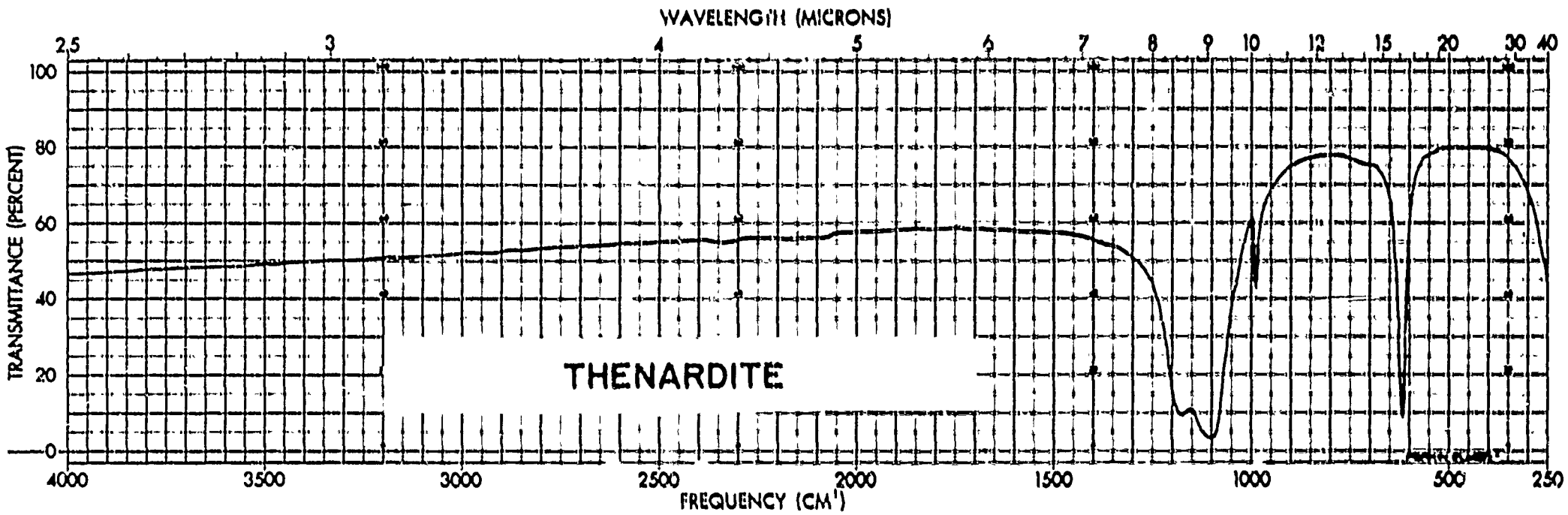
Matrix: KBr

Grinding time: 35 min

Mixing time: 40 min

WN(cm^{-1})	ST	SH
1168	M	M
1088	S	M
798	M	S
780	M	S
695	W	S

WN(cm^{-1})	ST	SH
514	M	M
464	M	M
397	M	S
373	M	S



		WN(cm^{-1})	ST	SH
Matrix:	KBr	1179	S	B
		1107	S	B
Grinding time:	10 min	994	M	S
		620	S	S
Mixing time:	20 min			

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13. ABSTRACT

This report discusses the techniques used in and the results of an investigation of the mineral constituency of the dust component of the atmospheric aerosol over White Sands Missile Range, New Mexico, conducted from November 1964 to August 1965. The eighty-one atmospheric dust samples, taken near the surface during this period, were analyzed by the light microscope technique of dispersion staining and by infrared absorption spectroscopy. Dispersion staining was used to determine the concentrations of quartz, kaolinite, illite, gypsum, and the carbonate family when the particle diameters were greater than four microns. Cases of exceptionally high concentrations of gypsum, quartz, and kaolinite, the month-by-month variation of the composite concentration, the seasonal variation of the gypsum concentration, and the lowest single-sample composite concentration are discussed in relation to the mineral content of area soils and meteorological conditions. Comments are made relative to the possible influence of extraterrestrial and sea-salt particles on the observed concentrations. By extending infrared absorption spectra to 40 microns wavelength, it has been possible to identify the minerals gypsum, mirabilite, quartz, kaolinite, illite, calcite, and dolomite in microgram samples of atmospheric dust, although any particular sample might reveal only a few of these constituents.

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