CONTROL OF THE EFFECTS OF WIND, SAND, AND DUST BY THE CITADEL WALLS, IN CHAN CHAN, PERU

by

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(ABSTRACT)

Chan Chan, the prehistoric capital of the Chimu culture (ca. A.D. 900 to 1450), is located in the Moche Valley close to the Pacific Ocean on the North Coast of Peru. Its sandy desert environment is dominated by the dry onshore turbulent and gusty winds from the south. The nucleus of this large urban community built of adobe is visually and spacially dominated by 10 monumental rectilinear high walled citadels that were thought to be the domain of the rulers. The form and function of these immense citadels has been an enigma for scholars since their discovery by the Spanish ca. 1535. Previous efforts to explain the citadels and the walls have emphasized the social, political, and economic needs of the culture. The use of the citadels to control the effects of the wind, sand, and dust in the valley had not been previously considered.

Through the use of theoretical constructions and wind tunnel experiments, it is established that the form of the classic variant of the citadel was developed from a longtime interaction between the man-built environment and the natural

environment. The Chimu had designed a courtyard system that reduced stress and discomfort from wind, sand, and dust by means of architectural features that included: the rectilinear citadel plan with the long axis parallel to the prevailing winds; the contiguous courtyards with the long axis in common; the high exterior walls; the high interior transverse walls; and the triangular cross section of the walls. It is demonstrated that these features kept out the blowing sand, reduced the wind speeds at pedestrian level, and kept dust, entrained in the airstream by the anthropogenic activity outside the walls, from entering the enclosures. It is also demonstrated that there is a correlation between the degree of protection afforded in a sector of the citadel and the social, political, and economic activites that took place in that sector.

Preface

My original pursuit was an independent study that provided a diachronic overview of the changing urban settlement patterns of the prehistoric Moche and Chimu cultures in the Moche Valley. During the time of my preliminary investigation, I very fortunately met Dr. Michael E. Mosely at the 1984 meeting of the Andean Institute in Berkeley. After I explained my interests to Dr. Moseley, he kindly offered me the use of archival data from 400 surficial site surveys in the Lower Moche Valley made during the 1969 to 1974 Chan Chan-Moche Valley project. With the acquisition of this important information (that had not been previously analyzed) I decided to expand my scope and make this study the subject of my Master's thesis.

As my project progressed I quickly realized that I knew very little about the natural environment in arid zones. My background was in the temperate climates and the wetlands of the Louisiana delta. To better understand the living conditions of the Chimu and Moche and to be able to interpret their movements I began an intensive study of the physical environment in arid zones, particularly the deserts.

In my concomitant study of archaeology in the Valley, the abrupt move of the Moche IV from the urban site of Huaca del Sol to the Moche V administrative site at Galindo near the Valley neck was investigated. The report of a major shift in cultural iconography indicated a catastrophic event

(Bawden, 1983:228) that is speculated to be linked either to enemy (Huari) military expansion, tectonic uplift, unusual flooding rains, or inundation by eolian sand.

The sand theory was especially intriguing. This seemed to me to be the most rational cause for the trauma that showed in the Moche V cultural artifacts as reported by Bawden. My emphasis and objective changed and became centered on the the source and movements of sand and how the Moche and Chimu adapted their settlements and dwellings to the conditions imposed by the effects of these environmental factors.

The shift in emphasis channeled me into the study of the wind, sand, and sun and their effects on the inhabitants of Chan Chan. Special consideration was given to the unique configuration of the 10 monumental citadels whose form and function had never been satisfactorily explained. This eventually evolved into the topic of my University of New Orleans Master's thesis, Wind, Sand, and Sun in an Arid Zone: Selected Aspects of Prehistoric Urban Adaptations in the Moche Valley, North Coast of Peru (1985).

I have since modified my view, I now believe that the wind, sand, and dust were the important natural environmental elements for architectural design in the nucleus of Chan Chan, especially in the design of the major walls of the citadels. Following this modified line of reasoning, using theoretical constructs and a wind tunnel, this dissertation investigates the form and function of the major walls of the citadels of Chan Chan and demonstrates the relationship between the natural environment, the walls, and the activities that took place inside the walls. The research was based on consideration of selected elements of the natural and built environment and the archaeological record--a method never before used to explain these prehistoric monumental structures.

Acknowledgments

My gratitude to co-director of the Chan Chan Moche Valley Project who gave me access to his extensive files, library, photographs, and maps in the United States and Peru; to who shared his data on the physical characteristics of the adobe walls; to for his indepth study of the Rivero citadel; and to the many other scholars whose contributions to the study of archaeology, the physical environment, and the characteristics of airflow around buildings provided the foundation for my research.

I am deeply indebted to members of my doctoral committee who took time from their own endeavors to guide and criticize me during my research and the preparation of this manuscript. I am especially indebted to for stimulating and sustaining my interest in Peruvian archaeology; and to , committee chairman, for his very critical readings and useful comments and suggestions for my research and dissertation and for his valuable guidance throughout my doctoral program.

Finally, my gratitude to my best friend and lifetime companion who has done so much to make so many things possible, my wife .

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Chapter 1

The Enigma of the Walls

> Archaeological research has determined that the prehistoric people in arid zones were among the very first to establish villages and the first to develop cities of different forms. These forms have evolved through the ages, carefully adjusting to the environment and the accompanying climatic stress. Some cities have persisted for thousands of years without interruption. The extant patterns and forms of these communities have served as laboratories and have made valuable contributions to contemporary planning and architectural design (Golany, 1978:20). According to Jacobs, "Cities are an immense laboratory of trial and error, failure and success, in city building and city design" (1961:538).

Introduction

The preserved ruins of the ancient adobe city of Chan Chan located in the arid Moche Valley on the North Coast of Peru served as the field laboratory for this investigation. This urban community, built and inhabited by the Chimu (ca. A.D. 900-1450)(see Figure 1), had a population estimated to be as high as 50,000 (Moseley & Mackey, 1973:328)(1) and was reported to be the largest prehistoric adobe city in South America (1973:318). The nucleus of the city is visually and spatially dominated by 10 rectilinear citadels (known in Spanish as ciudadelas) that had similar architectural features that were used repeatedly for more than 400 years (2). Since their discovery by the Spanish conquerors, the form and function of the citadels and of the unusual high adobe walls that bound the exteriors and divide the interiors of the citadels have been enigmas that have intrigued scholars. The central concern of this dissertation is to address this enigma and to investigate and explain the Chimu rationale for designing and building the major citadel walls.

Hypothesis and Objectives

Previous investigators have advanced theories concerning the citadels and the walls that are universally based on the social, political, and economic needs of the Chimu culture. There has never been a systematic investigation of a causal relationship between the effects of the natural environment and the design and construction of the citadels. This study makes such an investigation and offers an explanation for the high walls and the spatial configuration of the citadels that is founded on the hypothesis that the citadels were designed and constructed to alleviate human distress and discomfort caused by the wind, sand, and dust in the natural environment of the Moche Valley.

The hypothesis is evaluated and tested by the use of theoretical constructs, archaeological records, field observations, and empirical wind tunnel experiments that are combined as complementary resources to attain the following objectives:

1) To demonstrate that wind, sand, and dust can cause human stress and discomfort.

2) To demonstrate that wind, sand, and dust were present in the Moche Valley and of a magnitude that could cause human stress and discomfort.

3) To demonstrate that the Chimu and their Moche predecessors were aware of the wind, sand, and dust and had experience in alleviating the human stresses and discomfort from these elements.

4) To demonstrate that the citadel walls designed and constructed by the Chimu alleviated human stress and discomfort by:

a. Keeping out blowing sand.

b. Reducing relative wind speeds inside the courtyards.

c. Diverting the airstream containing entrained dust and keeping it out of the courtyards.

5) To demonstrate that there is a correlation between the Chimu activities in the citadels and the human stress and discomfort alleviated by the major walls.

Limitations

The scope of the investigation is limited to the study of: 1) the major exterior and interior citadel walls; 2) the effects of the wind, sand, and dust; and 3) the type and distribution of human activities inside the walls. The study of individual buildings inside or outside the citadels is not included.

Wind tunnel experiments are limited to determining relative wind speeds inside the citadels and to visualizations of airflow patterns that simulate air entrained dust in, over, and around the citadels.

Sources of Information

Information was gathered from: contemporary archaeological reports of the North Coast of Peru; scientific data that accentuated wind, sand, and dust movements in any arid zones, but in particular that of the North Coast; studies of airflow patterns around buildings; and studies of construction methods, materials, and architectural designs in hot dry climates. Michael E. Moseley, Co-Director of the Chan Chan-Moche Valley Project, gave access to the project archives stored in Chicago at the Field Museum of Natural History and in the Trujillo office of Alfredo Navarrez. The photographic archives of Abraham Guillen at the Instituto Nacional de Cultura in Lima were examined for views of the area and for details of Moche and Chimu ceramics for the purpose of identifying environmental adaptive features in the architecture. The collections at the Museo Nacional de Antrpologia y Arqueologia and the Museo Amano in Lima were searched to identify Moche and Chimu cultural artifacts. Exhibits in the University of Trujillo Museo and in the private collection of Jose Cassinelli-Mazei were studied for additional information that could influence the investigation.

In the Moche Valley the sites of Huanchaco, Galindo, Huacas del Sol and la Luna, Chan Chan, Huaca Dragon, Huaca Esmeralda and Salaverry were visited (a huaca is a monumental shrine). Sand patterns and wind movements were observed at these locations and on the coast between Trujillo and Casma. Sand patterns were also observed near Casma at Manchan, Sechin, and the then new excavations by Carol Mackey at Cahuacucho. At each location wind direction, wind speed, and time of day were observed and recorded by use of compass, watch, a short length of yarn, and a Dwyer windmeter (3).

Literature Search

The earliest Peruvian written accounts concerning the Moche Valley go back as far as Pedro Cieza de Leon, a Spanish soldier and writer who chronicled his observations of the ancient sites in 1553 (Lanning, 1967:19). To most early writers the treasure from the graves, not the archaeology or history of Chan Chan was of prime interest. The Spanish settlers made an industry of excavating for gold and silver burial goods. This lucrative practice, encouraged by the government of Spain, continued throughout the colonial period (A.D.1532-1821) and overshadowed other activities. The first attempts at studying and mapping the area were commissioned by Compañon in the 18th century and provided plans of Chan Chan and the Rivero citadel (Kosok, 1965:80). In the 1800's, descriptive accounts with a broader scope were written by the travelers and explorers Humboldt (1814), Tschudi (1847), Rivero and Tschudi (1851), Hutchinson (1873), Squier (1877), Bastian (1878), Weiner (1880), Bandelier (1893), Middendorf (1895), and Seler (1895).

Systematic archaeology began with Uhle (1903) at the turn of the century. Others that followed were Hrdlicka (1912), Kroeber (1926, 1930), Holstein (1927), Johnson (1930), Olson (1930), Larco Herrera (1931), Ubbelhode-Doering (1939, 1959), Horkheimer (1941), Schaedel (1951a, 1951b), and Kosok (1965).

The early Andean culture studies developed under the influence of the Kroeber's "superorganic" concept (Moseley, 1983:430). This concept presumed that climate in the most recent geological epoch was static and, therefore, any changes that were made in the lifestyles or environment had to come from culture.

Major advances in archaeology were made in 1946 when the Institute for Andean Research began an intensive project in the Viru Valley on the North Coast, just south of the Moche Valley. Involved were Wendell Bennet, William Duncan Strong, Julian H. Steward, Gordon R. Willey, Junius Bird, Clifford Evans Jr., James A Ford and Donald Collier. The project produced several publications, but the most important for this study was Willey's Prehistoric Settlement Patterns in the Viru Valley (1953). This work changed the course of archaeology in Peru. Instead of merely studying ceramic chronologies, archaeologists investigated the total culture within its environment. It was a more holistic approach that has since influenced subsequent research (Lanning, 1967:21).

The later Chan Chan-Moche Project, 1969-1974, under the co-directorship of Moseley and Mackey, produced more major advances that have been influential in the study of the Moche Valley. The project goal was an analysis of the architecture and patterns of environmental exploitation for the purpose of reconstructing the development of social, economic, and political organization on the North Coast of Peru (Day, 1982:xiii). As a result of this effort, Moseley and Mackey, with the help of their students and co-workers, produced Twenty-Four Architectural Plans of Chan Chan, Peru (1974). Several monographs, based on investigations in the Valley, added to the literature. They included: Sheila Pzorski's Prehistoric Subsistence Patterns and Site Economics in the Moche Valley, Peru (1976); Thomas Pzorski's Survey and Excavation of Burial Platforms at Chan Chan, Peru (1971); John Topic's The Lower Class at Chan Chan: A Quantitative Approach (1977); Theresa Topic's Excavations at Moche (1977); Day's Architecture of Ciudadela Rivero (1973); Klymyshyn's Intermediate Architecture in Chan Chan, Peru (1976); Keatinge's Chimu Ceramics from the Moche Valley, Peru (1973); Kolata's Chan Chan: The Form of the City in Time (1978); Conrad's Burial Platforms and Related Structures on the North

Coast of Peru: Some Social and Political Implications (1974); and Andrews' A Preliminary Study of U-shaped Structures at Chan Chan and Vicinity, Peru (1972). Later the Proyecto Riego Antigua 1976-1977, involving some of these same investigators, expanded the scope of the Chan Chan project and examined the irrigation systems of the Moche Valley. The highlights of the results of several of these studies are comprehensively summarized in Chan Chan: Andean Desert City (Moseley & Day, 1982).

The Chan Chan-Moche Valley projects were interdisciplinary. The physical sciences had a greater role and contributed additional detail that enhanced the interpretation of the site, artifacts, and cultures. Subsequent investigations have continually become more complex, encompassing disciplines not previously included under archaeology, but now considered essential for a total holistic view. An investigative team might now include experts in geology, climatology, geography, remote sensing, botany, biology, physical anthropology, agronomy, and hydrology, in addition to archaeology.

Previous Investigators and the Emergence of the Enigma

The spacious citadels and the high walls at Chan Chan have been the subject of speculation and investigation for several of the scholars listed in the literature search. There are unresolved questions that still need answers.

Hardoy (1973:367) spoke for many of these scholars when he asked:

> Why were the walls built? Why was the city organized into separate wards, or citadels, and why did these apparently have no useable entrances? Did these complexes contain groups which, for political, social or economic reasons were obliged or wished to remain isolated from each other?

To answer these questions, Hardoy (1973:367-68) surveyed and summarized the theories and opinions of earlier researchers:

> In 1877 Squier wrote that the population was separated for municipal and social reasons, although he himself admitted that there must have been other simpler ways of achieving such isolation besides creating a number of fortresses (Squier, 1877). Horkheimer also supported the theory that the walls were built to control the free movement of the population. Bennett, on the other hand, believed that the citadels may have represented subdivisions of Chimu society, perhaps clans (Bennett, 1946). Mason leaned toward the second hypothesis, adding that each citadel may have been the domain of a sub-chief (Mason, 1957). This is the same opinion that Harth Terre expressed to me when he suggested that a citadel was the precinct of a chieftain and his closest servitors. It has also been proposed that the citadels served as centers for groups of specialized artisans (Miro Quesada, 1957: Horkheimer, 1944) or as market centers acting as redistribution centers or as centers of manufacture (West, 1970). . . . The importance of storage space, the number of walk-in-wells, the careful street pattern and the quality of architecture are indicative that the citadels were the residential quarters of Chan Chan's elite groups (Day, 1973).

West (1970:74) offered another group of summarized answers:

> Most investigators have agreed that each ciudadela was inhabited by a distinct social unit (Middendorf 1894:375; Squier 1877:159-60; Mason 1957:97). Horkheimer (1944:61) postulates that each ciudadela was inhabited by a craft guild or group which lived and worked there. Adolph Bandalier (in Radin, 1942:248) expressed the opinion that not even three-quarters of the area was occupied by buildings; the rest was garden plots. . . . It has even been suggested that Chan Chan was a fort built by peoples surrounded by enemies -- a refuge for Chimus in time of war, perhaps occupied by garrisons of soldiers who lived in the small rooms in the ciudadelas (Kimmich, 1917:453). . . . Schaedel (1951:232) has classified Chan Chan as an "elite" community.

In the late 1700's a Spanish cleric, Bishop Martinez de Compañon suggested that the citadels had been palaces for the rulers (Moseley & Mackey, 1973:332). More recently, Mackey reasoned that each ruler constructed a citadel to be his seat of government during his life and his mausoleum after death. The towering walls were built to provide seclusion and to separate his domain from the rest of the community, not for defense. This scenario fits closely but not perfectly the ethnohistory of the Chimu that lists nine monarchs. The old legendary king-list records ten independent monarchs before the Inca conquest of Chan Chan. The first one was thought to be mythical, leaving nine (4). There were nine burial platforms, one in each of nine citadels: . . . "a clinching argument for this theory" (Moseley & Mackey, 1973:344).

The most intensive and thorough investigation of the citadels and their form and function was reported by Day in his unpublished dissertation Architecture of Ciudadela Rivero, Chan Chan, Peru (1973). Day's study was primarily based on an analysis of the organization of artifacts inside the major citadel walls. His interpretation of the data stressed the social, economic, and political factors that influenced the architecture and spatial arrangement. Day recognized the citadels as "part of a complex system of human organization related to environmental exploitation [the production of agricultural products], access to products, and labor management" (1973:94). Day felt that "the high walls and patterns of controlled access were probably security measures to protect the material wealth of those who occupied them" (1973:97).

Recent efforts to explain the form and function of the citadels of Chan Chan have been universally founded on the same social, political, and economic aspects of Chimu society. But, none of the scholars has explored the relationship between the citadels' man-built configuration and the natural environment in the Moche Valley (5). For a more holistic approach to the study of the citadels, the influence of the natural environment must also be included, it cannot be thought of as being completely separate from the social, political, and economical environment. There is an important interaction between the natural forces in the

Valley and a community's efforts to control these forces that is reflected in the architectural design.

Vernacular (6) architectural activity originates as a protection against environmental forces. With time, there is a merger of the built environment and the natural environment and as a result of this combination a different environment emerges. In a feedback loop, architectural activity in turn tries to cope with this newly established environment. This reciprocal interaction will continue until there is a relatively stable architectural model adapted to the locale. Architectural stability established through such an interchange preserves a valid appearance for a long time and the artifacts are able to survive the manifold changes in social, political, and economic relations of a culture (Turan, 1983:144). This investigation of the extant citadels at Chan Chan, built over a period of more than 400 years, reveals an architectural stability established through such an interaction.

Complementary Questions that Complete the Picture

The investigation into the dynamic interchange between architecture and the natural environment adds another dimension to the study of Chan Chan that complements the contributions of previous researchers. The inclusion of the effects of technology and physical environment on the form and function of the citadels broadens the scope of the efforts to solve the enigma of the walls. To include this additional dimension, more questions about the citadels should be posed. We should also ask:

Why were the major exterior walls consistenly built to an average of 10 m (meters)? What was the function of the major transverse walls that divided the citadels into three sections? Why were the interiors of the six citadels built in the last part of the construction sequence divided into three parts? Why was the major axis of the citadel always oriented approximately north-south (7)? Why was the entrance to the citadel usually in the same north side location? What influence did the major walls have on the activities inside the enclosure? What were the environmental factors that caused human stresses for the Chimu? Which of these stresses were perceived to be of sufficient importance to require a modification to the habitat?

These questions, reflected in the stated objectives, guide this investigation of the relationship between the architecture of the Chimu and selected aspects of the physical environment in the Moche Valley. The results of the investigation provide insights into the architecture and settlement patterns in all arid zones, but in particular those of Chan Chan and the North Coast desert of Peru.

Endnotes

1. Population estimates for Chan Chan have varied considerably, but have consistently remained high. West estimates between 58,000 and 100,000 (1970:84); Bandelier 40,000 (1942:248); Holstein 200,000 (1927:36); and Collier around 50,000 (1961:106).

2. Each of the citadels has been given a name. In alphabetical order they are: Bandelier, Chayhuac, Gran Chimu, Laberinto, Rivero, Squier, Tello, Tschudi, Uhle, and Velarde. The position of each these citadels in the construction sequence will be discussed in chapter 4.

3. In the literature there is some confusion in the use of the terms wind speed and wind velocity, some authors occasionally use them interchangeably. In this study the wind speed will indicate the magnitude of the speed of the wind, and wind velocity will indicate both the magnitude and direction.

4. The history of the rulers begins with the mythical culture hero, Taycanamo. On his death he was succeeded by his son Guacri-caur who conquered the lower part of the Moche Valley and theoretically had the first burial platform. He in turn was succeeded by his son Nancen-pinco who conquered the upper part of the valley and the coast between Zaña and Santa. There were seven other nameless rulers and finally the great Minchan-caman who completed the expansion by

extending the borders from Tumbes in the north to Carabayllo in the south (Lumbreras, 1979:182). Minchan-caman was conquered by the Incas and is therefore not commemorated with a burial platform.

5. The physical environment has several dimensions that can be divided into the natural environment and the built environment. The natural environment refers to: 1) places and geographical features such as mountains, valleys, deserts, swamps, and oceans; 2) environmental conditions such as temperature, climate, wind, and rain; and 3) the flora and fauna of a locale. The built environment refers to the results of people's alterations of environments, such as buildings, monuments, cities, and farms. In some cases the definition of the built environment is extended to include alterations of natural environmental conditions, such as air, water, and land pollution (Altman & Chemers, 1984:4).

6. Rapoport (in Markus and Morris, 1980:11) distinguishes between key terms as follows: He defines "primitive" as buildings or dwellings built in societies with little specialization, where there is no technical vocabulary and where most structures are based on a model that has persisted for a long time. He defines "vernacular" as a pre-industrial technique where anonymous specialized tradesmen or craftsmen continually adjust a common type or style model according to the needs of the user. "Monumental" is defined as structures with a specialized function, usually

the domain of churches, tombs, palaces or public buildings that are the work of a professional individual or team of designers.

7. The orientation of the longtitudinal axis of the citadels was generally north-south with the actual orientation of each citadel varying slightly from the mean direction. This variation could have been due to the necessity to line up with the prevailing wind in the immediate area of each citadel. The citadel Bandelier deviated the most from the mean, but still maintained the same general direction.

It has been suggested that the similarity in orientation might have been due to "astronomical sightings" along the citadel's main axis. Archaeological investigations of "sightings" have usually been founded on a precise alignment that permits viewing of a planet or star through an opening in a religious building. Since the citadels are secular buildings, with only one opening in north wall that is used as an entrance, and an axis alignment that is not percise, it is difficult to give credence to any such suggestion.

Chapter 2

Human Stress and Discomfort

Human reactions to perceived stress and discomfort due to the effects of elements of the natural environment often shape the form and character of the man-built environment. This chapter discusses the interaction between the natural and man-built environments and establishes the wind, sand, and dust as stress and discomfort causing phenomena.

The Physical Environment and Human Comfort

According to Fitch in American Building: The Environmental Forces That Shape it, ". . . the ultimate task of architecture is to act in favor of man: to interpose itself between man and the natural environment in which he finds himself, in such a way as to remove the gross environmental load from his shoulders" (1975:1). Fitch continued with, "The building--and by extension, the city--has the task of lightening the stress of life; of sheilding man from the raw environmental stresses; of permitting homo fabricans to focus his energies on productive work" (1975:16).

As an adjunct to Fitch's statements, Triggers' principle of hierarchial resolution of conflicting tendencies claims that in cases where the selection of a settlement pattern requires a compromise among opposing considerations, the resulting configuration will reflect the relative importance of the factors involved (1968:72). According to this principle, given a choice of reaction to any one of several stresses in the natural environment, the human response to lighten the climatic stress will most often be to react or interact with the greatest urgency to those factors that are perceived to be the most life threatening or to cause the most discomfort.

Saini, in his Building in Hot Dry Climates adds an another important element when he discusses environmental considerations in designing dwellings and maintains that:

> Apart from the problems of physiological comfort generated by adverse climate, by far the most significant irritant in arid lands is air pollution by dust and sand. There is little scientific evidence to suggest that the presence of dust and sand particles in the atmosphere is a hazard to human health but they do possess a considerable nuisance value which is most obvious to the people who live in these regions. Apart from the dust storms which periodically limit visibility, particle-polluted air causes discomfort and irritation to the eyes, nose and throat, and it also has a demoralizing effect on people (1980:30). . . .

With Saini's information, the first of the stated objectives is attained. It is established that wind, sand and dust caused human stress and discomfort and that some alleviation was required to improve living conditions. Using the previously stated Triggers' principle, if the wind, sand, and dust of are of a magnitude that was percieved to be relatively important by the Chimu, a response to the effect of these elements of the natural environment could be reflected in the built environment. This investigation strives to demonstrate that the Chimu's response to perceived stress and discomfort from wind, sand, and dust is disclosed in the design and construction of the walled citadels at Chan Chan.

Alleviation of Human Stress and Discomfort

Many societies have alleviated climatic stress and discomfort in their particular locale by building shelters to act in favor of man. In the arid, windy desert of the Sahara the Bedouin nomad designed a tent built of hides, while in the cold, windy climate of the Arctic the Eskimo, with different materials but with the same logic, developed the igloo built of ice. The interaction between an individual's subjective perception of stress and the physical environment takes many avenues. Adaptations or accommodations can be accomplished in various ways: by minor or major structural modifications to the habitat; by the acclimatization of the human body to the environment; or even by the movement to a more hospitable location. When the environment is perceived to be merely disagreeable, a minor modification or change in habitat readily serves to improve the degree of comfort. In this type of adaptation economic status is often a factor, with the rich and powerful having the resources and mobility that enables them to locate their dwellings on the more agreeable sites. At the other end of the spectrum, combinations of adaptive adjustments have even made it possible to survive in the harshest enviroments without a feeling of overwhelming discomfort, i.e. the Australian Bushman, the Bedouin, and the Eskimo.

The human reaction to prevailing natural environmental conditions is highly subjective and often dependent on the individuals or societies perception of comfort and discomfort. People have different individual priorities and, therefore, often have dissimilar criteria. Comfort criteria can depend on a multitude of variables, such as: the forces that act on the human body, i.e. physical, thermal, sonic; the activity of the individual; the climate and the season; meteorological conditions, i.e. temperature, percipitation, sunlight, and humidity; and the physical and psychological state of the individual (Gandemer, 1978:6).

The criteria for comfort or discomfort are multifaceted and contain physiological and psychological factors that are complex, subjective, and difficult to measure (1). Contemporary research on human comfort is mostly concerned with conditions in offices and dwellings that have all the conveniences of modern living. The studies have been based on subjective opinions obtained from participants exposed to controlled environments that simulate modern conditions. As a result, the parameters used to construct the psychrometric charts and to define comfort zones are extremely out of context with the environmental conditions on the North Coast of Peru. The Moche and Chimu existed in conditions that were "off the charts." Different indicators to determine comfort and stress were required for this investigation.

In this study, an indicator for comfort in a windy environment is established through the use of a Beaufort Scale that has been modified by Jackson (1978:257). This Scale relates the physical manifestations or affects of the wind on an open terrain landscape to the sensations felt by an individual at that location. A comparison between the manifestations and the sensations felt at different wind speeds gives an indication of the relative improvement or degredation of the individual's comfort. This procedure will be more fully discussed later.

Alleviation of Human Stress and Discomfort in Ancient History

Parry's article Climate and Town Planning (1979) reveals a long history for the interaction between the man-built environment and the natural environment. According to Parry, archaeological evidence suggests that the ancient Egyptians were the first to use "zoning" in their town planning and that they were well aware of the advantages of site orientations that utilized beneficial winds. In the fifteenth century B.C., Tell el Amarna on the east bank of the Nile took advantage of the dominant cool summer winds that blew from the north and north-west. The quarters of the upper class were situated in the desirable northern end of town. The workers quarters were located in the south and west of town where they got little benefit from the cool summer winds and bore the brunt of the hot and dusty desert winds when they blew from the west or south. The northerly location and orientation for the quarters of the upper class elite also seems to be a recurrent feature of site planning in the ancient Middle East that applied to Babylon, Bagdad, and Assur, the early capital of Assyria (1979:203).

Greek and Roman planners were also aware of the advantages of site orientations that garnered beneficial effects from the climate. In his medical geography Hippocrates recommended an easterly aspect as the healthiest orientation, while Aristotle said that a city that fronts the east and receives easterly winds is the most healthful. The Roman Vitruvius' De Architectura, dating from B.C. 30-27, is deeply influenced by climatic awareness (Parry, 1979:203). Vitruvius' principles of site choice and town layout contained suggestions on how to avoid the funnelling of prevailing winds, how to avoid the south winds and heat, and how to prevent excessive humidity. He devoted a whole chapter to climate as a determinant of the style of the house. Vitruvius' writings are said to have layed dormant during the Middle Ages. However, his principles were subsequently revived in Alberti's Ten Books on Architecture in 1485 and proceeded to serve as a major influence on the architects, builders, and town planners of the Rennaisance (Markus & Morris, 1980:5). The 16th century Royal building codes, used by the Spanish conquerors to found new cities, mandated a street orientation that took advantage of prevailing winds (Crouch et al., 1982:9). In what could have been a direct line from Vitruvius, the Spanish colonial city of Trujillo, built close to the ruins of Chan Chan, was oriented according to the mandates of this Royal code.

The ancient Chimu, like the early Egyptians, Greeks, and Romans, made decisions for their built environment that were influenced by the natural environment. The culmination of their efforts to alleviate climatic stress and discomfort is found in the final form of the extant ruins at Chan Chan.

Endnotes

1. The technical aspects of designing for human comfort may be found in American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc. (1985). Handbook of Fundamentals. New York.; Givoni, B. (1976). Man, Climate, and Architecture. London: Applied Science.; and Olgay V. (1963). Design With Climate. Princeton: Princeton Press.

Chapter 3

The Environmental Setting of Chan Chan

> Wind, sand, and dust have been established as stress and discomfort causing elements of the natural environment. The following investigation of the environment at Chan Chan argues that the extent and magnitude of these elements at the site were more than enough to have been perceived as stress and discomfort causing.

The Natural Environment in the Moche Valley

The Moche Valley lies on the west coast of South America at approximately 8 degrees south latitude and 79 degrees west longtitude, about 550 km (kilometers) north of Lima, in what is described as the North Coast of Peru (see Figure 2). The coast extends inland from the ocean in a gently sloping plain and is bounded by the Cordillera Negra mountain range of the Andes. The range intersects the ocean immediately south of the Moche River and then recedes inland to the north and forms the wedged shaped northern pampas. North of the river the land slopes evenly from north to south, while the land on the south bank slopes sharply east to west. The south side is delimited by geological outcroppings and the high southern bank. The Moche River, following a geological fault, descends rapidly down the steep western slope of the Cordillera Negra from 3980 m to sea level in a mere 102 km (Moseley et al., 1983:301). When it rains, the sparsely vegetated river basin erodes with mass wasting, supplying alluvium with the rock, gravel, and sand that forms the

Valley floor.

The lower Moche Valley is usually without rain and the terrain is either rocky or sandy desert with little vegetation. The average annual rainfall is 1.6 mm (millimeters) (ONERN, 1973:44). When irrigated, or when ground water or river water are accessible, the desert becomes desirable fertile farm land.

A high pressure air mass off the coast in the Pacific supplies winds rotating counterclockwise. This circulation pattern generates the south to north coastal winds and the maritime onshore prevailing winds. The wind speeds vary between 0 and 24 km/hr during the day, but achieve maximum velocity from the south between one and four in the afternoon. The winds reverse direction in the evening bringing cooler air which, in combination with the loss of insolation after sunset, condenses the moisture in the air. This leaves a heavy surface dew that dampens the desert terrain and forms a sparsely vegetated zone on the mountain sides. The humidity in the Valley is normally high, close to 85% with an average 62% cloud cover (ONERN, 1973:51-52) (see Figure 3).

The onshore wind is affected by the longshore Humboldt cold current that flows up the coast northward from the Antarctic. The winds approaching the coast from the ocean are moisture laden. When these winds pass over the cold Humboldt current, the moisture condenses and falls to the ocean as rain. Later, when this dried air passes over the warm land it heats, increases its capacity to hold moisture, and as a result evaporates the moisture from the surroundings. The Humboldt current also dominates the coastal food chain that supports the large Peruvian fishing industry. The cold current and high pressure air mass combine to create a temperature inversion which keeps the usually present cloud system very stable and prevents rain (Johnson, 1976:167). The net result is a windy and turbulent desert environment, lacking rain, where the air and soil moisture, heated by the sun, rise to form a layer of clouds that carry the water from the coastal plains to the mountains. During the rainy season the clouds in the mountains condense and feed the steep sloped river system. The river flow peaks during February and March and then drops off rapidly. The water table on the coast, fed through this river runoff, springs, and irrigation systems, peaks between June and September (ONERN, 1973).

Since the latter part of the Cenozic geological era the river course on the coastal plain has continued to move slowly southward toward the village of Moche. Its lateral movement is controlled by the erosive cutting of the river flow in the alluvium and the limiting geological rock formations adjacent to the rivers south side (Cerro Orejas at the valley neck, Cerro Arena at midvalley, and Cerro Blanco near the valley mouth). Cerro Cabras, 10 km north of the river, is the only prominent protudence on the north side (Moseley & Deeds, 1982:31).

There is geological evidence that the coast, the coastal plains, the river, and the mountains have been changing in physical configuration. The Nazca oceanic plate and the South American continental plate converge close to the Peruvian continental margin with an average rate of 10 cm (centimeters) per year.. The induced tectonic movement results in an apparent uplift of the mountains and coastal plains. There are attendant affects on the river, the water table, and landforms along the ocean coastline (Moseley et al., 1983:301). Early sunkens gardens (also called mahamaes or wachaques), 4.5 km inland, originally close to the water table, now lie 10 to 12 m above the water (Moseley et al., 1983:310)(1). Earthquakes, such as the disastrous 1970 event, have also changed the terrain.

World wide glacial melting (ca. B.C. 13,000) raised the level of the oceans an estimated 85 to 135 m. When it stabilized (ca. B.C. 8,000), it had submerged more than 75 m of Moche Valley coastline (see Figure 4). The sea rose faster than the land and raised the onshore water table. Later, tectonic uplift became the controlling factor and the land rose faster than the sea, effectively lowering the onshore water table. The change from a rising sea level to a rising land level is geomorphologically evident in the sea cliff that follows the coast inland of the littoral zone (Moseley et al., 1983:307).

The El Niño, an intense tropical rain storm, periodically impacts on the Peruvian coast with castastrophic results. Normally the climate is dry tropical, controlled by the Humboldt current. A world wide weather change driven by solar energy at times shifts the ocean current and warm ocean temperatures, significantly upsetting the normally stable inversion that keeps the coast arid. The weather becomes unstable and changes radically to a wet tropical regime with torrential rains that can last for months. Major catastrophic El Niños occurred prehistorically in A.D. 400 (Moche), A.D. 1100 (Chimu) and in recorded history in 1925 and 1983 (Feldman, 1983:16-18).

As a result of these El Niños the following consequences occur, with different levels of intensity: the marine food chain breaks and the usually plentiful fish species vanish; the sparsely vegetated river valley floods and erodes with heavy damage to the plains, homes, cities, fields, roads, drainage and irrigation systems, and coastlines; the river course carries heavy boulders, gravel, and sand; when the land has risen, due to tectonic uplift, the channel erodes deeper into the plain; the river discharges its sediments into the ocean changing the landforms at the mouth and coastline; irrigation canal intakes are disrupted and canals fill with sediments; adobe bricks used for building melt. Sometimes this is followed by locust and disease (Rowe & Menzel, 1948:53). As an aftermath to El Niño, a weather aberration might persist for two or three years. The change in weather pattern often causes a drought which brings a loss of crops.

This description of the Moche Valley supplies a synopsis of the natural processes and forces that influenced the Chimu and Moche people and their built environment in the large scale meso and macroenvironment. As a further background for the establishment of the interaction between the natural evironment and the built environment, the processes and forces affecting wind, sand, and dust in the more limited meso and microenvironments of the lower Moche Valley will be examined (see Figure 8)(2). A more detailed description of the mechanisms of the processes and forces that affect wind, sand, dust, and solar radiation can be found in Appendix B.

Wind Velocities in the Valley

Sand will move only when there is wind of sufficient speed (3.5-4 m/s [meters/second] or 12-14 km/hr) and duration to transport the sand particles from an adequate source. The manner in which sand moves and deposits depends upon the velocity and flow characteristics of the airstream, the parameters of the sand source, and the obstacles to the sand movement. To demonstrate that wind and sand in the Valley could have caused human stress and discomfort, it needs to be established that the valley winds, at the sites under consideration, have the high speeds required to transport sand. Several informational sources have been used and the data synthesized to make the determination.

According to Johnson (1976:187), the coast of Peru is dominated by the south to southeast winds for the entire year. At Lima, at 7 a.m., 62% of all observed surface winds are from the south. Farther north, at Puerto Chicama (70 km north of Trujillo), the 7 a.m. readings show the wind from the southeast for 37% of the time period, south-southeast 43%, and south 15%. The afternoon winds are similar but with an increase in those from south-southwest. Average wind speeds are 7.4-14.8 km/hr around Lima but become stronger reaching an average of 24 km/hr at Chimbote (110 km south of Trujillo) and 18.5 km/hr in many other locations. The winds throughout the year are particularly strong at dusk. There is also a tendency for the wind speed to be higher in the latter half of the year.

A description of the method of observation is not given with the above data and the actual hourly wind speeds and their duration and direction cannot be accurately determined. The given velocities are the averages from several years of measurements that smooth out the high and low values and mask much of the sand moving potential at each location. The data does however, give an indication of the meso and macroclimate of the entire coast.

Another set of values were taken over a period of 21 years at a location near Trujillo at Huanchaco, approximately 5 km from Chan Chan (ONERN, 1973:44) (see Figure 3). These data show a mean monthly wind from the south at 19.5 km/hr for 249 days of the year and from the southeast at 20 km/hr for 15 days. The wind speed from the south ranges from 0 to 24 km/hr. Once again a description of the method of observation is not given. But, the data does give an indication of the mesoclimate for the region observed from a closeby weather station. This same information indicates that the wind is fairly consistent in direction and speed 68% of the time. These data also show that the wind speed is sometimes greater than the 3.5-4 m/s (12-14 km/hr) required to move sand. Generally these figures give a reasonable estimation for the region, but, as will be shown later, in the smaller more limited microclimate they do not necessarily apply.

The wind speeds and their directions vary considerably, often influenced in two ways by the topography of the terrain in the region. First, narrow valleys have hot upslope winds in the daytime and cooler downslope winds at night, usually with greater velocities than those of the surrounding territory. Secondly, there is a channeling of the regional wind into certain directions by the contours and protrudences of the terrain (Johnson, 1976:185). This second effect was demonstrated by Finkel (1958) and Lettau and Lettau (1978) when they tracked the paths of barchan sand dunes in the Atacama desert of southern Peru. They determined that the dunes and the sand moving winds followed the direction of the contours of the terrain, not the direction of the prevailing regional wind. These same topographical influences occur in the Moche Valley and maps and aerial photos were helpful in identifying them.

The airfields shown on Figure 5 indicate a south-southwest to north-northeast runway at Huanchaco on the coast and an east-west runway closer to the mountains at Laredo (near Galindo). Since runways are always built parallel to the dominant wind at the locality, the dominant wind at Huanchaco is from the south-southwest and from the west at Laredo. The main plaza in Trujillo is oriented to take advantage of a south wind in accordance with colonial city planning ordinances mandated by Spain (Crouch et al., 1982:9). This plaza and the runways give evidence of major differences in prevailing wind directions in the valley.

Personal observations at these sites at 10 a.m. on different days gave the same as the above wind directions with a 3-5 km/hr wind speed. At the top of the southernmost wall of the Velarde citadel at Chan Chan, a south wind with gusts of 16-32 km/hr was observed at 1:30 p.m. From the top of Huaca Esmeralda a southeast wind of 3-5 km/hr was observed at 11:00 a.m.. At this same location the tree tops adjacent to the site were bent to the northwest, indication of a consistent strong and dominant southeast wind. Numerous whirling "dust devils" were observed in the recently plowed agricultural fields.

The winds south of the Moche River move in a more complex manner. The path of the airstream was tracked using aerial photos 1-17 produced by the Peruvian Servicio Aerofotografico Nacional (SAN) in 1942. The barchan dunes, the transverse dunes, the sand sheets, and the vegetation patterns indicate that south of Salaverry the wind moves from the south and southeast across the plain along the side of Cerro Salaverry to Cerro Chico; north at Cerro Chico and then northeast up the valley along the mountains in an eliptical path. North of Salaverry the wind is influenced by the land projecting into the sea and flows in a more northerly direction coming from the south. Part of the airstream travels between Cerro Chico and Cerro Blanco, but the major component flows between Cerro Blanco and Huaca del Sol. Here it turns to follow the same elliptical path noted above. The pattern suggests that the massive Huaca del Sol influences the airstream at a critical junction (see Figure 6).

It is evident that there are winds in the Valley that have the velocities necessary to move wind and dust. The pattern of sand movement and the source of the sand also need to be determined.

<u>Eolian Sand Movement in the Valley</u>

In the mountains, the wind flows up the sides, valleys, *quebradas* (dry gulches), and occasionally over the mountain top, with major turbulence along its path. Aerial photos and topographic maps indicate that most lower mountain slopes on both sides of the river and along the plains have deep extensive eolian sand sheets. At Galindo the mountain slopes are clear of sand.

Investigation of aerial photographs establishes that the wind on the north side of the river carried sand from the coast in a northward direction. When the wind came under the influence of the mountains, the airstream split and flowed along the contours of the terrain with increased turbulence. Part went up the mountain slopes and *quebradas*, some eastward and some westward toward the valley neck. By the time the westward wind reached Galindo it had already deposited its sand load, leaving the mountain slopes clear.

On the south side of the Moche River there was a similar scenario with the wind depositing sand sheets along its elliptical path. Massive sand deposition stopped at Cerro Oreja just across the River from Galindo in the valley neck. High velocity winds continued to move up the mountains and valley, but they did not have a large volume of sand to transport.

When sand-laden wind encounters the mountains, the turbulence from the surface drag and direction change results in sand deposits that blanket the slopes and fill the low areas. This dry sand accumulates on the slopes until its properties of creep and flow respond to the pull of gravity, then the build up cascades downward to a lower level. In a continuing dynamic interaction, the eolian landforms change and in turn changes the airstream flow patterns. The magnitude of the change is highly dependent upon the quantity of sand available from the source.

The Source of the Sand

Evidence that the Moche Valley floor is built up of alluvium is easily verified at the village of Huanchaco. The vertical faces of the high bluffs show multi-layered strata of a mixed material with a wide range of aggregate size, including a significant component of sand. These materials came down the mountain slopes suspended in the torrential rains of the latter part of the Cenezoic era. They spread out in a fan shape, filling the depressions and forming the large plains between the mountains and the sea. Each major torrential rain deposited another layer. Later as a result of wave action when the sea level rose, the beaches were submerged, the gentle underwater sloping shelf formed, and the bluffs were shaped.

The same hydraulic process occurred at every major river valley along the Peruvian coast, supplying a source for eolian sand that was continually moved northward by the littoral currents. In this manner, sand was transported along the coast many kilometers from the original area of deposition.

The river systems continued to bring sediment to the ocean in an annual cycle. The quantity of load depended on the geological structure, slope, vegetation and rainfall in the upper basin. During a rainy El Niño the intense erosion in the river valley, quebradas, and plains supplied enormous amounts of a range of different size sediments.

Sand deposited in the ocean was brought to shore by the continuing wave action. This wave energy winnowed and sifted the aggregates and brought the smaller particles to the beach. Here the sand particles were exposed to the drying and transporting action of the high velocity onshore winds.

Aerial photos (SAN, 1942:No. 17) of the beach adjacent to Port Salaverry vividly illustrate an onshore sand source. A sand sheet, located downwind from the Huaca del Sol, started at the water's edge and extended inland. At the ocean's edge the flat sand sheet was wet and difficult to move. As it progressed inland it dried and became more susceptible to wind action. Initially, sand ripples formed, eventually the wind from the ocean transformed the ripples into the dry transverse dunes that provided a ready source for eolian transport to the north.

In the same photos, examination of the wave pattern at the Port Salaverry harbor indicated that wind and current were strongly influenced by the prominent land projection that extended into the sea. This projection along with the man-made breakwater determined the sand deposition pattern on the beach. Whenever the coastal sand pattern changed, the pattern of deposition on inland areas also changed.

More recent improvements to the Port have provided additional examples of the effects of shoreline alterations (see Figure 7). In the late 1960s, the Peruvian government extended the breakwater, dredged the harbor, and built groins (also called moles) to protect the beaches lining the harbor from erosion. Personal observation found a shoreline different from that of the 1942 photos. The onshore location of the sand sheet had shifted, the beaches at the groins had filled with sand, and nearby beaches had eroded from sand starvation. Three kilometers up the coast, the seaside resort at Las Delicias has severe beach erosion, stretching inland, that has destroyed coastal buildings and roads. Archaeologists working inland at Huaca la Luna reported a recent shift in sand movement and deposition patterns that occured after the Port improvements were completed. In the new pattern, sand is deposited on the northern corner of the Huaca and cleared on the southern (M. Cornejo, [archaeologist at the University of Trujillo] personal communication, 1984). These dynamic shifts reveal the geomorphological effects of a change in the location of the source of a sand supply.

Earthquakes recur in the area as they have for centuries. The 1970 quake, reported to be the most disastrous in historic times, was centered in the offshore Peruvian trench close to Chimbote. The quake destroyed major portions of Chimbote and Casma and about 20% of Trujillo. Landslides and major shifts in the soil occured where the water table was close to the surface. Shortly after a quake, seismic tidal waves are a potential danger to the coast (Ericksen, 1970:21-23). The tidal wave associated with the 1960 Chilean earthquake produced the highest waves yet recorded at Chimbote. Earthquakes and their aftermath can be contributing factors for changes in shoreline configuration and sand deposits.

Significant amounts of sand for eolian transport can be exposed to the wind by tectonic uplift which raises the beaches locally or regionally along the coast. A lowering of the level of the ocean can also uncover expansive beach areas, with rich sand deposits.

It has been shown that the Moche Valley had the necessary conditions for the large scale eolian transport of sand and dust, more than enough to cause human discomfort and stress. The archaeological record demonstrates that the Moche and Chimu inhabitants of the Valley reacted to the perceived stress and discomfort from these elements and developed the methods to cope and adapt.

Endnotes

1. The sunken garden watertable farming technique has been used in the vicinity of many prehistoric sites along the dry Peruvian coast. These gardens are pits excavated to a depth where moisture from the water table is accessible through capillary action. The process makes cultivation and the production of crops possible in an arid environment. The use of sunken gardens is confined to areas where a high water table occurs naturally or is caused by the accumulation of excess water at the lower end of an irrigation system. It is used where water is near, but does not quite reach the surface (Kautz & Keatinge, 1977:87).

2. The definition of the terms micro, meso, and macroenvironment depends on the discipline under discussion. See Figure 8 for a graphic representation of the definition and scale of these terms as used in climatology. Notice that the term "local" is defined as being between the micro and meso climates on the scale.

Chapter 4

The Moche and Chimu in the Moche Valley

> The existing archaeological data develops a long and continuous record of prehistoric cultures that adapted to the wind, sand, and dust of the Moche Valley. An examination of the record of the Moche and Chimu cultures and their man-built environment provides a scenario that illuminates the events and processes that led to the design of the classic form of the citadel.

The Moche Culture in the Valley

The Moche were the immediate predecessors to the Chimu. Most chronologies of the North Coast assign a period of approximately A.D. 200 to 700 to the Moche cultural phase (Donnan, 1973:1). Based on stylistic changes in the characteristics of the ceramics (Larco Hoyle, 1948), this interval has been divided into the five subphases shown in Figure 9. In a further classification, Phases I-IV have been designated as being in the Early Intermediate Period and Phase V as being in the Middle Horizon.

The Moche state has been identified as a military expansion polity that was confined to the Moche Valley in subphases I and II, but later expanded to cover nine valleys from Motupe to Nepeña, a distance of about 350 km. Most of the expansion took place during the later subphases III and IV, and it was during this period between approximately A.D. 330-700 that most of the large Moche centers were established (Conrad, 1978:283; Donnan, 1973:125,131).

As part of this expansion, the Moche located the capital of their kingdom adjacent to the Huaca del Sol on the south side of the Moche River. In this Early Intermediate Period, the Moche developed a thriving community with extensive irrigation canals and cultivated fields on both sides of the river. Between Moche IV and V there was a catastrophic event that appeared in a marked change in the designs of their ceramics. The archaeological record shows that the kingdom contracted and that there was a sudden move of the capital farther north to Pampa Grande in the Lambayeque Valley. Concurrent with this move, an administrative center was located nearby at Galindo on the north side of the neck of the Moche Valley. Shortly thereafter the state collapsed (Moseley & Deeds, 1982:39).

The sudden move of the Moche IV from the Huaca del Sol to Galindo (Moche Valley) and Pampa Grande (Lambayeque Valley) has been of special interest to investigators. In Bawden's words:

> . . . the abandonment of the earlier Moche state capital surrounding the Huacas del Sol and de la Luna, the creation of a huge new center at Pampa Grande much farther north, the loss of the valleys south of Moche, and the appearance of certain architectural innovation at the settlement of Galindo indicate significant changes at the commencement of the Middle Horizon . . . . Thus, the entire thematic concept manifested by the realistic "portrait heads" of Moche IV art appears to have been rejected, together with various motifs that dominate earlier art . . . . Emerging from this massive occupational retreat is an entirely new settlement pattern, one that

> must reflect a different system of social and political integration. Moche V sites are located in the neck of the river plains, away from coastal access and in a very unfavorable location for exerting multivalley political authority. . . . Obviously the Moche polity at the end of the Moche IV phase was in such a state of disruption that a complete reorganization of administrative structure and settlement configuration was required . . . . It is a common cultural phenomenon that change is most manifest in areas under greatest stress. Such modification as a response to danger is commonly seen in archaeological and historic studies of ancient states (Bawden, 1983:228-231).

Following the same "state of disruption" line of reasoning and offering the possible cause for the disruption, Moseley stated:

> Driven inland by strong unidirectional winds, longtitudinal dunes arose behind the emergent littoral zone and overrode and buried the shoreline Phase IV (Moche) settlement. South of the river, dune formation created a sand sea that swamped the reconstructed urban center surrounding Huaca del Sol, as well as its sustaining irrigation system, triggering abandonment of the site and resettlement on land surfaces that first stabilized in the Middle Horizon or beginning about A.D. 500 (Moseley, 1983:431).
>
> . . . behind the bank are yardangs or butte-like erosional remenants of sandy loam, which stand several meters high and contain Early Chimu sherds. Early and Middle Chimu occupational debris are found on the deflated (eroded) surfaces between the yardangs. This end of deposition and the onset of erosion can be dated to within the Early Chimu phase (Moseley et al., 1983:307).

According to this scenario, then the effects of sand movement had to have caused human stress and discomfort and had to have been of major concern to the people of the Moche Valley.

The Moche IV and V Settlements

The archaeological record reveals that the site between the Huaca del Sol and Huaca la Luna was first inhabited in Gallinazo times, ca. B.C. 200. Excavations indicate continuous habitation and growth that reached its maximum during Moche IV subphase. Two adobe brick Huacas dominate the landscape. Huaca la Luna, the smaller structure, is built on the steep lower slopes of Cerro Blanco and rises 30 m above the plain. Across a 500 m wide area stands the massive Huaca del Sol. The remnant of this structure stands 40 m high and its base at the major axis is 380 m long, oriented parallel to the direction of the dominant wind. The Moche capital was located on the plain between the massive Huacas (Topic, 1982:263) (see Figure 10).

The Huaca del Sol stands at the edge of cultivated fields, now only 600 m from the river. In earlier times, the river bed was much farther east and the fields in front of the Huaca were more extensive. There were trees along the river and along the coast around the river mouth that supported a large animal population: among them were jaguars, foxes, and boa constrictors. The river mouth area, influenced by the high water table and the vegetation, was humid (C. Campana, [archaeologist at the University of

Trujillo], personal communication, 1984). The trees existed until the early 1900s when they were cut down and used for railroad ties (M. Cornejo, [archaeologist at the University of Trujillo], personal communication, 1984). Campana reported an excavation at the edge of this area where sand-embedded tree trunks, arranged in three staggered rows, indicated that growing trees were used as a windbreak to protect cultivated fields (personal communication, 1984). This is a technique still used along the Peruvian North Coast, as well as in other arid regions.

The south side of the Moche Valley had extensive cultivated fields supplied with water from the river and a well developed irrigation system. The Moche had all the requisites that enabled them to build a viable urban community. But, this was not destined to last. The archaeological record indicates that there was a radical change in environment during Moche IV (Bawden, 1983:228-231). As a result of this change, there was a move by the Moche IV away from the coast to the inland necks of the valleys.

Investigators in the early 1900s found flat open plains between the Huacas, with no evidence of buildings. The Moche urban site had been completely covered by sand. Long sections of the irrigation canals throughout the valley were sand filled and cultivated fields were sand blanketed. Most existing small surficial sites on the plains of the valley floor contained only late Moche and Chimu artifacts (Moseley, personal communication, 1984). Earlier sites were sand covered. Interestingly, Moche legend in current circulation tells of a city still buried under the sand on the slopes of Cerro Cabras (Mackey, personal communication, 1984).

As previously suggested, sudden and out of the ordinary stress from the disruptive wind and sand were encountered. The cause of this occurence is, at present, uncertain. The most straightforward explanation is widespread tectonic beach uplift with immense new sand deposits available for wind transport. Any changes in the coastline configuration, wind characterics, or local coastal currents could have resulted in new sand sources all along the coast that had far ranging inland environmental affects.

The El Niño of ca. A.D. 400 also might have been an influence, but it is doubtful that it was causal. Investigation did not show any record of disruptive amounts of sand after the 1925 or 1983 events and, on the basis of this evidence, it is difficult to conclude differently for the A.D. 400 event. It is possible that a sustained drought in the aftermath of the El Niño could have caused loss of vegetation and loss of sand stabilization permitting unusual sand movement.

It is speculated that the stresses during this catastrophic period were different from those previously experienced. The sand came in greater quantities than the Moche IV knew how to handle with their existing methods. It came from new directions and deposited in a different manner. It covered their fields and water sources. It covered the mountain sides and cascaded downward to cover their buildings. The usual windbreaks of vegetation and other protective devices and techniques could not effectively stem the tide. And it all happened over a relatively short time.

One might also assume that the traditional religious beliefs and customs did not help. Confusion reigned in this new situation and, finally in helpless desperation and as a last resort, Moche IV were forced to move to evade the steadily oncoming sand flow that was innundating much of their kingdom. This was not a local event, sand moved in on them all along the coast. The site could not be adapted, a major move became necessary. The Moche fled from the blanketing sands to the only clear areas in the regions, places that were secure, had some open fields for cultivation, and had water. They fled to the necks of the river valleys. The archaeological record shows a move of the capital to Pampa Grande in a northern river valley and the establishment of an administrative center, at nearby Galindo (see Figure 11). Here the Moche V subphase began.

The disruptive wind and sand continued for an uncertain period covering the plains and sites between the mountains and the coast. Eventually the sand source was depleted, sand movement lessened, and the plains stabilized once again. Irrigation systems on the plains closer to the mountains were cleaned of sand and extended. Excess water from irrigation and cultivation high on the valley plains filtered to the coast. Additional water from the river, surface springs, and irrigation raised the water table and productive farming again became possible in the lower valley. When the fields on the lower plains were no longer threatened, the Moche V settlers moved out of their confined, somewhat inhospitable, rocky mountain site, and started once again to cultivate and settle the open Moche Valley closer to the coast.

As the communities grew and people, vegetation, and animals consumed more water, the flow in the irrigation system diminished and the water table dropped. Farmers dug deeper to find water, eventually forming immense sunken gardens as much as 10 m below the surface of the terrain. Some sunken gardens were so large that they contained a platform in the interior that was probably an administrative center (Moseley, 1978: 31).

The material excavated (sometimes called "spoil") to form these sunken fields was often piled around the top perimeter forming a high wall that kept out the wind and blowing sand, thereby protecting the young and tender plants growing in the bottom of the gardens from wind damage. The turbulent, high velocity drying wind was blunted and water losses from evaporation and evapotranspiration reduced. The effects of the environment were controlled and as a result crop production was increased, water conserved, and the microclimate ameliorated.

The highly successful technique of sunken garden farming is still practiced in the Valley. On the ocean side of the bluffs below Chan Chan, lush melon patches were personally observed growing in damp protected sandy plots dug into the terrain. Farther inland, at the existing Tschudi sunken garden, still in use, the water observed in a modern well was said to vary with the water table as much as 10 m. During my 1984 research in Chan Chan, the water table was unusually high because of the major El Niño in 1983. In other parts of the valley, springs that had been dry for many years were flowing again (A. Suysuy, [archaeologist at University of Trujillo], personal communication, 1984). The water table level reflected a constant change in supply and demand.

At the beach at Huanchaco, totora reeds, used for boat and home construction, were observed growing in sunken gardens. The excavated material was mounded to protect the plants from the ocean winds. On top of the mound there was a reed fence designed to give the plants additional protection. Here was evidence that wind and sand are ever present environmental stresses and that the Moche Valley heritage of prehistoric control methods still supplies useable solutions.

The Chimu Culture in the Valley

During the Middle Horizon there was an unexplained transition of cultures in the Valley, Moche activity diminished and and the Early Chimu culture developed on the north side of the Valley. With time, the terrain and water resources in the lower Valley had stabalized and farming, that depended on a high water table, became possible. The Chimu kingdom flourished and in the Late Intermediate Period, (A.D. 1000-1476), the Middle and Late Chimu built their captial city of Chan Chan, at the edge of their vast cultivated fields (Keatinge, 1975:216).

The fortunes of the Chimu in the Valley depended heavily on the water supply. The Early Chimu improved the supply by cleaning the abandoned sand filled Moche built canals and revitalizing and expanding some of the existing Moche irrigation systems. Later, the Intermediate and Late Chimu constructed a more extensive and elaborate system of new canals. As agriculture prospered, the city grew, and population increased. Due to erosion and deepening of the river bottom, the canal inlets that diverted water from the River became inoperative; the bottom of the inlet canal was eventually higher than the water in the river. The Chimu changed and modified the location of the canal inlets to compensate for this and to overcome the threat to their water supply. But, this practice reached a limit when the minimum drainage slope necessary to allow flow in the canals on the Valley floor could no longer be attained. In desperation, the Chimu began the construction of the La Cumbre canal that would bring water 80 km from the Chicama River in the adjacent Valley (Moseley & Deeds, 1982:32). The project was never completed. As the water supply continued to diminish the Chimu were forced to gradually spatially contract their agricultural system.

During the Chimu hegemony, Chan Chan was the controlling storage and distribution center for the Valley and the majority of the population resided within its perimeter. The citadels were the domain of the rulers and the location of the center of power. Only three small rural administrative centers adjacent to cultivated fields and habitations have thus far been located (Keatinge, 1975:216). The Moche Valley was under Inca domination when the Spanish conquerors arrived in A.D. 1532, the Chimu having been subjugated ca. A.D. 1470. The urban nucleus of Chan Chan was virtually abandoned and no longer functioned as a viable community. The deposed Chimu rulers, elite, and the best artisans had been scattered throughout the Inca empire (1). With the rulers gone, the interiors of the deserted Chan Chan citadels were occupied by the remaining lower class workers. The open spaces in the expansive courtyards became small farms and the empty buildings were used for shelter and storage. The once impressive power structure of the Chimu had been destroyed and their capital city was inhabitated by "squatters" (Day, 1982:xiv). The Spanish conquistadors saw a deserted Chan Chan dominated by the monumental high walled enclosed citadels that were the culmination of the longtime interaction between the natural environment and the Chimu designers and builders.

The builders of the primitive, vernacular, and monumental structures in the Valley had developed architecture and settlement patterns that met the needs of their society. The Chan Chan found by the Spanish was the result of a process of trial and error and success and failure in a continuum of efforts to develop the most useful and effective designs for the built environment. The inhabitants of Chan Chan had utilized the available resources in the Valley to address their perceived requirements.

The Chimu at Chan Chan

The prehistoric city of Chan Chan was built adjacent to the vast cultivated agricultural fields that sustained the large Chimu population. As stated earlier, at its greatest extent Chan Chan is estimated to have encompassed a total area of 24.5 sq km (see Figure 12). The nucleus of this extensive urban settlement covered about 6 sq km. The buildings in the densely settled central area have been classified by the Chan Chan-Moche Valley project researchers as lower class, intermediate, and monumental (Day, 1982:61-2). The lower class building types extended out from the western and southern perimeter of the central area. The lower class sections were crowded, containing randomly spaced small dwellings with common walls that had no formal architecture. The intermediate types (sometimes called elite) were concentrated in the central section of the urban area and often were closely associated with the monumental architecture. The intermediate structures were more formal in plan than the lower class types, and similar, but less complex than the citadels. The most complex architectural planning was exhibited by the 10 monumental citadels with exterior adobe brick walls measuring from 200 to 650 m on a side and rising to heights of an estimated 9 to 11 m (see Figures 13 and 14). Keatinge and Day (1974:229) considered them to be the residences of a powerful elite because of their impressive size and internal complexity.

Three of the citadels are located close to the bluff near the sea and the others extend inland in two rows. Most of the monumental construction was laid out along an axis of roughly N 12 degrees E. This orientation gave a semblance of organization that indicates the Chimu practiced site planning (Moseley, 1975:224)(2). Extensive man-made sunken gardens, cemeteries, and pits dug to obtain raw materials needed for the manufacture of adobe, were located on the less desirable windy south side of the settlement, close to the bluffs and sandy beaches.

In general, the citadels are rectangular with the long axis oriented approximately north-south, parallel to the prevailing wind in the area. This is the same orientation as the main runway at the nearby Huanchaco airport. The architecture and internal arrangement of these units is similar, but no two are identical. The classic variant of the citadel (as defined by Topic & Moseley, 1983:154) is a large enclosure with high walls built as a unit. It has a single entrance in the north wall, farthest from the sea coast, and the interior courtyard is divided into northern, central, and southern sectors by high transverse walls. Often there is an annex or wing on the side of the citadel. The southern sector (sometimes called the conchone) usually has few buildings and considerable open space, the other sectors have little open space and contain repetitive groups of structures with a formal arranged in a grid like pattern. Each sector has an entrance from the adjacent sector through a large courtyard with sets of benches along three of the walls. A ramp leads up to a raised area of smaller courts which contain one or two U-shaped structures (also called audiencias) that were up to 6.5 by 10.3 m in size (Klymyshyn, 1976:8). There were often burials under the ramp and the U-shaped structures. Interlaced aisles or passages connect these courts to contiguous groups of storerooms arranged in rows. A dominating feature of the classic form of citadel was the ruler's burial platform located in its own court in either the central (most often) or southern sector. The classic citadel was the final stage in the developmental sequence. The earlier units had many of the same components but especially lacked the three part division of the enclosure. The enclosures were also distinguished by the plan of the burial platform and the type of U-shaped structures used (Topic & Moseley, 1983:154).

The northern sector of the classic citadel contained a narrow elaborate entrance, colonnades, corridors, a kitchen usually with a large walk-in well, courtyards lined with storerooms, and U-shaped structures that served as administrative centers for the elite and also controlled the entrance to the adjacent storerooms. The central sector was very similar except that it had fewer U-shaped structures, more storerooms, and usually contained a massive burial platform: the arrangement suggests that the central sector was the royal sanctuary. The southern sector was usually free of standing structures, often had a walk-in well, and showed evidence of extensive domestic and animal activities (Keatinge & Day, 1973:230) (see Figures 15 and 16).

The citadels were built sequentially and the order in which they were built was indicated by a seriation of the adobe bricks used in construction (Kolata, 1982:78-82)(2). In the first phase of construction, the original nucleus of the city was formed by a Chayhauc-Uhle axis in the southeast corner of the site. Chayhauc was the first citadel built and had the simplest organization, with no internal high walls. Following this, the oldest part of Uhle was built in two stages, an eastern and western section. Later, large annexes were built to the north and west. Uhle showed an increasing complexity in the internal organization. The city grew to the west with the construction of Tello and Laberinto. Laberinto was the first citadel to be partitioned into three sectors that incorporated more complex organization. From that time forward, all citadels conformed to this tripartite design. It became the "classic" form.

The second major phase of construction included the erection of the largest citadel, Gran Chimu, and an expansion of smaller structures to the north and west. The third phase was the most extensive and involved a filling in of the space in the south-central section of Chan Chan. The attempt to fit new construction into this limited area suggests that land for building was at a premium. There were several instances where older structures were torn down to make room for the new in-fill, a precursor to a type of urban renewal practiced in modern cities to this day. Following in the construction sequence were Velarde, Bandelier, Tschudi, and Rivero. The final units became smaller and more rigid in conforming to the previously adopted complex internal organization (see Figure 17). Rivero, the last citadel to be completed, had an additional set of unique high interior tapia (rammed earth) walls built parallel to the exterior walls. The purpose for the double walls, separated by 4 m, is uncertain and presents another enigma for investigators.

Kolata had difficulty in deciding where to place Squier in his chronology but felt most secure in placing it after the Gran Chimu. Moseley places Squier as the final citadel. He suggests that it was under construction in the period when Chan Chan was under Inca domination, but it was never completed (1975:224).

<u>Moseley's Sequence</u>

1. Chayhuac
2. Uhle
3. Tello
4. Laberinto
5. Gran Chimu
6. Velarde
7. Bandelier
8. Tschudi
9. Rivero
10. Squier

The construction sequence provides another important ingredient for this investigation. The chronology supplies physical evidence that indicates the evolutionary progression in the interaction between the built and natural environment.

The citadels ranged in area from 87,900 sq m (square meters) for Rivero to 221,000 sq m for Gran Chimu. The average area for the other citadels was approximately 140,000 sq m (Day, 1982:55). Rivero (without the wing or annex) was approximately 185 m by 375 m and Gran Chimu was approximately

365 m by 605 m. The walls averaged between 9 and 11 m in height and were approximately 3 m wide at the base and 50 cm wide at the top (Kolata, personal communication, 1988). They were built of either adobe or tapia and sloped with a batter of about 7 degrees from the vertical. The base of the walls was built on a layer of small boulders partially buried in the earth. On this base adobe sections, assembled in about 2 m squares with materials from local pits, were layed up in well defined courses whose horizontal and vertical joints were filled with mortar (Day, 1982:55-56). The exterior high walls were adobe brick, the inner transverse high walls were usually of tapia and approximately 2 m less in height than the exterior walls (Kolata, personal communication, 1988).

The majority of the walls of the lower class, the intermediate class, and the buildings inside of the citadels were built of adobe brick and seldom were over 2 to 3 m high. Sometimes the surface of the adobe would be covered with a mud plaster made from the same ingredients as used for the brick. These shorter walls, less than 1 m thick, would often have the same type stone foundation as the major citadel walls but would be built straight up without a batter. Roofs and minor elements were often a combination of reeds and adobe mortar with some wood supports. The lower class buildings were constructed with common walls in an unorganized random manner (in much the same fashion as modern day third world squatter communities) and had more reed components.

According to Schaedel, former director of the Department of Archaeology at the University of Trujillo, no two storied adobe buildings were found in the Moche Valley (personal communication, 1984). The limited structural strength of adobe in compression and shear made it difficult to build to great heights without a broad base for a foundation: too broad to be practical for other than massive religious structures, i.e. Huaca del Sol and Huaca la Luna. The same load bearing limitations hold wherever adobe is used. Mission churches in the Southwest section of the United States had adobe walls with a maximum height of approximately 10.7 m (35 ft) and often relied on buttresses to brace exterior walls (National Park Service, 1978:2). The structural strength of the adobe was probably the factor that limited the maximum height of the major walls of the citadels to approximately 9 to 11 m.

Rectangular low walled buildings were part of the architectural heritage of the early Chimu (3). Aerial photos show two Moche ruins on the slopes of Galindo with the same shape but of different size. Although these ruins were separated by approximately 500 m, they had almost the same orientation of the longtitudinal axis that implied a west northwest wind. The orientation and rectangular shape were, therefore, known design features. The extremely high exterior walls of the Chimu and the internal high walled transverse partitions appear to be new elements. The height, tripartite division, shape, and orientation of the citadel walls developed early and remained fairly consistent throughout the history of Chan Chan. This suggests that these were successful design features worth retaining and repeating.

Other previous adaptative features are recognizable in the Moche pottery designs. The shapes and iconography showing habitations gave good examples of the use of flat and slanted roofs to alleviate the effects of wind and sun in the dwelling and patio. The slanted roof deflected the wind upward and caused a low pressure area that drew the hot air up and out of the dwelling in the day time. At night this same design allowed the cooler calmer night wind from the opposite direction to enter. Slots in the roof and openings at the sides helped promote the cooling circulation. In addition, archaeological investigation reveals structures of similar design with patios oriented to provide protection from high velocity winds (Campagna, 1982). Some dwellings even had two patios to allow for the seasonal change in wind direction (Suysuy, personal communication, 1984).

Other examples include the remains of Moche roofless windbreaks, with stone foundations and three sides of reeds, that are found in many areas of the valley (Moseley & Mackey, 1973:323). The same type of windbreak, constructed in the same manner, was observed at a contemporary site close to

Galindo. In the natural environment, the calm area in the crescent of the large barchan sand dunes also provided an effective windbreak for the desert traveler. Perhaps, the three sided U-shaped audencias, where the Moche and Chimu authorities held court and audiences, originated as a windbreak. Through cultural and environmental adaptations these structures could have evolved to the elaborate U-shaped form found in the citadels and major administrative buildings. Many adaptations for wind control were known by the Chimu. The task for the settlers at Chan Chan was to apply these known adaptations to alleviate the perceived stresses and discomfort of the local environment.

The Chimu Response to the Environment

The archaeological record indicates there was a settlement at the Chan Chan site before the first citadel was built. As the settlement grew, the Chimu gained experience and they eventually utilized this experience in building their city. The first citadel, Chayhuac, was built in part from spoils excavated from sunken gardens adjacent to the site (Moseley & Deeds, 1982:35).

Prior to the walled structures the sand had been stabilized with vegetation and large scale sand movement was not a severe problem. Even in a sand storm with high wind speeds, sand is too heavy to travel higher than two meters above the surface (see Appendix B). However, it is speculated that as the population grew, the continued heavy traffic of people and animals, through mechanical action, pulverized the sand on the desert floor and created the finer dust particles. Squier (1877:127) wrote of riding through the streets outside of Trujillo "fetlock-deep in dust" (estimated 10 to 15 cm). Moseley and Mackey (1973:318) found sand and dust everywhere inside the ruins when they began their mapping project. Dust, when undisturbed, lies layered on the ground and is moved only with high velocity winds. Disturbed dust, on the otherhand, is susceptible to movement by turbulent winds of lower velocities. As activity increased, the dust problem magnified. Bagnold's classic book, The Physics of Blown Sand and Desert Dunes (1941), describes a powdery surface on the Anatolian Plateau which laid undistrubed by relatively strong winds. He noticed great clouds of dust that were kicked up from this dormant surface by passing flocks of sheep (Greeley & Iversen, 1985:253). Bagnold's theories on sand and dust were developed from his observations of eolian phenomena in the desert.

The intensity and turbulence of local winds exacerbated the dust problem. In the morning the winds from the coast were mild and fairly steady. The sand was slightly damp from dew that had formed on the surface during the early morning cooler temperatures. Neither sand nor dust moved readily under these conditions. But, by the afternoon the surface of the terrain was heated by the sun and the sand dried. Thermal currents from differential heating of the terrain caused increased turbulence and gusts. The afternoon wind speeds increased and conditions were favorable for the movement of sand and dust. This was the everyday pattern that confronted the people of Chan Chan.

The Chimu solution for control of the effects of the wind, sand, and dust was a design of exterior and interior walls of adequate height that diverted the flow pattern of the turbulent dust ladden wind. The wind was channeled to flow over the top or around the sides of the enclosures. The important proper wall design for effective control was a lesson that was probably learned from the sunken gardens. There were several benefits from the citadel design that made the courtyards more habitable: the wind, sand, and dust from outside the walls was diverted; the concentration of dust was diluted by entrained air as the distance from the source of pollution increased (Hesketh & Cross, 1983:103); evaporation and evapotranspiration were reduced; and wind speeds were lowered. These benefits, along with water from the wells, cultivated plants and trees, and shaded colonnades contributed to a more pleasant ambience for the elite who lived in the enclosures.

During the time of the Chimu the citadel's adobe walls were maintained in good condition and blowing sand could not travel over the top of the walls and enter the courtyards.

Though the extant walls had deteriorated with time from lack of maintenance, more sand was expected to be observed outside the citadels than was found inside. It was theorized that blowing sand would accumulate more readily outside the walls around obstructions to the airstream. But, site inspection of the courtyards unexpectedly revealed large quantities of mounded sand around many of the interior adobe structures, with the largest quantity located just inside the upwind south wall. The open areas between interior structures had the appearance of a deflated desert plain, with a surface of small stones and pebbles and very little accumulated sand. There was more sand inside the walls than outside and this required an explanation.

Site investigation indicated that some of the sand just inside the upwind citadel wall entered through breaks in the wall. Some courtyard sand can be attributed to the squatters' anthropogenic activities and some sand can be attributed to the destructive treasure hunting methods of the Spanish. But, the larger quantity most likely came from the deterioration of the aging adobe. Significant deterioration had resulted from spalling due to repeated cycles of nighttime dew and daytime solar radiation, from degredation caused by salt in the adobe (4), and from erosion caused by winds that entered through breaks in the walls (Day, 1973:73). (The damaging effects of wind erosion were personally observed in the Velarde citadel.) In the approximately 500 years since the Inca conquest, sand, from all of these sources, was trapped inside the citadel walls and was progressively accumulated. It is speculated that entrapped sand was not a severe problem for the Chimu when continually maintained citadel walls served their intended purpose and kept out the blowing sand. The present day lack of massive accumulations of eolian sand around the outside of the citadels suggests that during Chimu times blowing sand was more a comfort problem than one that threatened the site.

As the city grew and more structures were built the microclimate changed in a dynamic manner. The airflow pattern was influenced by diversion and turbulence from man-made obstructions. The wind shifted in speed and direction depending on the shape and spacing of the structures. In the interchange between the built and natural environment, adjustments and refinements were continually made to the layout inside and outside of the citadels until the most suitable adaptative methods were developed. The designs became stabilized and the features of the classic variant were repeated in future citadels. The empty urban spaces between the citadels filled and eventually formed the random pattern that is seen in the extant ruins at Chan Chan (see Figure 18).

Although this particular pattern is unique to the Moche Valley, there are other arid zone cities in other parts of the world that have adapted their settlement patterns and architecture in much the same manner, similar confirgurations evolved. As an example, Yazd, a city in Iran has urban features resembling those found in the nucleus of Chan Chan. There are: 1) dwellings built with common walls, 2) narrow winding streets, 3) sites without wide through streets, 4) high walls to give additional circulation and shade, 5) water wells enclosed behind dwelling walls, 6) vegetation to improve the ambient temperature, 7) extensive use of patios, 8) city walls with only one entrance, and 9) an orientation that takes advantage of the dominant wind of the locale. Other Iranian cities (Nain, Zavareh, Kashan, Abarque, Boshrouyeh, and Sirjan), sharing some of the same features as Yazd, provide additional examples of similar arid zone built environments, in different geographical locations, that resulted from a community's efforts to alleviate perceived stresses from the natural environment (Tavassoli, 1983:121-135).

Endnotes

1. Dispersion of the social, political, and economic structure of conquered people was a standard Inca practice that assured political control. The best artisans and some of the rulers and elite were sent to the Inca capital at Cuzco and large segments of the population were dispersed to other distant locations. This technique made it difficult for any opposition to Inca rule to form.

2. According to Kolata (1982:73), Andrews (1974) proposed a different seriation based on a subjective interpretation of stylistic variations among the U-shaped structures. This seriation suggests the following chronological order, starting from the earliest: Chayhuac, Tschudi, Rivero, Velarde, Bandelier, Laberinto, Tello, Uhle, Squier, and Gran Chimu.

3. The amount of influence by the militaristic Huari (also spelled Wari) from the Andean highlands on the built environment of the Chimu is still uncertain. Moseley did not find any evidence of a Huari presence during his investigations in the Moche Valley. On the other hand, Isbel (1977:50) feels that the Huari had a major influence in the Moche Valley and that the large double walled rectangular enclosure of the Rivero citadel may be the end product of a Huari type enclosure that evolved on the North Coast. Isbel claims that Chimu enclosures shared a number of features with

the Huari sites of Pihillotaqta and Viracochapampa and could have evolved from such planned units after the collapse of the Huari control.

Moseley (1975:225) claims that his investigation shows that most types of structural features found at Chan Chan can be traced to local antecedents and the settlement pattern was largely the outgrowth of developments that took place within the Moche Valley. In terms of layout and general organization the Galindo enclosure is similar to the earliest of Chan Chan compounds and may be seen as the architectural antecedent of the citadels. He states that his findings do not support the contention that Chan Chan, or other urban centers on the north coast, became settlements around A.D. 700 as a result of a military invasion issuing out of the sites of Tiahuanaco or Huari in the south central Andes.

The view that the Huari influenced urban settlements on the north coast was also held by Lumbreras (1974:165), Lanning (1967:139), and Rowe (1963). Mackey (1982:322) believes that this viewpoint can be traced to Kroeber: "In Kroeber's brief 1925-26 visit to the North Coast he did not notice any large sites which predated the Middle Horizon. He also observed that Middle Horizon ceramics represented a break with the previous Moche style and that this stylistic break was due to invaders from the sierra (1930:111). These observations were reinterpreted by other scholars to mean that Huari invaders were responsible for urbanism during the

Middle Horizon."

4. Day determined that the adobe walls with the greatest salt content had deteriorated the most, while those with little or no salt were well preserved. The concentration of salt varied with the location of the raw material source. Usually, the sources closest to the beach had the greatest concentration (1973:73).

Chapter 5

Physical Simulation of the Citadels at the Site

Using theoretical constructions, the archaeological record, and personal observations, the rationale for the stated hypothesis has been progressively developed. Several of the assumptions made about the citadels' design have been based on a series of contemporary composites that illustrate airflow patterns around buildings. A close examination of these composites provides a foundation for both the theoretical constructs and the wind tunnel simulations experiments that test the ability of the citadels to reduce human stress and discomfort from the effects of the wind, sand, and dust.

Comparative Composites of Airflow Patterns

Evans in Natural Air Flow Around Buildings (1954) investigated and recorded the three main characteristics of airflow for various building shapes and orientations. The characteristic patterns, eddies, and pressures were combined with the basic building dimensions to supply composites that graphically illustrate the general nature of the airstream around obstructions (see Figures 19, 20, and 21). These composite illustrations, along with those of other researchers, provide pertinent background information for the development of the hypothesis and the analysis of data from the wind tunnel experiments (1).

An examination of the Figure 22 composites indicates that as the height of the building increases, the depth of the downwind shadow or zone of protection also increases while the airflow pattern over the top of the building remains constant. Figure 23 demonstrates that a thin wall provides a deeper downwind shadow or area of protection than a thicker wall of the same height and length. Figure 24 illustrates that as the length of the building increases, (with depth and height constant) the length and depth of the downwind shadow also increases. Lawson's illustrations (see Figure 25) demonstrate the effects of the spacing of buildings normal to the wind, while Figure 26 indicates that a rectangular building placed with the long side perpendicular to the wind results in a greater downwind shadow than the same building placed at an angle. From another source, Figure 27 demonstrates the variation in wind speed and area of zones of protection that result from a windscreen perpendicular to airflow. As shown previously in Figure 22, the same general pattern over the top of the obstruction holds regardless of any height change. Saini (1980) illustrates the effects of courtyards and windscreens on the distribution of dust in the enclosures (see Figures 28 and 29). A more comprehensive overall view of airflow patterns and the deposition of sand and dust around groups of buildings in a variety of spatial arrangements is illustrated in Figures 30 and 31 by Gandemer (1978).

These many composites illustrate the airflow patterns that can generally be expected around buildings in a natural airstream. From these insights and expectations assumptions were made about the aerodynamics of the Chan Chan citadels and their ability to keep the wind, sand, and dust from entering the courtyards. But, more is needed for a thorough investigation, assumptions are not enough. Quoting from Evans (1954:4):

> While a reasonable understanding of the characteristics of airflow combined with a knowledge of local conditions and wide experience will provide a good basis for assumptions, this is not enough to enable a complete determination of airflow patterns. The only logical and known way to determine the effects of a given building on the airflow pattern prior to construction is to study the air patterns around and through a scale model subjected to a technically sound wind tunnel, or in a natural air stream under proper conditions.

Wind Tunnel Experiments

Two elements of the stated hypothesis were empirically tested in the low speed wind tunnel at the Environmental Systems Laboratory at Virginia Polytechnic Institute and State University's Price's Fork Research Center in Blacksburg, Virginia. Scale models were utilized to find the relative wind speeds and the diversion of the air entrained dust needed to attain stated objectives 2b and 2c. It is felt that the other stated objectives are adequately supported and attained through the theoretical constructs. All the objectives will be more fully examinied in the discussion and conclusions at the end of the paper.

Selected Criteria and Constraints

The variations in the size and configuration of the citadels were too numerous to test individually. To simplify the procedure, a generic model was developed to represent all the citadels. Since the citadels built toward the end of the Chimu empire incorporated the most complex features of the classic variant of the citadel as defined by Topic and Moseley (1983:154), it was inferred that Rivero, the last completed citadel in both the Kolata and Moseley sequences, would have the most advanced design. Therefore, Rivero was used as the basis for the design of the scale models to be aerodynamically tested. However, Rivero was the only citadel that had the unexplained double exterior walls, and Topic and Moseley had not differentiated between the single and double walls as one of the features of the classic variant. Their definition ignores or side steps the issue and merely states that the classic variant is a large enclosure with high walls built as a unit. It was felt that the determination of the difference in effectiveness of the single and double walls could be an important element in solving the enigma of the walls and it was, therefore, elected to aerodynamically test scale models of both types.

The normal fluctuations of the wind in the natural environment of the wind tunnel and the instantaneous changes produced in the flow patterns make it impossible to reproduce the same measurements when the same experiment is rerun. The data gathered are inherently general in nature and are representative of conditions occuring within the particular two minute period used to gather wind speeds at each of the data taking locations. Experience obtained from the experiments has shown that an experiment can be reproduced, but with each set of data the general pattern of the recorded wind speeds is usually slightly different. Wind measurements are not exact, they are the mean of a series of wind speeds measured over a period of time. As an example, Jackson's Modified Beaufort scale (1978:256) is based on previous research that establishes an 18% turbulence intensity as a norm for the variation in an average wind speed in open terrain (turbulence intensity [%] = [one standard deviation/mean wind speed] x 100). Statistically, this indicates that at one standard deviation, 68% of the wind speed readings will fluctuate within plus or minus 18% of the mean wind speed; a wide variation that occurs in what Jackson considers as a standard environment.

The configuration, spatial arrangement, location, and concentration of obstructions upwind of the citadels during Chan Chan's existence influenced the characteristics of the windward airstream. Any attempt to reconstruct these upwind obstructions in order to develop a simulation of the Chimu built environment that could be used to develop a boundary layer in the wind tunnel would require difficult subjective interpertations of many variables. Any attempt to simulate the obstructions to the airstream inside the citadels would be as difficut. To simplify the procedure and to restrict these experiments to the test of the citadels' aerodynamic effectiveness in the most elementary environment, it has been elected not to simulate the obstructions inside or outside the citadels. It has been elected to determine the effectiveness of the walls by visualizations and by recording the wind speeds outside and inside the citadels and comparing them to find relative wind speeds at 2 m scale height (pedestrian level) inside the citadels. The relative wind speed is the indicator of comfort, the spatial pattern of the relative wind speeds inside the citadels is the indicator of zones of protection or comfort.

The experiments test the effectiveness of scale models of the citadels using the airflow pattern inherent in the design of the Environmental Systems Laboratory wind tunnel. No attempt is made to simulate any type of boundary layer or to compare the inherent airflow pattern in the wind tunnel to the airflow in any type of terrain.

Objective of Wind Tunnel Experiments

To determine the effectiveness of scale models of the major citadel walls in reducing wind speeds and diverting entrained dust by:

1. Comparing the wind speed at 2 m pedestrian level scale height inside the courtyards to the upwind speed at 10 m meterological station scale height outside the models in

order to find the relative wind speed at each designated location.

2. Using generated smoke and moveable "telltales" to visualize the airflow patterns in, over, and around the models.

Procedures for Relative Wind Speed Experiments

A list of equipment, computor software, and the calibration procedures employed in the relative wind speed experiments are presented and defined in Appendix C.

1. Starting from the inlet side, the table was arranged with rows 1 thru 18 in 20 cm increments across the table, perpendicular to the wind. Columns A thru J were arranged in 20 cm increments parallel to the airstream and perpendicular to the rows to give an orthogonal 20 x 20 grid pattern (see Figures 32, 33, & 34).

2. Measurements were recorded and stored on a Data Logger which was programed to record the voltages generated by the anemometers designated as Probe 1 and Probe 4. In each relative wind speed experiment, one voltage measurement was recorded each second for four seconds. These four measurements were averaged and the process was automatically repeated for two minutes to give 30 average voltages for Probes 1 and 4, at each grid location.

3. Reference Probe 1 was positioned vertically upwind of the model at 10 m scale height between columns E and F on

row 3. Data Probe 4 was positioned vertically inside the citadel at 2 m scale height, on a sliding holding fixture that was moved to each grid location as needed.

4. The experiments were carried out at a fan rotation speed of 50Hz, producing a wind speed of approximately 9 ft/s (feet/second), allowing latitude for variations in the wind speed which would stay within the maximum voltage limit of the Data Logger.

5. At the begining and end of each experiment the reference and data probes were calibrated against each other at Probe 1 location at 10 m scale height and 50Hz fan speed. The readings were averaged and a correction factor calculated to account for the difference in voltage readings due to drift in the electrical circuit.

6. Experiment #1. Full citadel, with internal walls, and wind from the south, was performed to determine if relative wind speeds inside the citadels remained constant when external upwind speeds were varied. Data Probe 4 was placed at selected grid locations inside the enclosure, the upwind reference speed was changed to 9ft/s, 10.8 ft/s, and 13.9 ft/s, and the wind speed was measured at each location. In this experiment a pitot tube was used in the upwind reference location because the wind speeds required were too high for the hot wire anemometer.

7. Experiments #2 through #7 were conducted to find the relative wind speeds inside the scale models of the citadels

when the reference upwind speed at Probe 1 was approximately 9 ft/s (fan speed 50Hz). Measurements of wind speed were taken along the walls and at the intersection of the grid lines. The upwind short side of the citadel was designated as the south wall. Wind directions were chosen to simulate prevailing winds from the coast with the wind from the south (S) at 180 degrees, from the south-southeast (SSE) at 168 degrees, and from the southeast (SE) at 135 degrees. To facilitate positioning at an angle, the model was placed on a moveable base layed out in a 20 cm by 20 cm grid. The reference Probe 1 was always kept at the same upwind grid location. The relative wind speed experiments were:

a. Experiment #2. Full citadel, with no internal walls, wind from the south.

b. Experiment #3. Full citadel, with internal walls wind from the south.

c. Experiment #4. Full citadel, with internal walls, wind from the SSE.

d. Experiment #5. One sector of citadel, with double wall on three sides, wind from south.

e. Experiment #6. One sector of citadel, with double wall on three sides, wind from SSE.

f. Experiment #7. One sector of citadel, with double wall on three sides, wind from SE.

The full citadel was not tested at 45 degrees because the model would not fit the table at this angle.

Procedures for Data Processing

After each experiment, the raw data was transfered into a personal computor data file via the Data Logger's internal program. Using the electronic spreadsheet in the Lotus 123 computor software, the 30 voltages at each grid location were averaged, the mean wind speeds were calculated from these averaged voltages using the calibration curve equations developed earlier, and the correction factor applied (see Appendix C for calibration procedures). The relative wind speeds were calculated by dividing the internal wind speed (Probe 4) by the reference wind speed (Probe 1) and multiplying by 100 to give a percentage (Relative wind speed [%] = [internal wind speed/reference wind speed] x 100). The relative wind speeds developed from the anemometer measurements were plotted at each grid location on a plan of the structure tested and were subsequently used to produce the representative illustrations.

Procedures for Visualization Experiments

1. Experiment #8. Telltales were employed to investigate the flow patterns for each of the configurations and wind directions in the relative wind speed experiments. The telltales, mounted on a fixture perpendicular to the wind, were moved downwind from outside the citadel (row 4) to the farthest wall (row 15) inside the citadel, one row at a

time. In this manner the circulation pattern could be observed at each location (see Figure 35).

2. Experiment #9. After the telltale tests, smoke was introduced upstream of the citadel as an additional method of observing and determining the effectiveness of the walls in diverting the airstream. The smoke patterns were difficult to distinguish at the wind speeds used. As an aid to the investigation, a video camera was used to record both the smoke and telltale experiments. The video tapes were later viewed at slow speeds for a more detailed examination of the rapidly changing patterns. The information gathered in the visualization experiments was utilized in the preparation of line drawings that illustrate the composite results.

Table 1 and 2, and Figures 36 through 41 contain the data developed from the wind tunnel relative wind speed and visualization experiments.

Zones of Protection, or Downwind Shadows, as Indicators of Comfort

In Figures 36 to 40 the relative wind speeds at each grid location in Experiments #2 to #7 were recorded on separate plans of the generic citadel. Speeds in the same range were grouped and coded as zones to facilitate visual comparisons of the distribution of areas of protection. The coded zones served as indicators of the effectiveness of the citadels in alleviating stress and discomfort. The lower the relative wind speed the greater the protection and comparative comfort afforded. Zone 1, the dark cross hatched area in the figures indicates the most protection from the shadow of the walls (under 40% relative wind speed). Zone 2, shaded with the lighter diagonal lines shows intermediate protection (40-60% relative wind speed), and Zone 3, the area without lines shows the least protection (above 60% relative wind speed). Table 2 records and classifies, by percentage, the zones of protection in each sector and in the full citadel. The graphic representations in Figures 36 to 40 provide a useful means for determining the wind deterring capabilities of each sector of the citadels.

Airflow Fluctuations in the Environmental Systems Laboratory Wind Tunnel

The wind speed over a level tunnel floor, even without any upwind obstructions, fluctuates as an inherent function of the tunnel design. Figure 42, developed from calibration data at a fan speed of 40Hz, illustrates that with an unobstructed mean upwind speed of 5.90 ft/s, peaks and valleys at 5.63 and 6.17 ft/s are evident: a total variation of approximately 10% in a two minute period. A telltale in the same tunnel indicated that there are also significant concurrent fluctuations in the mean wind direction. The fluctuations due to the wind tunnel design, coupled with variables illustrated by Hosker (see Figure 43), reveals the infinite number of continually changing airflow patterns that can and will occur during any aerodynamic test of a model.

Experiments #2 to #7 were subject to a combination of fluctuations and variables that precluded precise results. As previously stated, the data recorded are general in nature and even under the most optimum conditions impossible to reproduce consistently with the same spatial distribution. Though the patterns of zones of protection developed in Figures 36 through 40 are not exact, they are valid indicators of the general effectiveness of the citadel and adequate for the purposes of this investigation.

Endnotes

1. The impetus for wind studies has come from the concern for public safety in the gusty winds of the downtown sections of major cities. Wind problems have become common in recent years as more tall buildings are built and as cities place increasing emphasis on public plazas and open spaces. Builders and designers are acutely aware of the potential liability from hazardous conditions that threaten public safety. Awareness is helped along by the creation of environmental wind codes in cities with histories of problems (Toronto, San Francisco, Melbourne, and Tokyo are examples)(Arens, 1982:8). Arens' article (1982) provides an excellent overview of the considerations involved in designing, modeling, and testing for wind studies.

Chapter 6

Analysis, Findings, and Discussion of the Experiments

A combination of the plotted relative wind speed data, the graphics developed from the visualizations, and the tables of zones of protection and relative wind speeds supply the data base for analysis. The findings from the analysis are the focus for the discussions of the relative wind speed-reducing and dust-diverting capabilities of the citadels.

Analysis and Findings of Variable Upwind Speed Experiment

Experiment #1 demonstrated that relative wind speeds inside the citadels (ratios of the inside to the outside wind speeds) remain constant even with a major variation in the outside upwind speed. The data in Table 1 demonstrates that when upwind speeds were increased from the 9 ft/s (50Hz) to 13.9 ft/s (80Hz), the maximum increase in relative wind speed inside the full citadel model, with internal walls, and wind from the south, was slightly less than 4%. From this and other data in the Table 1, it can be concluded that within the range of speeds used, a change in upwind speed has a minor effect on the relative wind speeds inside the citadel.

Analysis and Findings of Relative Wind Speed Experiments

In Experiment #2, the full citadel model, without internal walls and wind from the south, afforded the most protection in the southern sector, but offered progressively less and less protection as the northernmost wall was approached (see Figure 36).

In Experiment #3, the full citadel model, with internal walls and wind from the south, there was a marked improvement over the protection pattern obtained from the citadel model without internal walls in Experiment #2. The southern sector and the southern half of the central sector had a protection pattern similar to that of Experiment #2, but the other half of the central sector and the northern sector showed a substantial increase in Zone 1 protection. In this experiment, the northern sector had the most protection with the lowest relative wind speeds, a reverse in pattern from Experiment #2 where the southern sector had the lowest relative wind speeds. The change in pattern has to be attributed to the addition of the internal transverse walls (see Figure 37). Experiment #3 recorded lower relative wind speeds and a higher percentage of Zone 1 protection in each of the sectors than any other experiment in the series.

Experiment #4, the full citadel model, with internal walls and wind from the SSE, showed a radical change with a major loss of protection in the southern sector that occured with the shift in the direction of the airflow. Although the pattern in the southern sector had changed for the worse, the protection zones in the central and northern sectors did not change appreciably. The distribution of zones of protection was probably affected by high airspeeds and laminar flow along the exterior walls that diverted the SSE winds and kept them from entering (see Figure 38).

The next three experiments with the double walled, single sector model recorded results similar to those of the <u>southern sector</u> in the full citadel model. Experiment #5, with wind from the south gave patterns of zones of protection almost identical to those from Experiment #2. There were low relative wind speeds in the entire sector (see Figure 39). Experiment #6, with wind from the SSE, exhibited the same radical change as Experiment #4 with higher relative wind speeds and less protection. There was, however, a shift in the location of the Zone 3 winds from the center of the sector to a position closer to the east wall. This difference in location could be due to the double wall type of construction. Experiment #7, with wind from the SE gave the most dramatic increase of high relative wind speeds in the central part of the sector with slightly improved protection from the wind along the outside walls (see Figure 40).

<u>Analysis and Findings of Visualization Experiments</u>

In Experiment #8 the telltales revealed the airflow patterns inside and outside the model citadel. Generally the patterns illustrated by Lawson (see Figure 25) were very close to those obtained experimentally. Similar circulation patterns were found on the upwind and downwind sides of the shorter walls perpendicular to the wind. When internal walls were present, the major portion of the airstream went over the courtyards, but without internal walls the airstream came down to floor level in the northernmost section. Outside the citadel the airstream paralleled the walls at an apparent high speed. Inside the citadel, turbulence increased wherever the wind speed increased (see Figure 41).

In Experiment #9, the patterns obtained from the introduction of smoke upwind of the model reinforced the information from the telltales. The most vivid evidence came from the difference in the smoke patterns with and without internal transverse walls. Without walls and wind from the south the major portion of the smoke entered the enclosure and dipped to the floor in the northern section. With internal walls the major portion of smoke (a colleague and I subjectively estimated 85%) went over the top of the walls and was kept out of the enclosures. Some smoke did enter the courtyards but it was minimal (see Figure 41).

The smoke and telltale patterns inside, over, and around the citadel models changed when the angle of incidence of the upwind airstream changed. The smoke and telltale activity from turbulence inside each of the citadel's sectors increased with the increase in angle. The locations of increased activity were generally the same as those found by the zone differences in Experiments #2 to #7. The greater the zone protection, the less the smoke and telltale activity.

In summary, the smoke and telltale experiments indicate that the generic citadel model was most effective or efficient in controlling wind and smoke when there were internal walls and when the airstream was normal to the upwind wall and parallel to the longtitudinal axis.

<u>Discussion of the Quantitative Relationships Between Zones of Protection</u>

The quantitative relationships between zones of protection, sectors, and the variables used in the experiments are shown in Table 2. The comparison of zones of protection reinforces the importance of the internal walls. For example, without internal walls and the wind from the south, the southern sector has a high 90% Zone 1 protection and the northern sector has a low 22%. When internal walls are added, the southern sector remains at 90%, but the northern sector jumps to a significant 100% Zone 1 protection. When the wind shifts to the SSE the southern sector drops to only 36% Zone 1 protection, while the northern sector remains at a high 80%. These quantative relationships in conjunction with the graphic representations of the data serve as important aids for examining the activities that took place in each of the sectors.

In summary, the addition of internal walls always improved the protective capabilities of the citadels. The most significant improvement occured when the airstream was parallel to the long axis. When the wind shifted there was a change in the protection afforded. As the angle of incidence of the wind increased the protection afforded by the southern sector decreased but the level of protection in the central and northern sectors remained consistently high.

Discussion of Relative Wind Speeds and the Modified Beaufort Scale

Using the mean wind speeds outside the citadel and the relative wind speeds inside as criteria, it is possible, by the use of Jackson's Modified Beaufort Scale of wind velocities, to compare the effects of wind speeds in nature to the results of these experiments (1978:257)(see Figure 44). The results of this comparison can be used as an indicator of any change in human stress or discomfort due to the citadel design.

The mean velocity reported at Huanchaco by ONERN (1973:44) is 19.5 km/hr (5.5 m/s) from the south for 249 days per year. The maximum mean velocity recorded is 24 km/hr (6.67 m/s). The Modified Beaufort Scale at these wind speeds indicates the effects or manifestations of the wind that can be expected in a rural terrain at the upwind side of the citadels. By multiplying this upwind speed by the relative wind speed inside the citadel and referring this new wind speed to the Scale, the expected courtyard conditions or environment caused by the wind can be estimated. As an example, at the maximum outside upwind speed of 24 km/hr (6.67 m/s) and with a 40% relative wind speed inside the citadel, 9.6 km/hr (2.67 m/s) can be expected in the courtyard (24 x .40 = 9.6). Referring this new wind speed to the Modified Beaufort Scale we can determine the change in environmental conditions. In this case the environment would have improved from "hair disarranged, dust and paper raised," to a less intense "wind felt on face." Thirty-two km/hr (8.87 m/s) was personally measured at Chan Chan, a higher wind speed then that given by ONERN. This suggests that conditions at Chan Chan were at times more severe than indicated by the reported long term mean wind speeds by ONERN that average out the gusty peaks. The 32 km/hr (8.87 m/s) shows outside affects of "control of walking begins to be impaired" to the improved inside 40% (3.55 m/s) condition of "clothing flaps and hair disturbed." Conditions at different locations inside the citadels would of course change with changes in relative wind speeds, but the walls would always, to some degree, alleviate discomfort and the associated human stress.

Chapter 7

Conclusions, Summary, and Recommendations

A consolidation of the theoretical constructions and the results and discussions generated by the wind tunnel experiments establishes the correlation between activities inside the citadels and the design of the structures. The last of the stated objectives is attained, the stated hypothesis is confirmed, the overall results from the research are summarized, and questions for further research are posed.

The Design of the Citadels - Conclusions

The classic variant of the citadels can be viewed as a series of contiguous courtyards, along a single axis, whose high walls acted as windbreaks and prevented gusty winds, sand, and dust entrained in the wind from entering the enclosed areas. The upwind walls and sectors protected the downwind sectors of the citadels and helped to reduce the pedestrian level relative wind speeds. The long major axis also helped to improve the courtyard environment. As the distance from the upwind source of dust and smoke increased, dilution by clean air increased and the concentration of particulates in the airstream decreased. The downwind courtyards farthest from the source of pollution benefited the most and had less entrained dust at pedestrian level. Downwind from the outside corners, the long walls also provided a high speed laminar flow along the outside wall face that diverted winds coming from the SSE and SE and kept them from entering the enclosures.

The citadels were the most efficient and offered the greatest protection when the longtitudinal axis paralleled the upwind airstream. The prevailing wind in the Chan Chan area comes from the south 68% of the time. The wind direction in the locale of each citadel might be slightly different due to upwind obstructions. As the wind shifted from the south the protective pattern inside the citadel changed. With internal walls and the wind from the south all sectors received maximum protection. With the wind from the SSE and SE the protection lessened appreciably in the southern sector but remained high in the central and northern sectors. Without internal walls and the wind from the south, the north half of the citadel received minimal protection. When the wind shifted to the SE and SSE the protection was reduced still more and the courtyard winds became more turbulent. The double wall afforded slightly more protection when the angle of incidence of the wind shifted from the south. No other benefits from the double wall type of construction could be identified in these experiments.

From the composite illustrations it can be concluded that the higher, the thinner, and the longer the wall the deeper and more effective the zones of protection. The overall citadel wall height obtainable in a thin cross section was limited by the structural properties of the adobe. In order to extend the limits of the adobe and to reach maximum wall height, it was necessary to use battered or sloping sides and a foundation layer of small boulde a higher compressive strength. The resultant tall thin shape shown in the cross section of Figure 23 afforded the most protection from the wall along with the most economical use of labor and materials. The presence of the large huacas in the Valley demonstrated that the Chimu possessed the technology to build higher massive walls, but massive walls would not have been as efficient.

In summary, the experiments and composites have demonstrated that the walls reduced wind speeds at pedestrian level and reduced the entry of dust entrained in the airstream. The theoretical constructs have demonstrated that the heavier sand does not rise over two meters from the surface of the terrain and, therefore, cannot travel over the high citadel walls. The orientation, rectilinear configuration, height and shape of the walls, and the tripartite division were shown to be important elements that contributed to the alleviation of human stress and the improvement of conditions for human comfort. The design of the citadels was found to be more effective when the wind was parallel to the longtitudinal axis. Deviation from this direction markedly reduced the protection provided in the south sector.

Control of the Effects of the Wind, Sand, and Dust by the Citadel Walls - Conclusions

The ancient city of Chan Chan was situated in the arid lower Moche Valley where there were gusty, turbulent, high speed winds with enough force to move the sand transported from the beaches. By means of walled citadels the Chimu utilized wind control techniques, learned from their Moche predecessors at Galindo and from sunken garden and windbreak experience, to alleviate the dust generated by a large urban population.

At first these immense rectilinear structures had single open courtyards but as experience with this new building form accumulated the classic tripartite plan with two interior transverse walls developed. Throughout Chan Chan's history the orientation of the long axis of the majority of the citadels consistently remained parallel to the prevailing winds that blew from the south in approximately two-thirds (68%) of the time.

The height of the exterior walls in all of the citadels consistently remained between 9 and 11 m, as high as could be advantagously built from the available adobe materials. The higher and thinner walls gave a deeper protective shadow on the downwind side. The upwind wall, perpendicular to the prevailing wind, produced a shadow of protection and a circulation pattern with eddy currents on each side of the wall. The downwind wall produced a similar circulation pattern. The side walls prevented the wind from coming in from the sides. The combination of all of the containing walls lowered pedestrian level relative wind speeds and reduced the amount of entrained dust. Each courtyard in turn protected the adjacent downwind courtyard. The classic citadel configuration and orientation caused the major portion of the oncoming winds to flow over the tops of the exterior and interior walls and around the outside walls. Sand could not enter but the lighter dust particulates, produced anthropogenically and by gusty turbulent winds from the coast, became entrained in the airstream and could enter as part of the airflow. As the entrained particulates from outside the walls traveled downwind away from their source, the concentration was diluted by cleaner air from the natural airstream. The higher the walls and the greater the distance to travel, the more dilute the concentration. The dust that did enter was a low density suspension of the finer particulates much the same as illustrated by Saini (see Figures 28 & 29). Each successive downwind courtyard had improved protection from both wind and dust.

The citadels performed optimally when the wind came from the south. When the angle of incidence of the wind changed from the prevailing southern direction there was a marked increase in wind speed in the south sector. Although there were also minor speed differences in the central and northern sectors, these interior spaces continued to remain reasonably well protected. This can be attributed to the laminar flow along the outside of the longtitudinal walls that kept the SSE and SE wind and entrained dust from entering. In the classic configuration the walls functioned as effective windbreaks that lowered wind speed, reduced dust concentration, and also reduced evaporation and evapotranspiration. Comparison of upwind speeds outside the citadel to inside pedestrian level speeds, using the Modified Beaufort Scale, illustrates the difference in the effects of wind speeds on pedestrians. When the citadels reduced the adverse affects due to the wind, they also reduced human stress and improved living conditions. In the continuing interaction between the natural and man-built environments the Chimu utilized this improvement when they established the location for their more important social, political, and economic activities.

Chimu Activities Inside the Courtyards - Conclusions

According to the archaeological record (Moseley, 1983), the only entrance to the classic citadel was in the northernmost wall of the northern sector in a sheltered location away from the wind. Each of the other sectors was entered from the adjoining sector. The northern sector (with the calmest winds) contained the highest ratio of U-shaped audencias and fewer warehouses, this indicates intensive administrative activity and a large number of users. The central sector (also relatively well protected) had the majority of the warehouses and was thought to be the living space for the ruler. The limited access provided this area with privacy and security for the ruler and his material wealth. This combination of protection from the elements along with privacy and security possibly made this location the best choice for the rulers personal domain. The southern sector, the least protected, (especially when the wind was not directly from the south) was also the least desirable. This sector often had the burial platform, the most open spaces, the walk-in wells, the fewest number of buildings, the kitchen facilities, and the livestock. The people in this sector were probably the lower class retainers and workers that served the ruler. From a series of trials and errors, successes and failures, each sector had its function attuned to its local environment. The classic design utilized the technology of the time not only to control the environment but also to accommodate and reinforce the Chimu social, political, and economic structure.

Summary

The stated objectives have been attained through the use of the theoretical constructs, the archaeological record, personal observations at the site, and the results from the wind tunnel experiments. In turn, the stated hypothesis has been confirmed.

It has been demonstrated that the effects of the wind, sand, and dust in the Moche Valley were ever present environmental problems of a magnitude that caused human stress and discomfort. It has been demonstrated that the Chimu and Moche had recognized the detrimental effects of these elements and had used the experience gained through time, in an interaction with the natural environment, in constructing their built environment. It has been demonstrated that the citadels built by the Chimu, kept the sand from entering, lowered relative wind speeds at pedestrian level in the courtyards, diverted the entrained dust and kept most of it from entering the courtyards. The thin high walls, rectilinear plan, tripartite division, and orientation, incorporated in the last six citadels built were shown to be important design elements that reduced human stress and improved living conditions for the rulers and elite inhabitants. However, the enigma of the double exterior walls remains, the experiments showed no significant difference between the aerodynamic protective benefits of single and double walls.

It has additionally been demonstrated that there was a correlation between the social, political, and economic activities in each of the sectors and the amount of protection afforded by the classic variant of the Chan Chan citadels. In conclusion, it can be said that the form of the classic variant of the citadel, evolved in an interaction between the built and natural environment, alleviated the Chimu's perceived stress and discomfort from the effects of the wind, sand, and dust and accommodated their social, political, and economic cultural requirements.

Recommendations for Further Research

One of the more interesting results from these experiments was the beneficial downwind effects of the contiguous courtyards on the same axis. This unexpected protective feature deserves more investigation. Wind tunnel testing with variations in the width and length of the citadel, the height of the external walls, the number and spacing of the internal walls, and the orientation of the major axis could provide important design information about the wind and dust protection provided by courtyard enclosures. The enigma of the double exterior wall remains unresolved, further investigation into the effects of the double exterior wall could be a part the suggested courtyard oriented research.

The possibility that the U-shaped audiencias, used by the elite as administrative control centers, might have evolved from windbreaks or the crescent of the barchan dune has been mentioned. Further research could test the aerodyamics of the audiencias to find if there is any empirical basis for this speculation.

This investigation used relative wind speeds inside the citadels as indicators to attain the objectives and to test the hypothesis. The telltale and smoke experiments demonstrated that although the relative wind speeds in the courtyards did not change appreciably with a change in the upwind speed, there was a change in turbulence that could have effected comfort. Additional research on the effects of turbulence from obstructions inside and outside the citadels would add another dimension to the study of courtyard design and the alleviation of discomfort. Models could be constructed that would simulate the size, shape, and spatial organization of structures and methods similar to those in this investigation could be used for testing. Special anemometers designed specifically for recording turbulence are required.

Further investigation of the ongoing interaction between the natural environment and the built environment would lead archaeologists to a firmer understanding of prehistoric cultures. The well preserved ruins and settlement patterns of numerous ancient communities in pre-Columbian South America provide excellent sites for the investigation of adaptations and accommodations to climatic stress and discomfort. Possibilities for further research on the North Coast are two large Chimu cities said to have begun during the same Middle Horizon as Chan Chan, Apurle, the second largest Chimu city, located in the Motupe Valley and

Pacatnamu in the Pacasmayo Valley (Lanning, 1967:139). Christopher Donnan, an archaeologist at the University of California, Los Angeles, has been conducting extensive field investigations at Pacatnamu on a continuing basis. Aerial photographs of the ruins of this large site adjacent to the Pacific Ocean indicate an urban pattern and physical environment similar to that of Chan Chan. Pacatnamu would be an excellent candidate for further study.

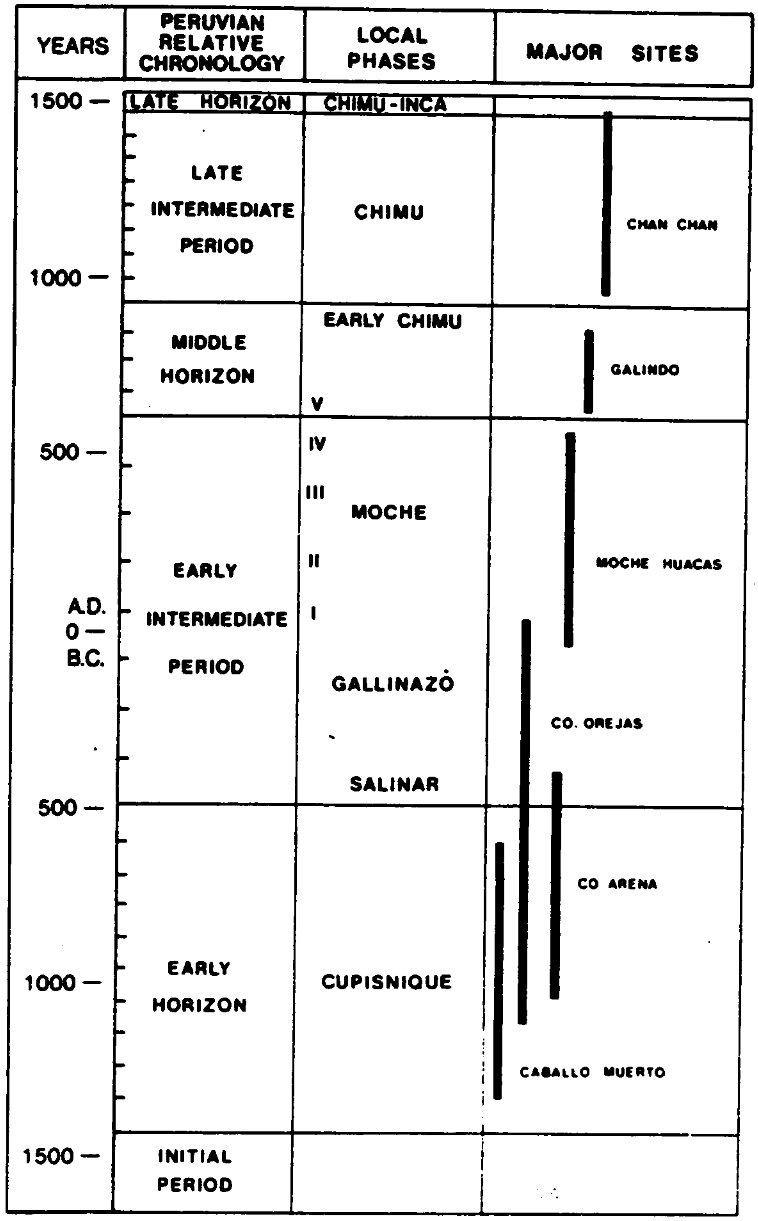


__Figure 1__ Chronological ordering of Moche Valley sites (from Moseley, 1982).

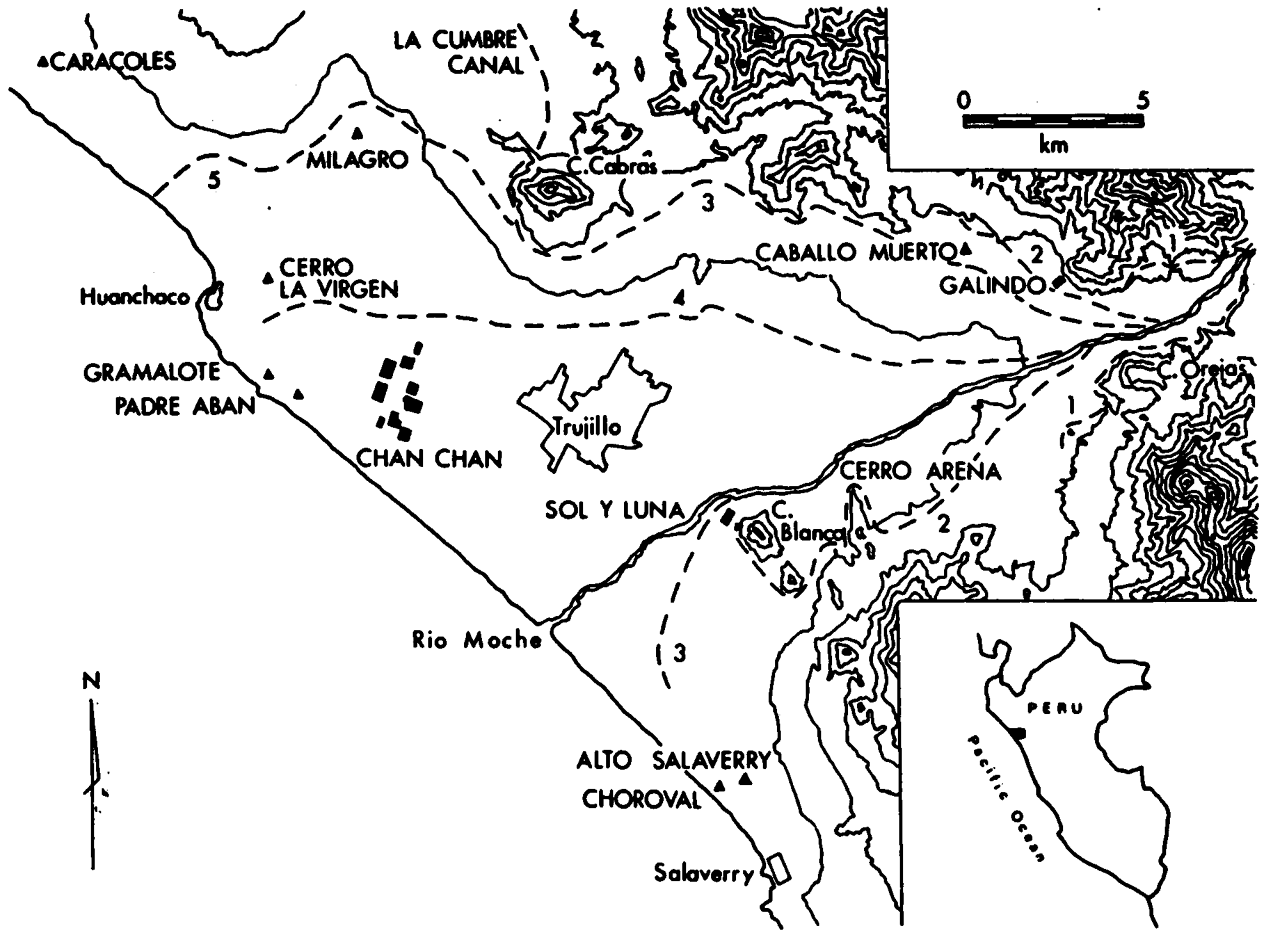
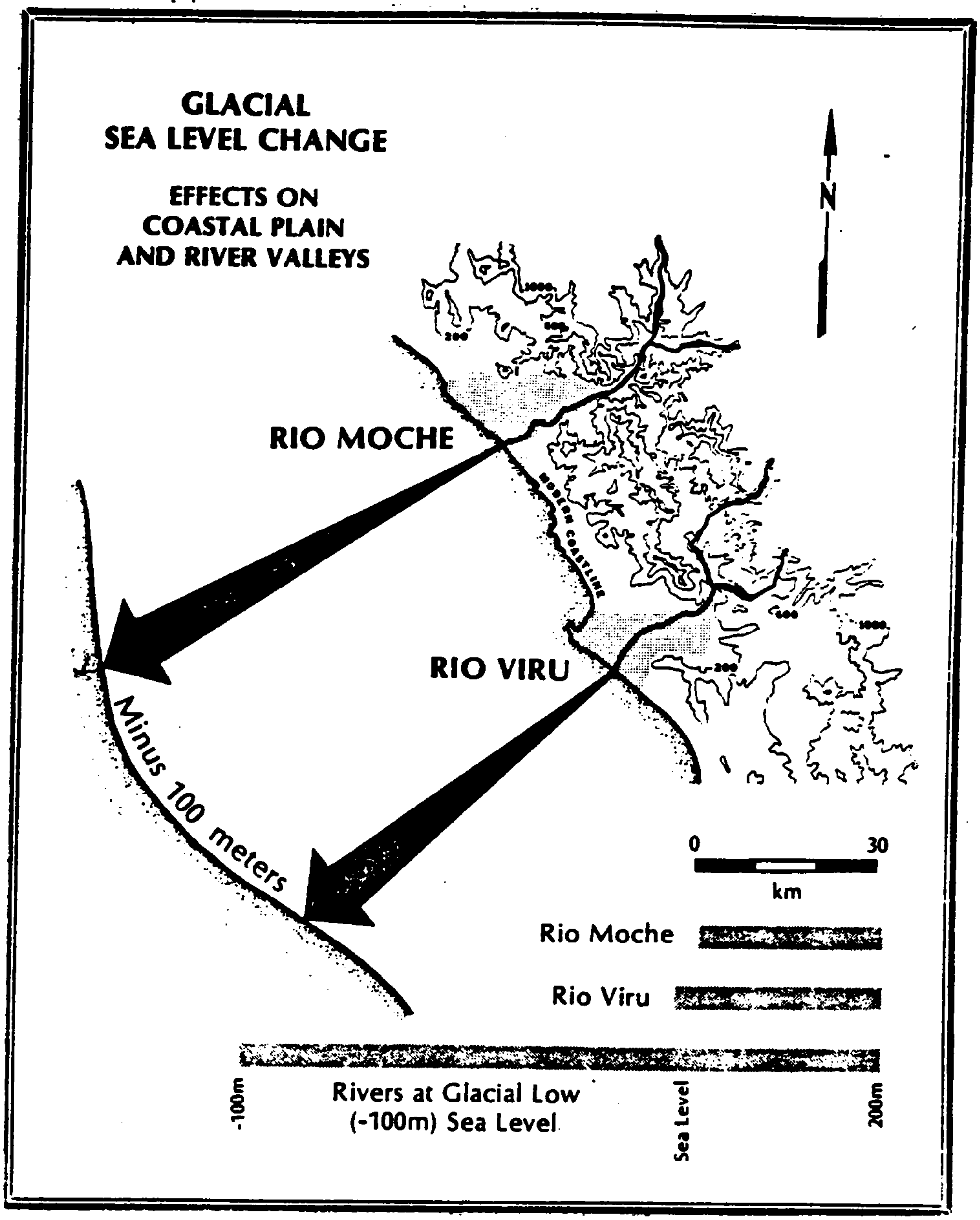


Figure 2 The Lower Moche Valley (from Moseley, 1982).

RESUMEN DE DATOS METEOROLOGICOS

Elementos Meteorológicos	Períodos de Registros Analizados	Unidad de Medida	Ene.	Feb.	Mar.	Abr.	May.	Jun.	Jul.	Ago.	Set.	Oct.	Nov.	Dic.	Promedio Anual	Total Anual
CUENCA DEL RIO MOCHE																
Estación Trujillo Corpac																
TEMP. PMME.	1949-70	°C	26.8	28.2	28.7	28.2	26.5	25.4	24.9	24.8	23.2	22.9	23.4	24.6	18.9	
TEMP. PM.			20.7	21.7	21.6	20.3	19.1	18.3	17.3	17.1	16.9	17.2	18.0	19.2		
TEMP. pmmo.			14.1	14.8	14.4	13.6	12.0	11.4	12.6	12.6	11.8	12.1	12.8	12.9		
PRECIP. TMME.	1943-70	mm.	2.0	0.9	4.0	1.0	3.0	3.0	0.5	7.0	1.0	7.0	0.0	1.0		1.6
PRECIP. TPM.			0.2	0.1	0.3	0.0	0.1	0.1	0.0	0.3	0.0	0.4	0.0	0.1		
PRECIP. tmmo.			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
HUM. RELAT. PM.	1961-67	%	82	83	82	84	82	84	82	84	84	84	82	82	83	
P. ATMOSF. PMME.	1949-70	mb	1013.2	1012.7	1012.6	1013.0	1014.3	1015.5	1015.7	1015.4	1015.6	1015.8	1015.1	1013.9	1013.1	
P. ATMOSF. PM.			1012.0	1011.3	1011.2	1012.0	1013.1	1014.1	1014.4	1014.3	1014.2	1014.3	1013.8	1012.8		
P. ATMOSF. pmmo.			1010.5	1010.0	1010.6	1011.0	1011.4	1012.7	1012.8	1013.2	1012.9	1013.2	1012.7	1011.5		
VIENTOS Dirección, Frecuencia y Velocidad Media.	1949-70	S	21-18	21-19	21-19	21-20	21-20	21-19	21-19	21-20	20-20	20-21	20-20	21-20		249-19.5
		SE	1-20	1-20	1-20	1-20	1-20	1-20	1-20	1-20	2-22	2-20	2-19	1-20		15-20.0
		Rango de Velocidad en Km/h.	0 a S22	0 a S22	0 a S20	0 a S22	0 a S20	0 a S20	0 a S20	0 a S28	0 a S22	0 a S22	0 a S24	0 a S20	0 a S-21.3	

Figure 3 Summary of meteorological data for station at Huanchaco, near Chan Chan (from ONERN, 1973).



<u>Figure 4</u> Glacial sea-level change (from Moseley et al., 1983).

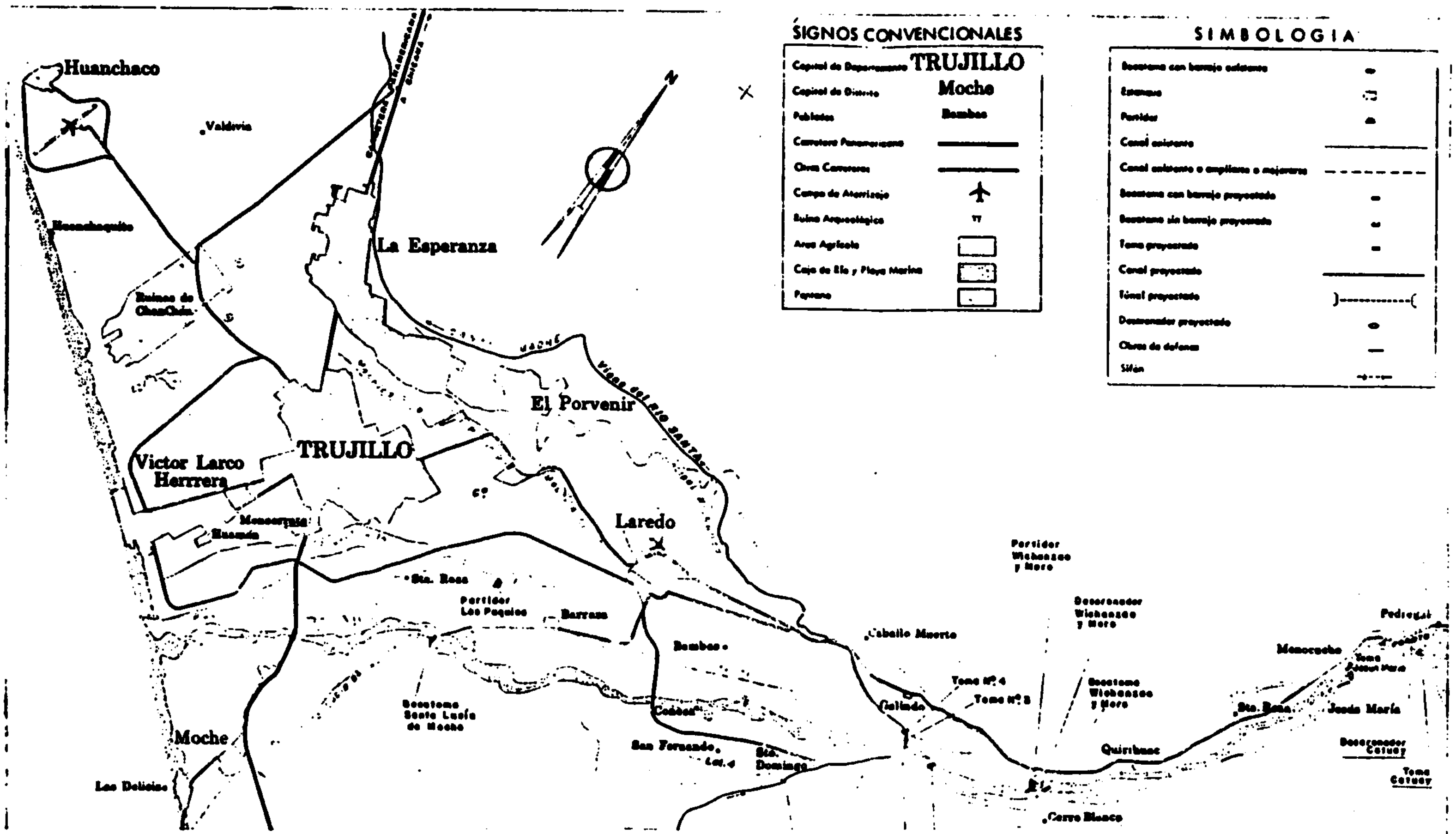
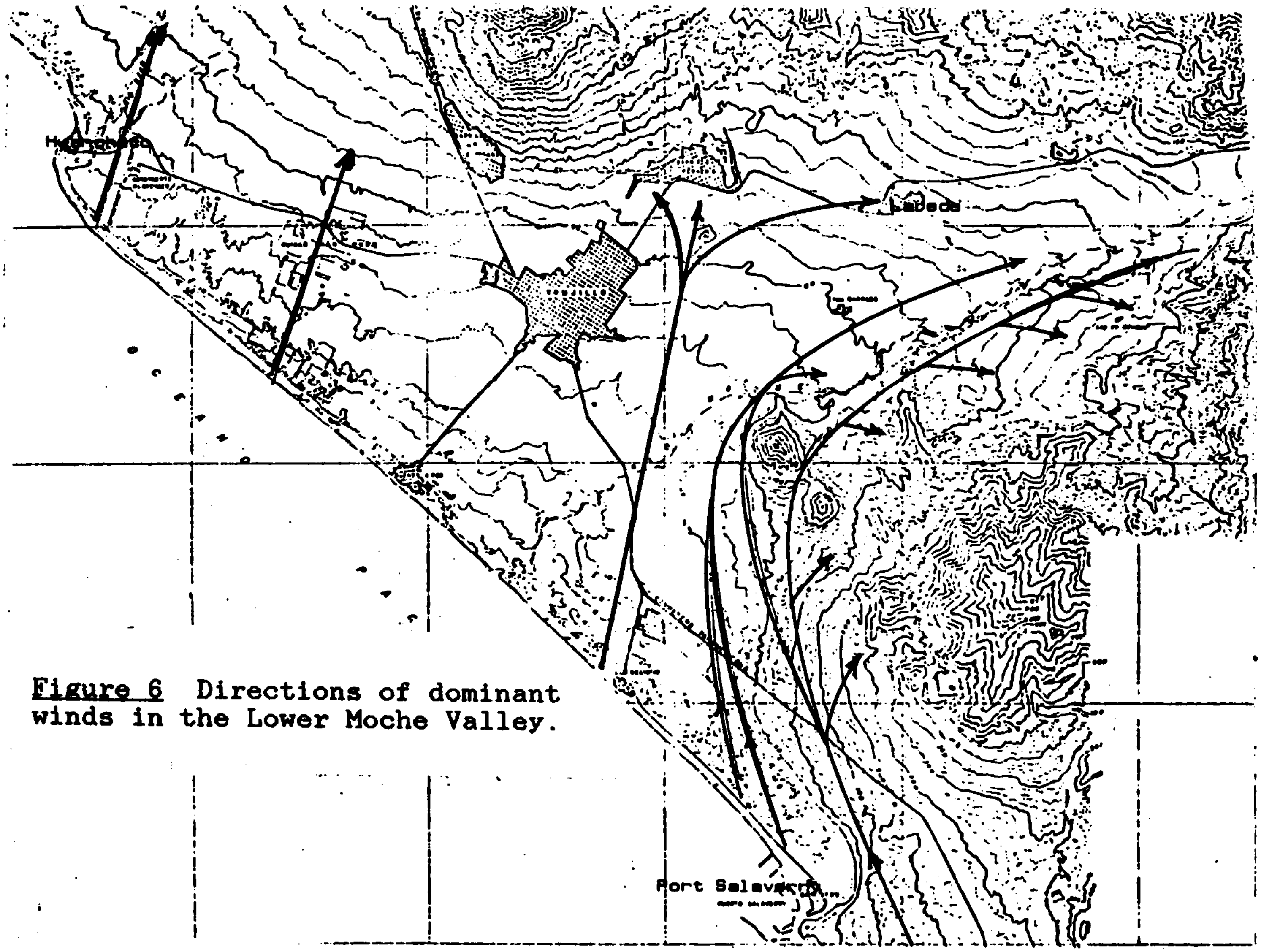
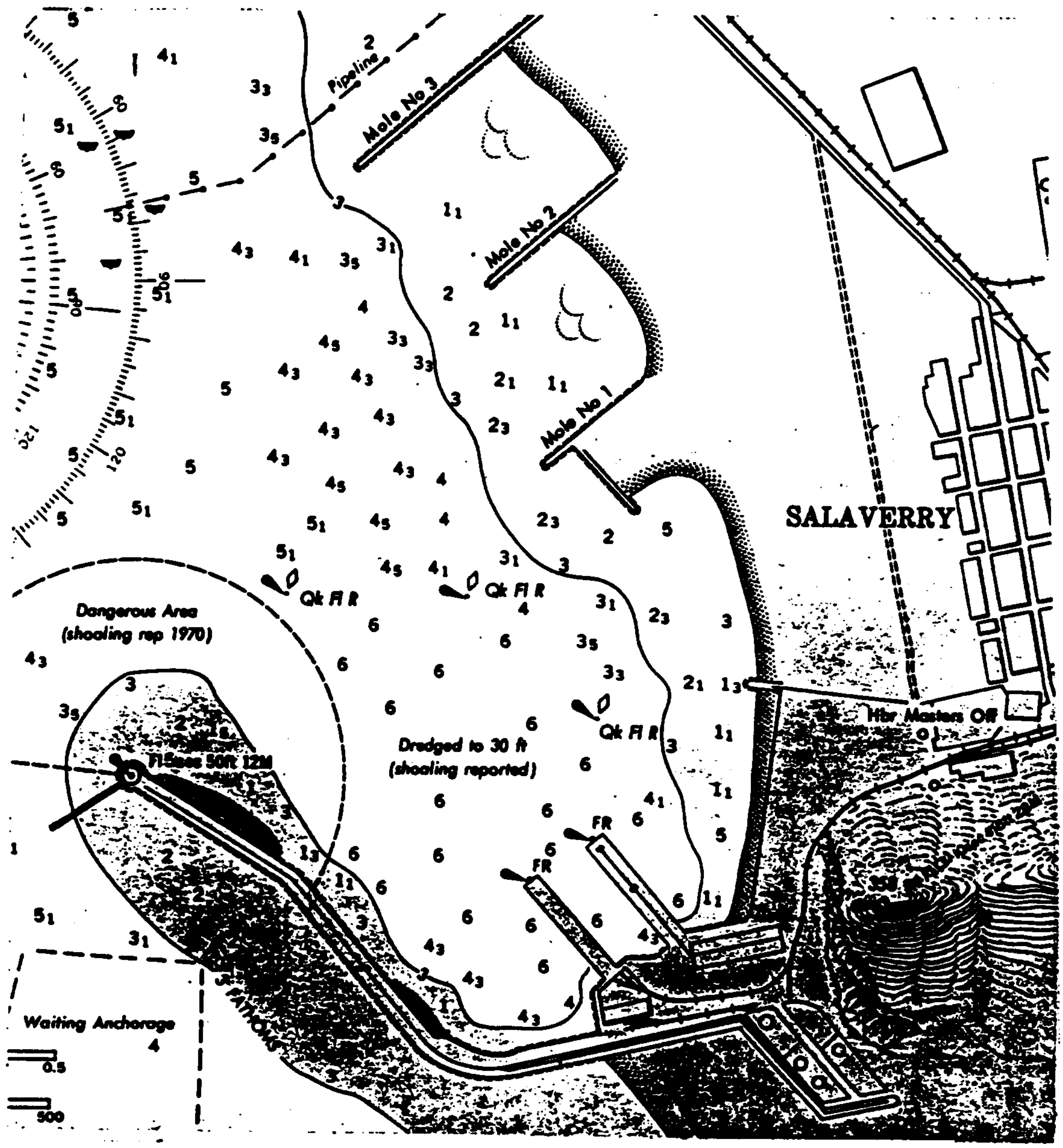


Figure 5 Runways at Huanchaco and Laredo indicating wind direction (from ONERN, 1973).



<u>Figure 6</u> Directions of dominant winds in the Lower Moche Valley.



<u>Figure 7</u> Port Salaverry showing moles retaining sand at beach (from Bancroft Library collection, University of California at Berkeley).

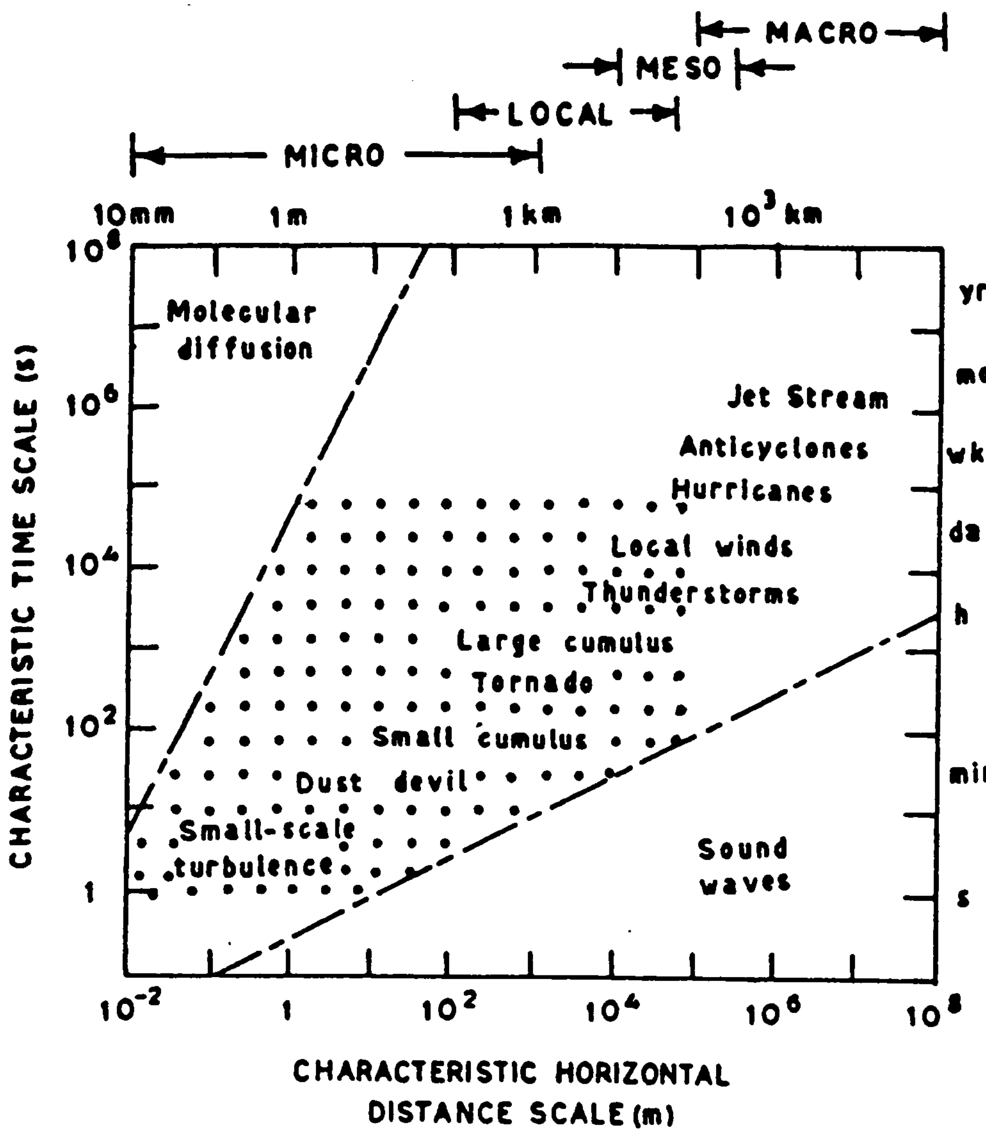
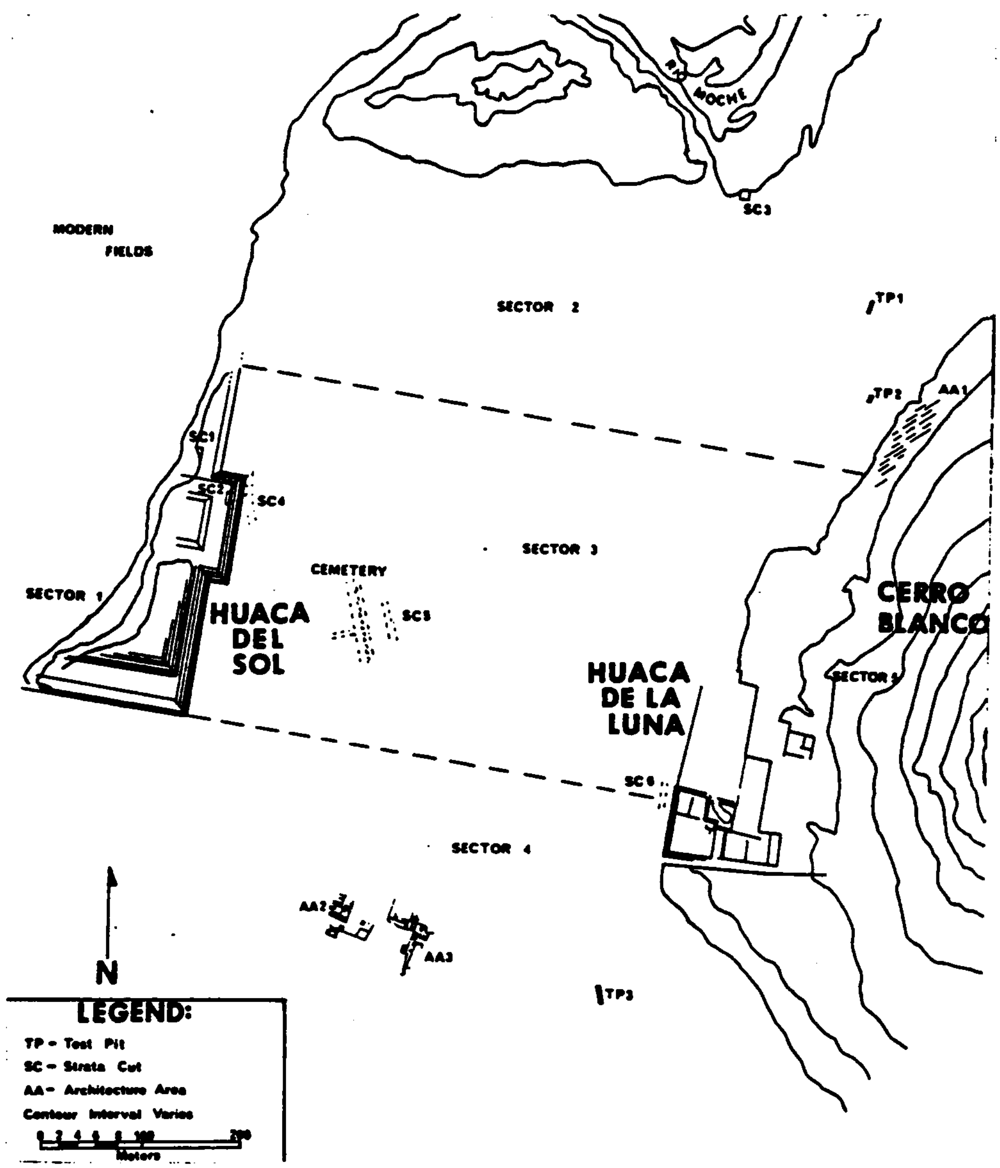


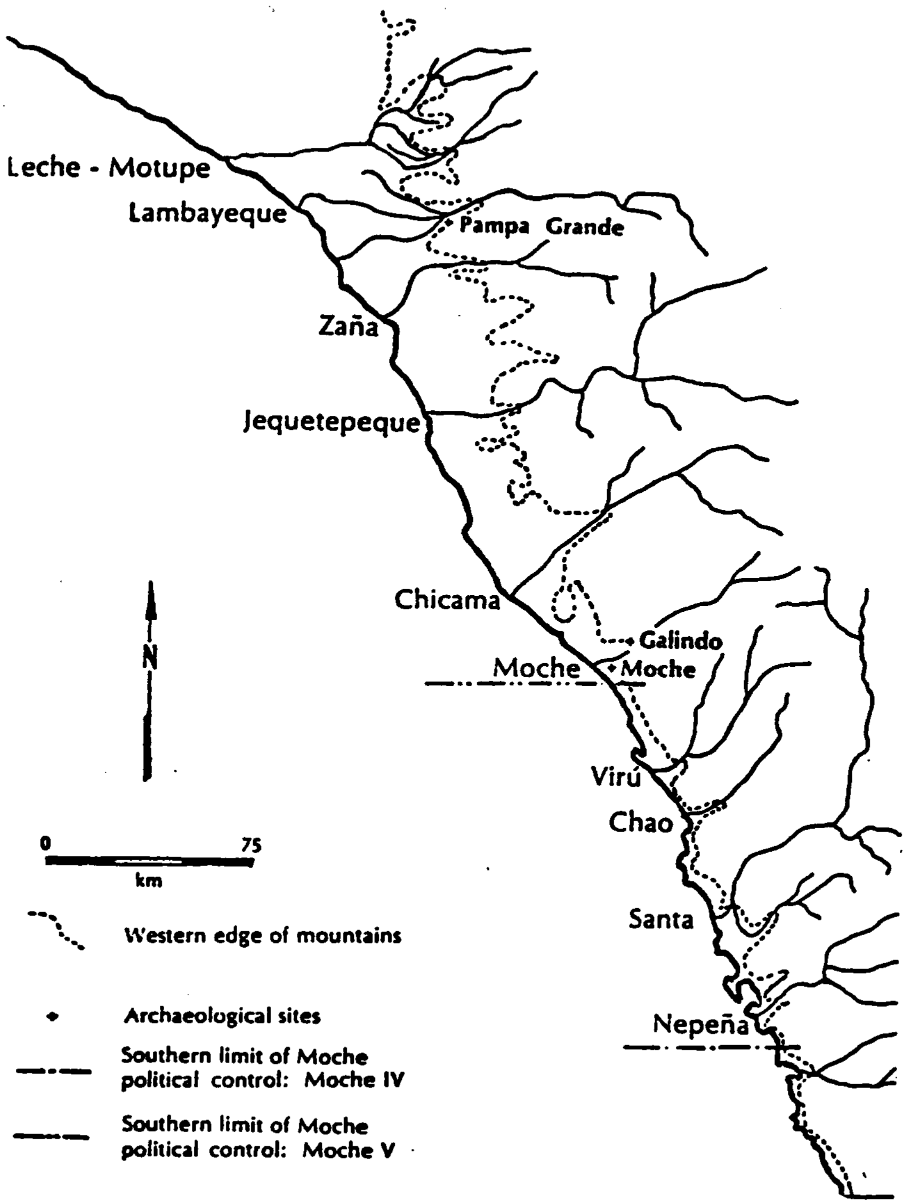
Figure 8 Scale of climates. The dotted area represents the characteristics of boundary layer features in the natural environment (from Sarma, 1987).

ABSOLUTE CHRONOLOGY	PHASE CHRONOLOGY	PALACE SEQUENCE
years A.D. 1400 - 1470	Late Chimu 2	Rivero Tschudi
1300 - 1400	Late Chimu 1	Bandelier Velarde
1150 - 1300	Middle Chimu	Squier Gran Chimu
1000 - 1150	Early Chimu 2	Laberinto Tello
900 - 1000	Early Chimu 1	Uhle Chayhuac

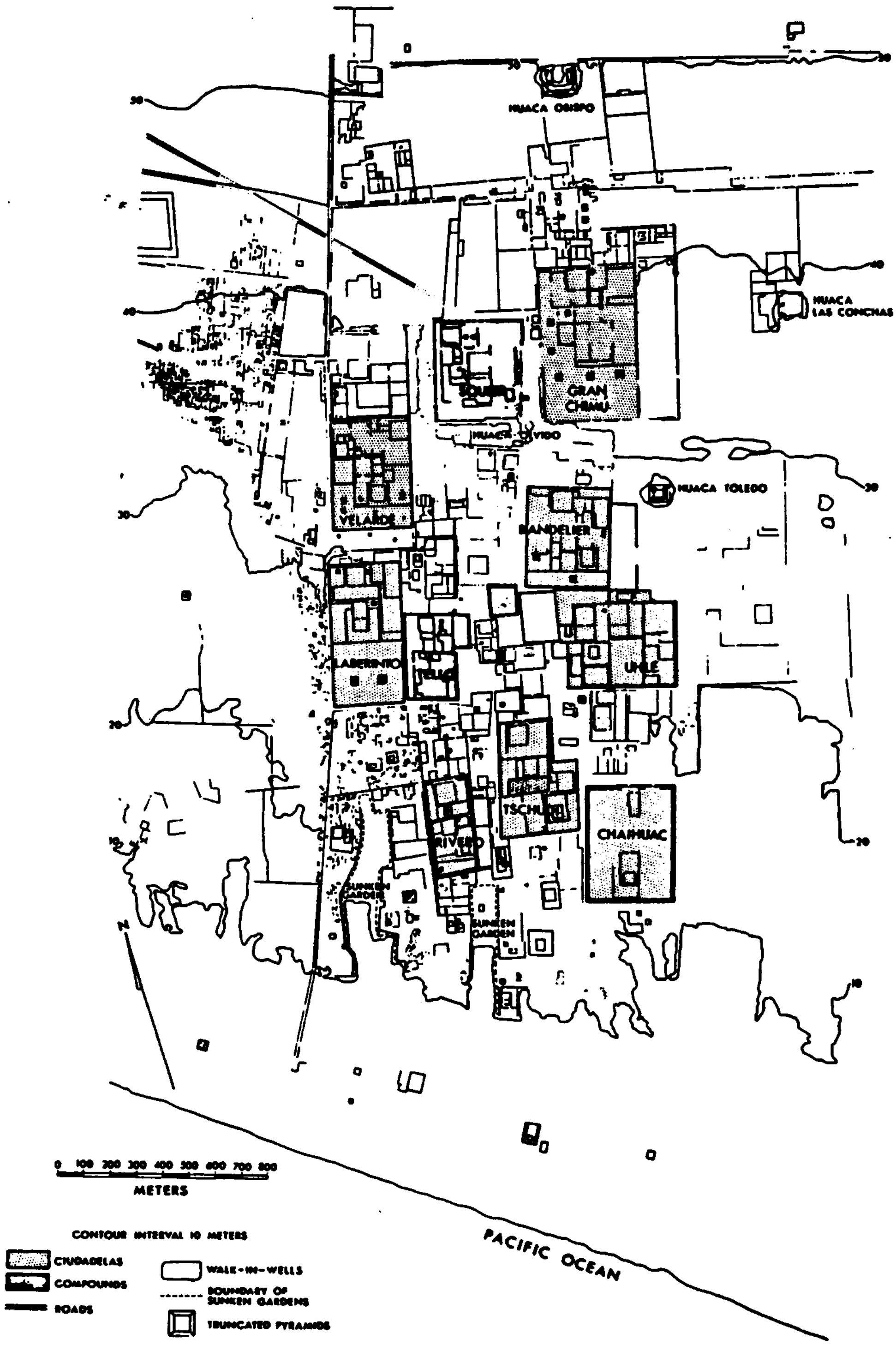
Figure 9 Chronological ordering of the citadels at Chan Chan according to Kolata (from Kolata, 1983).



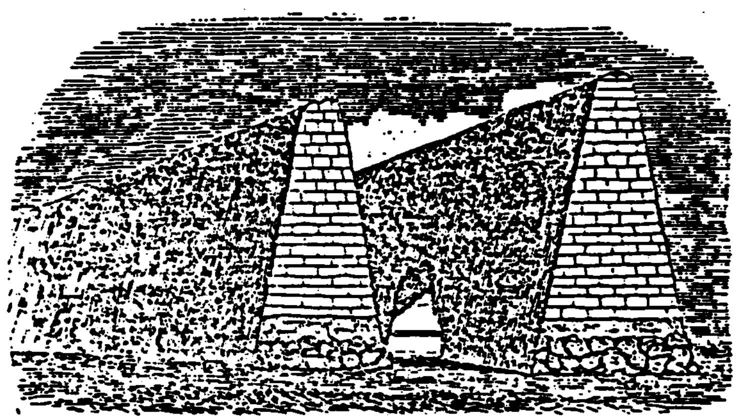
<u>Figure 10</u> Plan at Huaca del Sol and Huaca la Luna (from Topic, 1982).



<u>Figure 11</u> North Coast of Peru (from Bawden, 1983).



<u>Figure 12</u> Plan map of central or nuclear Chan Chan (from Day, 1982).



SECTIONS AND PORTIONS OF THE EDIFICES AT GRAN-CHIMU, IN THE VALLEY OF TRUXILLO.

Figure 13 Early drawing of adobe wall section at Chan Chan (from Rivero & Tschudi, 1853).

Figure 14 Oblique aerial view of Citadel Rivero (bottom) and Citadel Tschudi (top) at Chan Chan (from Moseley & Day, 1982).

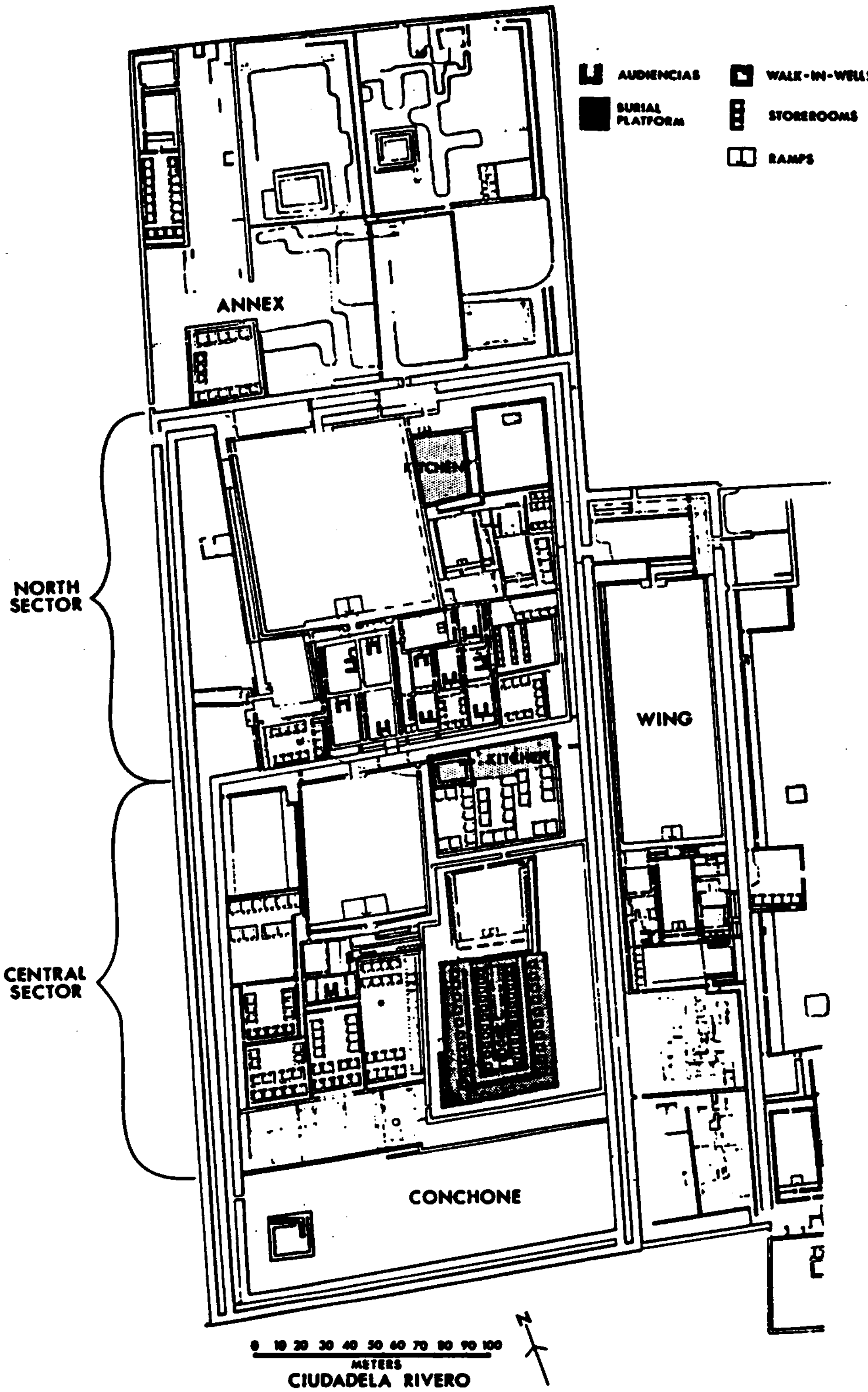


Figure 15 Plan of Rivero (from Day, 1973).

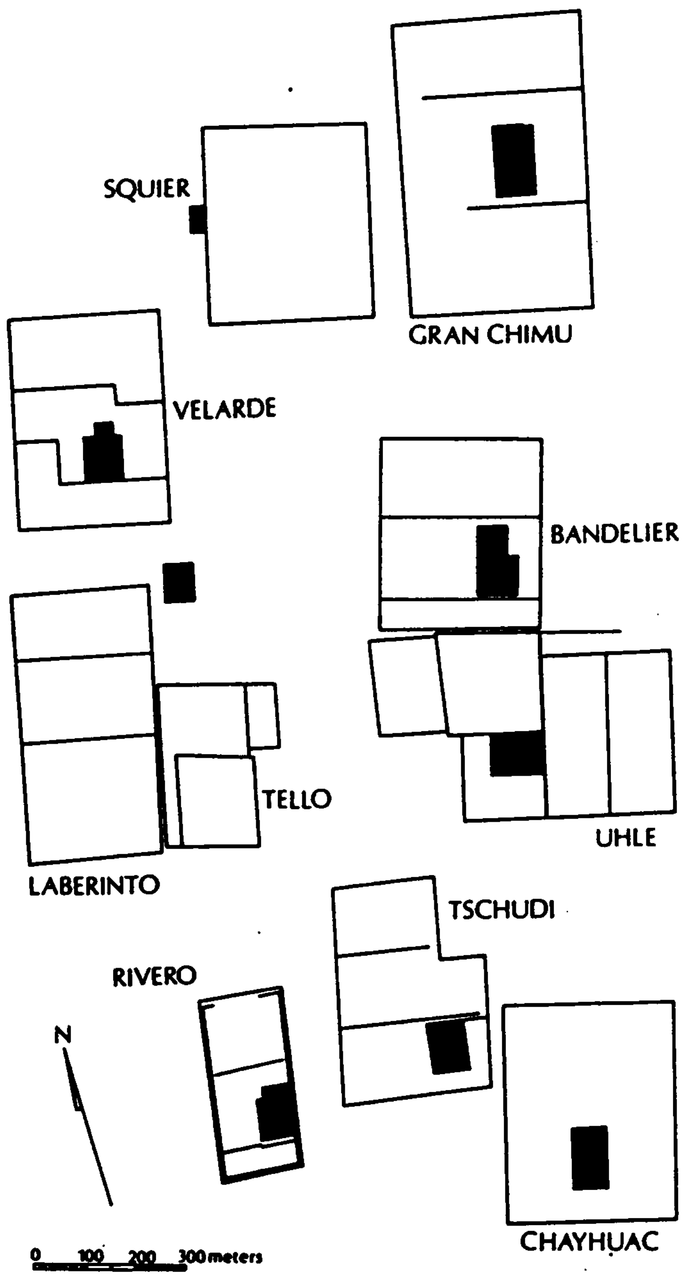
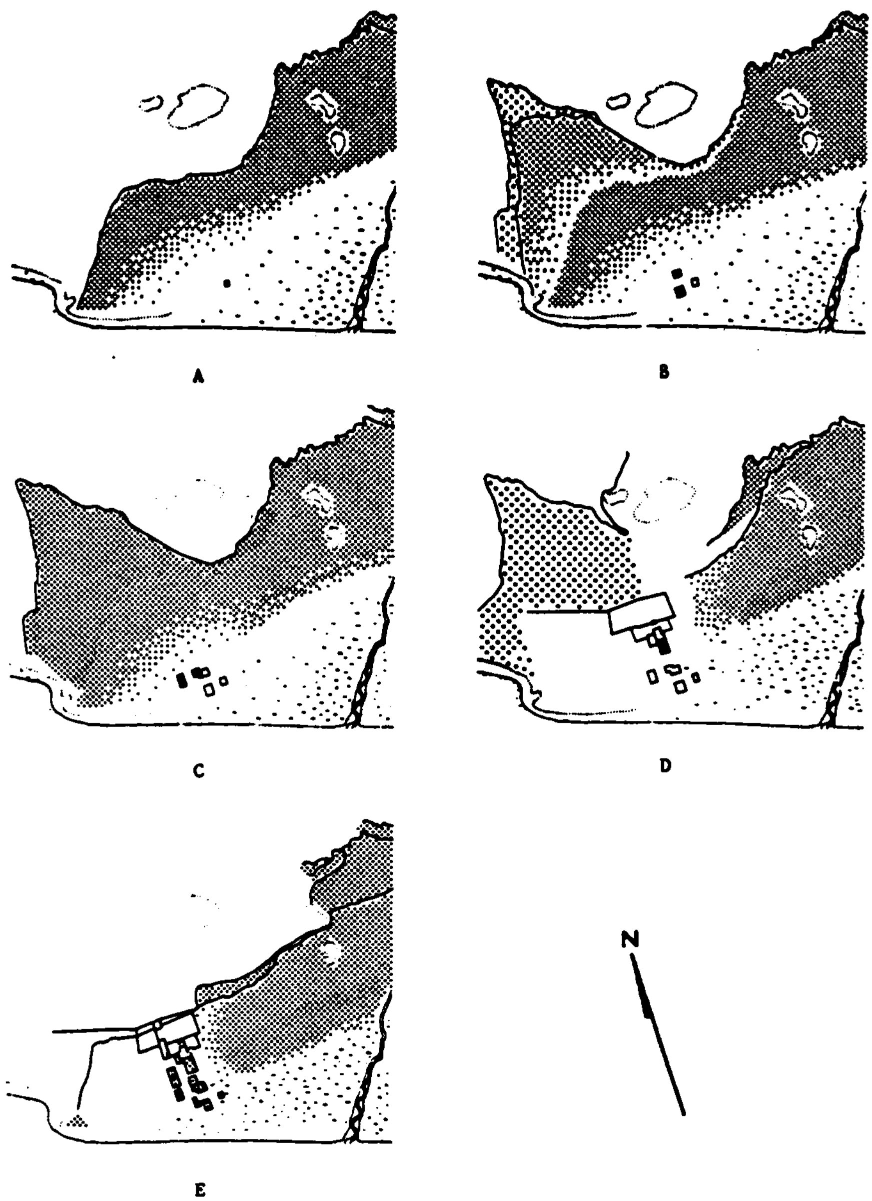


Figure 16 Simplified map of central Chan Chan showing the major walls and burial platforms (black) (from Conrad, 1982).



<u>Figure 17</u> Growth of Chan Chan. Dots represent field areas, marsh symbol represents areas of sunken gardens, and rectangles represent citadels and walled areas (from Moseley et al., 1983).

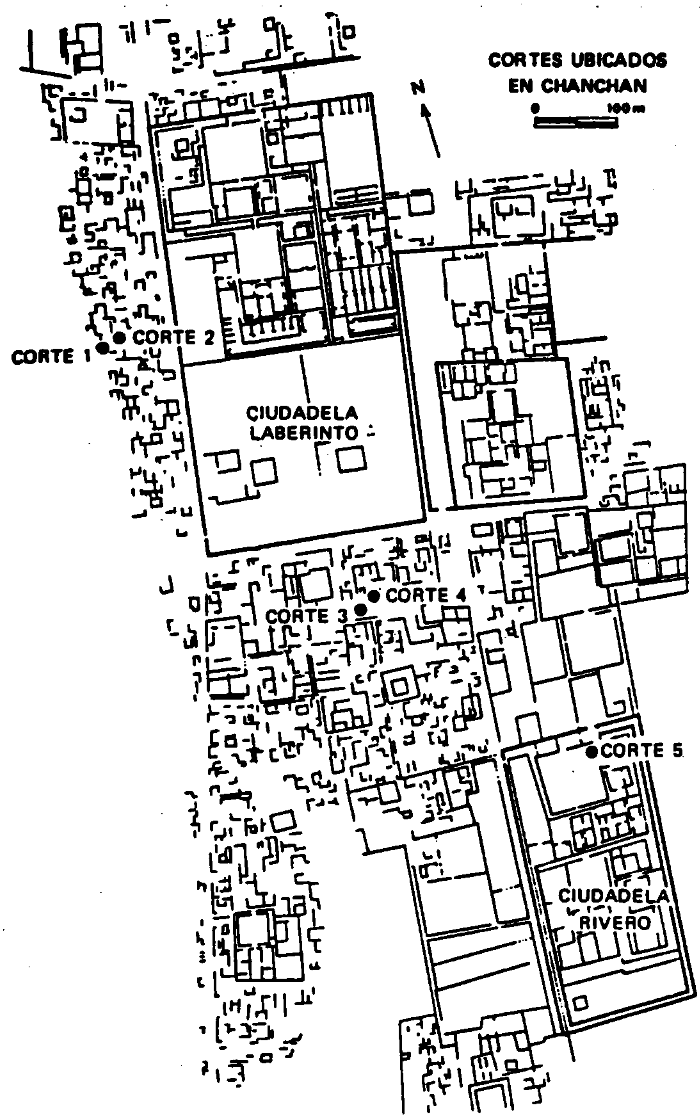


Figure 18 Plan of a section of Chan Chan showing randomly organized dwellings adjacent to citadels (from Ravines, 1980).

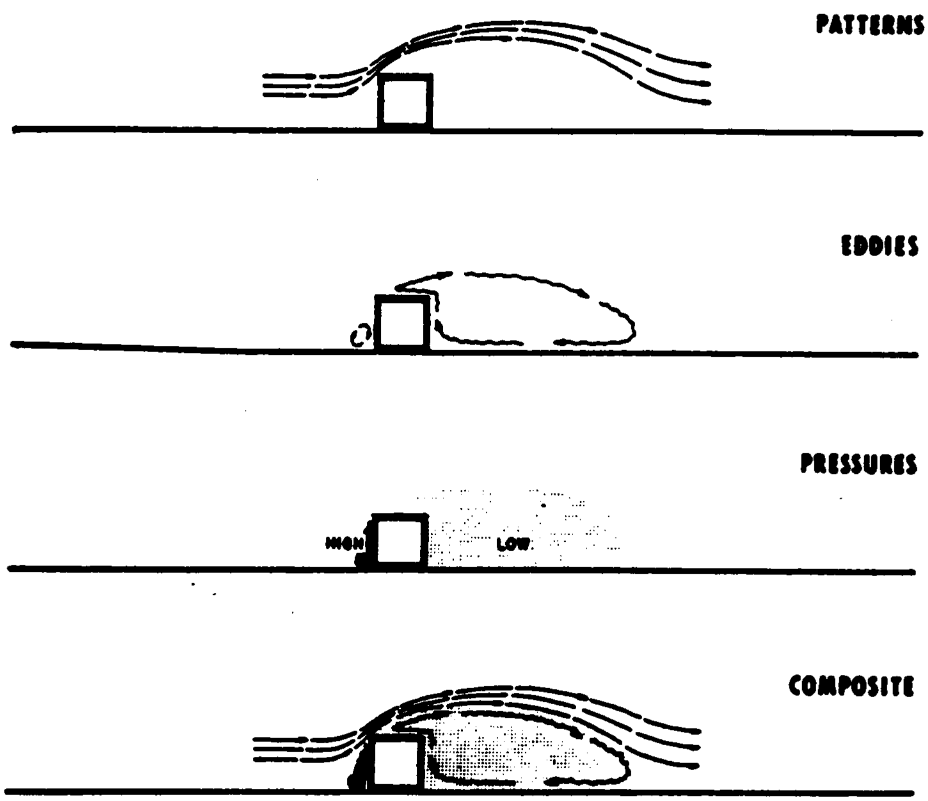


Figure 19 Elements of schematics representing airflow characteristics (from Evans, 1954).

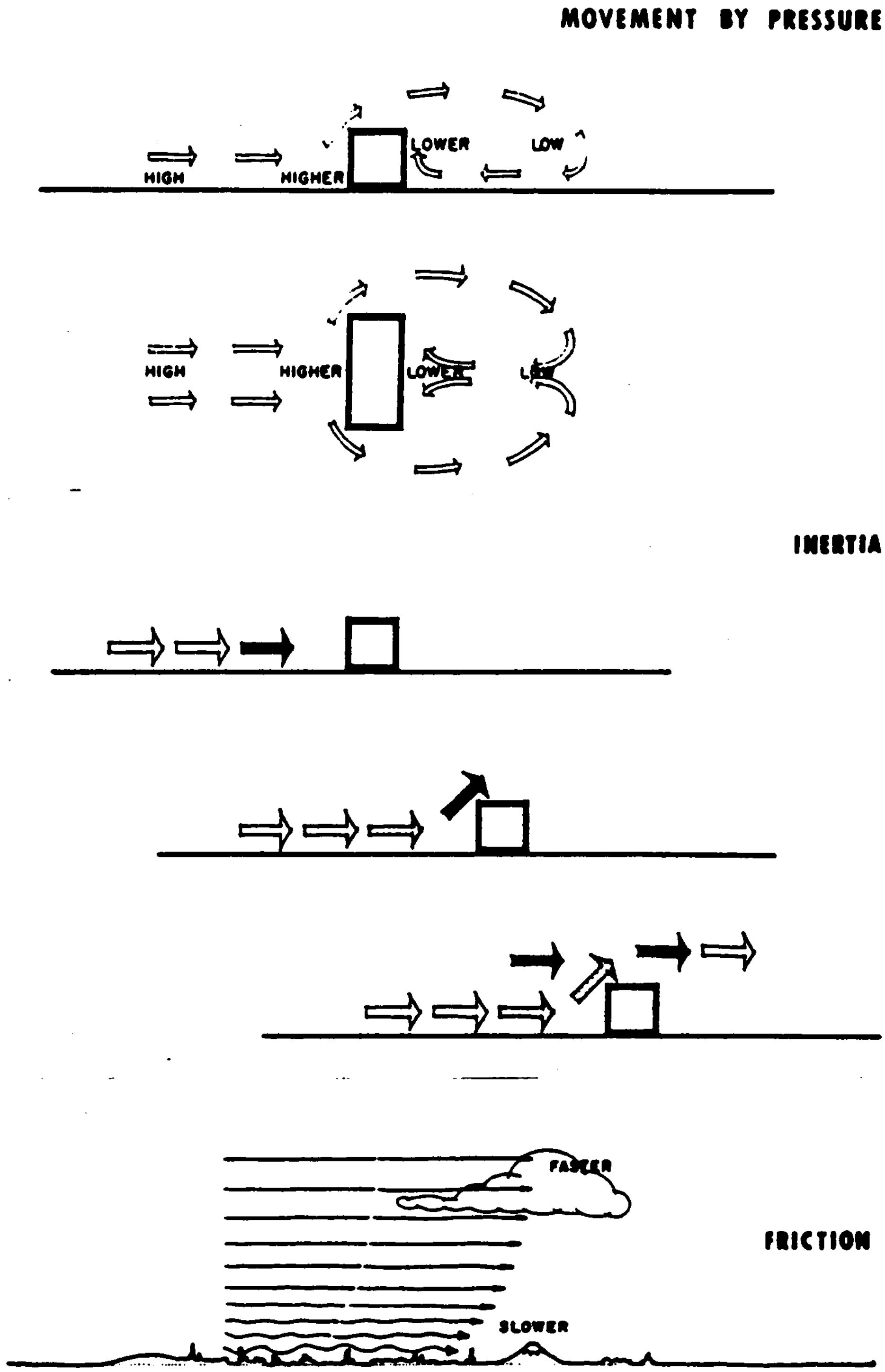


__Figure 20__ Major principles governing airflow (from Evans, 1954).

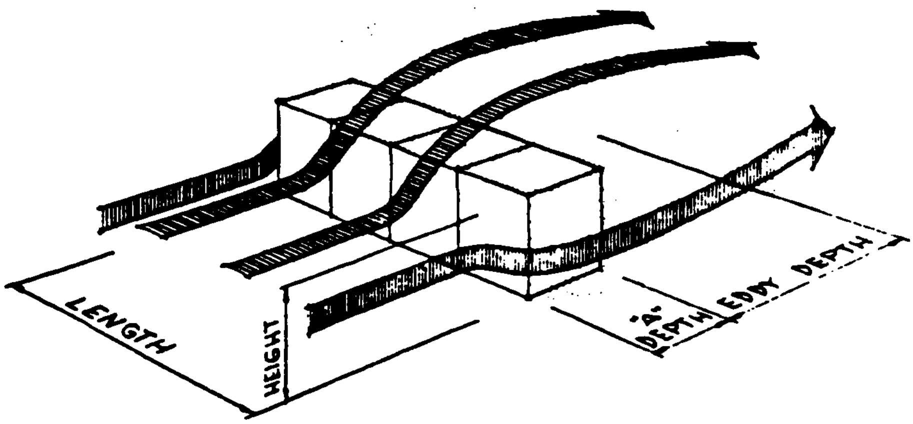


Figure 21 Basic dimensions of airflow schematics (from Evans, 1954).

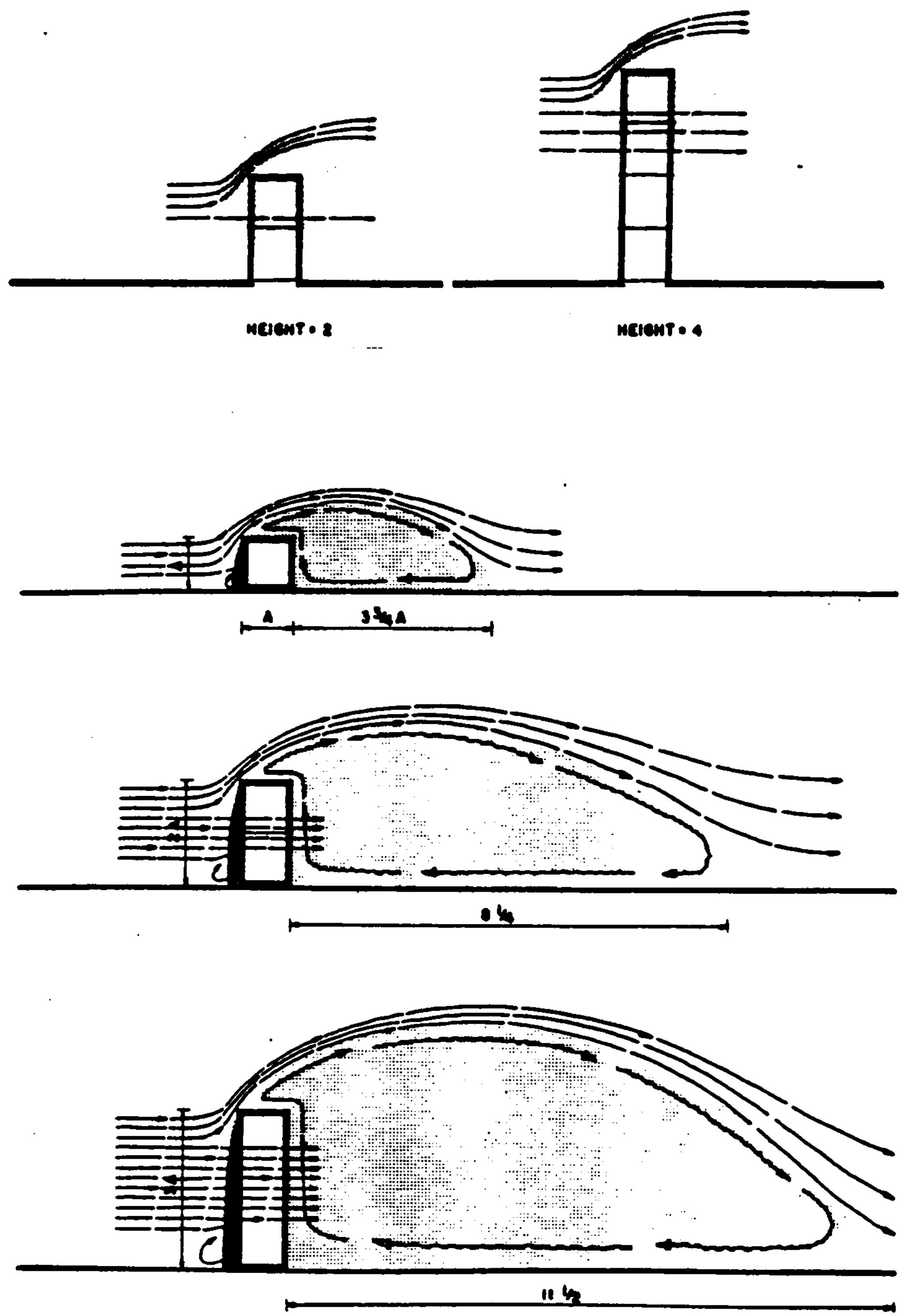


__Figure 22__ Consistent pattern over top of building (above) and change in downwind pattern with change in height (below) (from Evans, 1954).

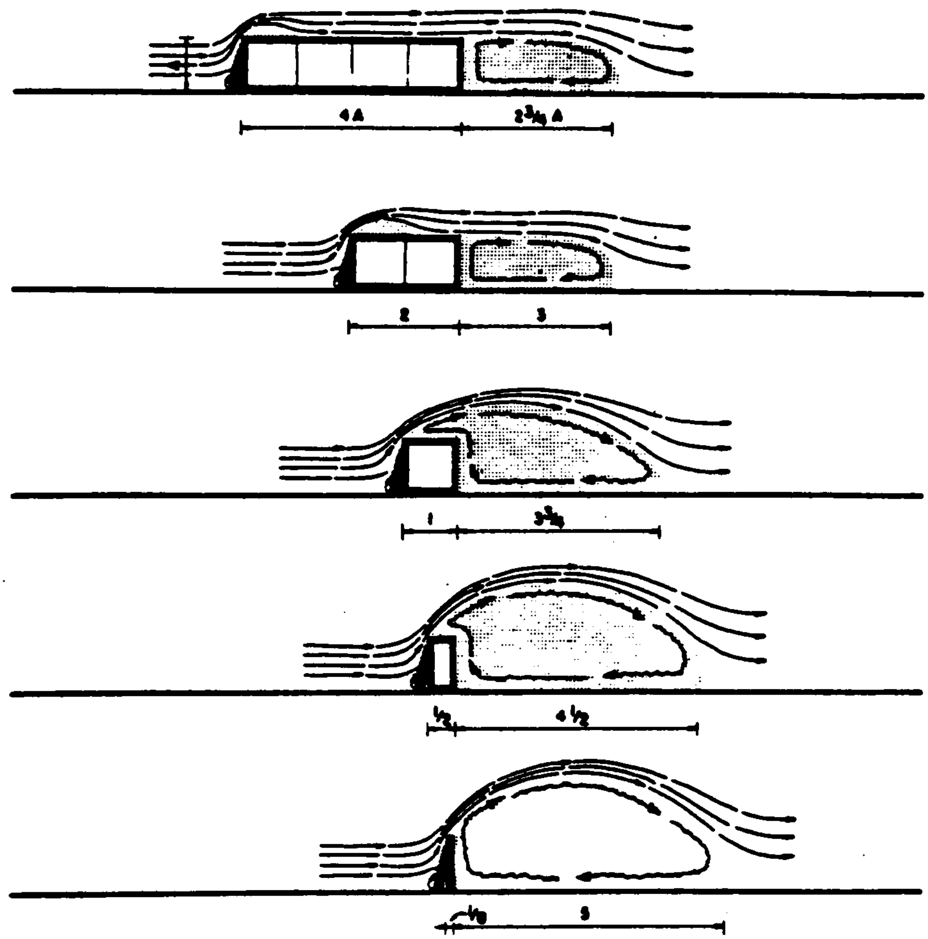
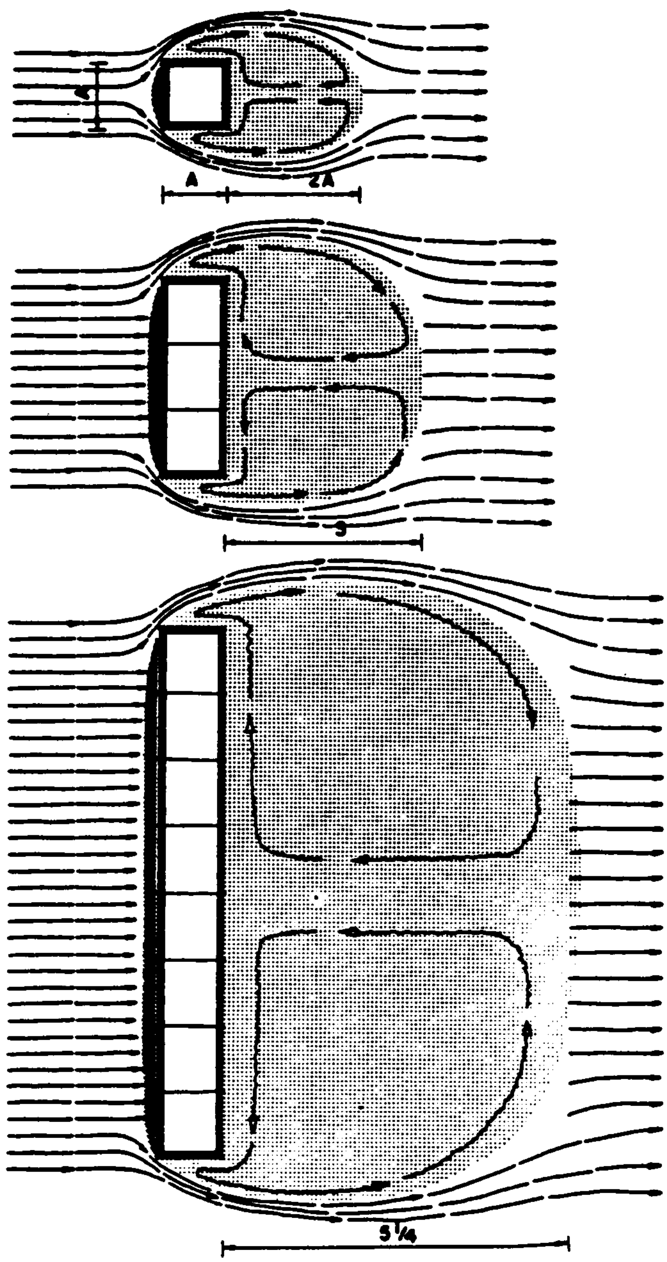


Figure 23 Change in downwind pattern with change in depth of building. The thinner obstruction gives the greatest increase (from Evans, 1954).



<u>Figure 24</u> Change in downwind pattern with change in width of building (from Evans, 1954).

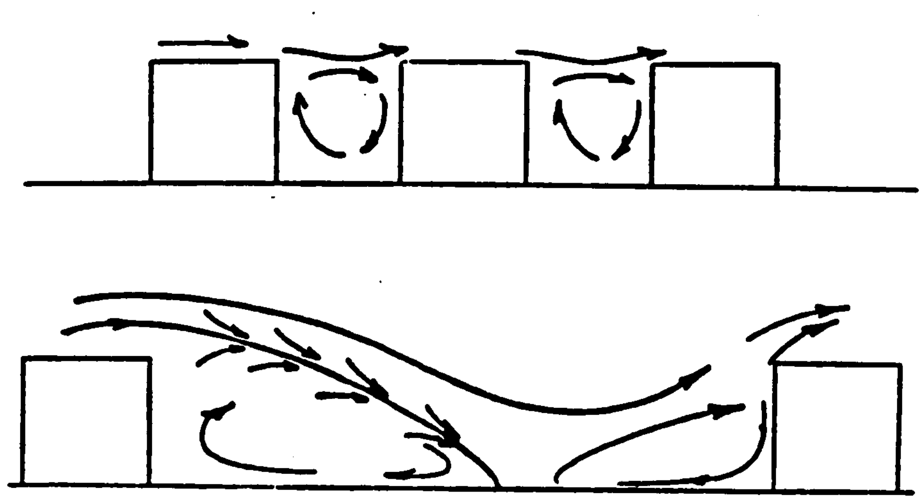


Figure 25 Airflow normal to rows of buildings (from Lawson, 1980).

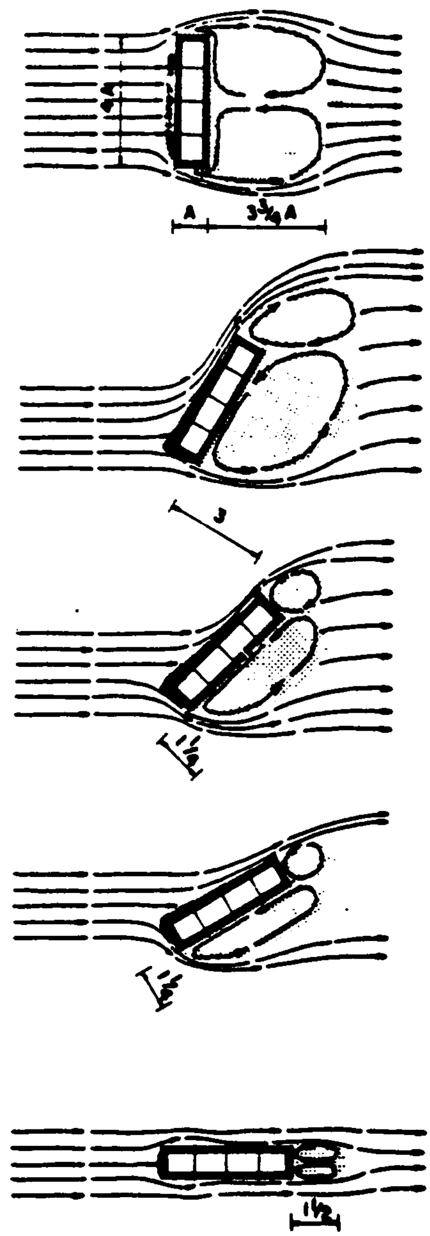
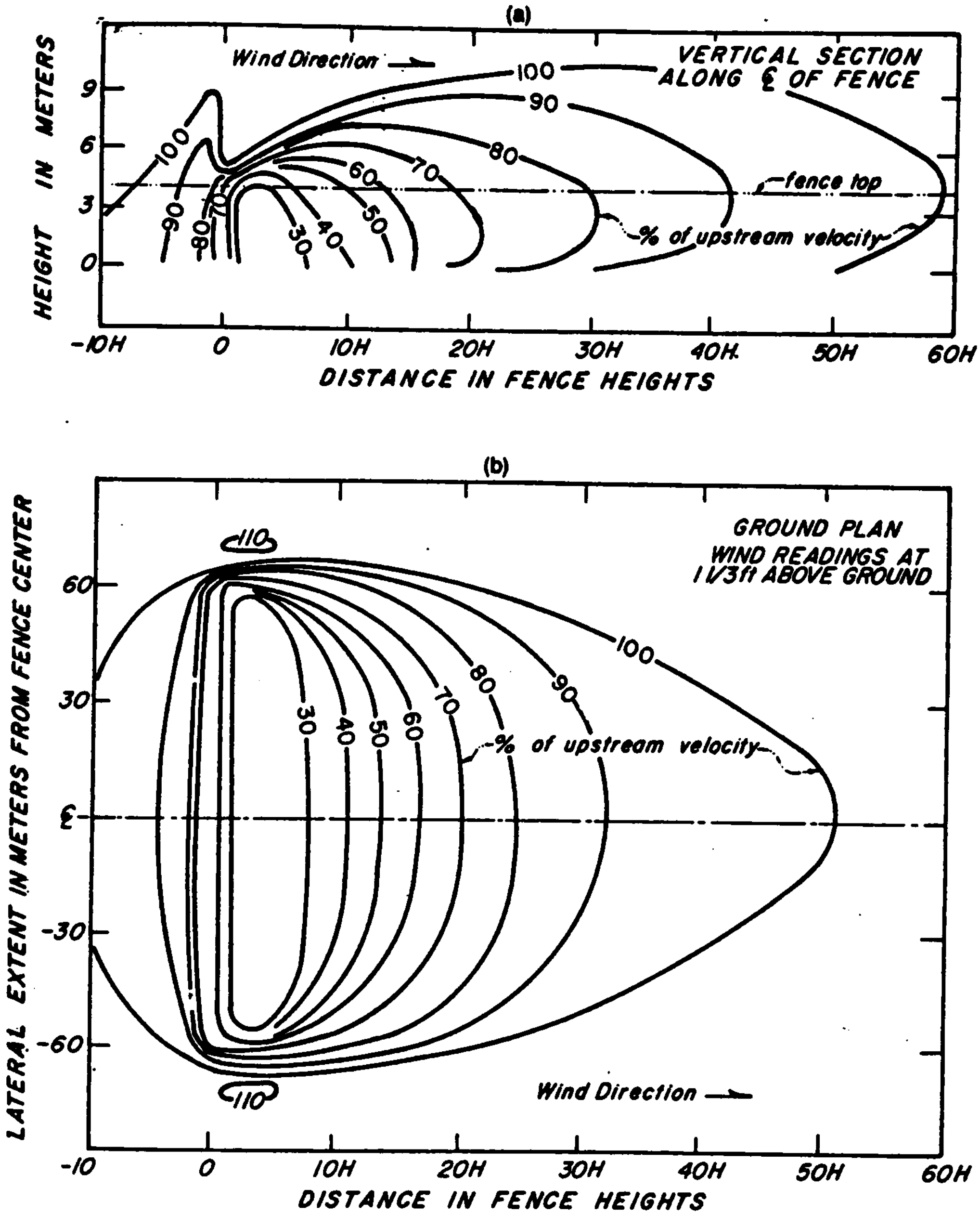
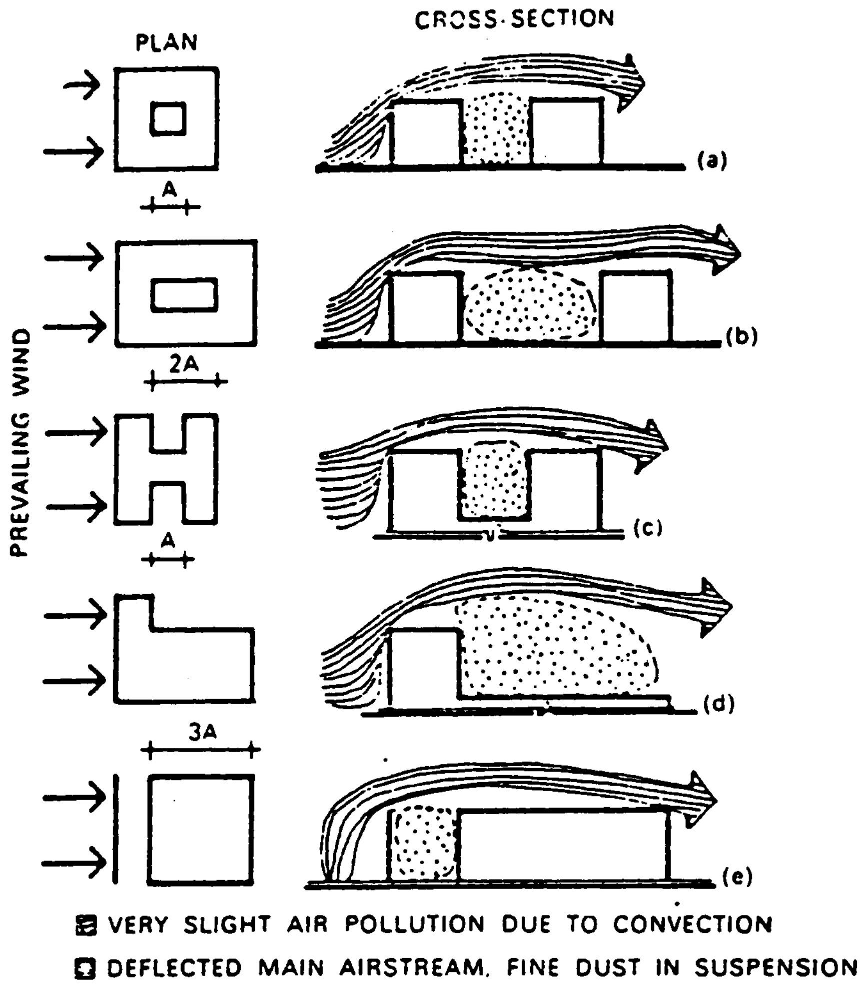


Figure 26 Change in downwind pattern with change of angle of incidence of building to wind (from Evans, 1954).

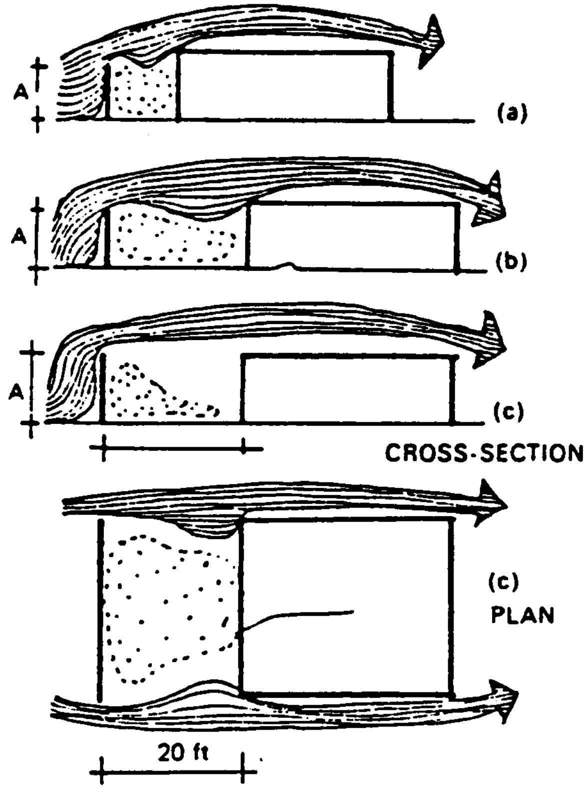


<u>Figure 27</u> Wind velocity patterns above a mown field with a windscreen. Side view profile (a), plan view profile (b) (from Hesketh & Cross, 1983).



Air pollution in courtyards: (a) *Central square court giving protection from sand and most of the wind-borne dust; orientation unimportant.* (b) *Central rectangular court giving good protection for depth up to 3A; for depths exceeding 3A the building should have long axis perpendicular to the wind direction. (c) Perimeter square court gives protection as in* (a) *against overhead dust but eddy whirls caused by sideslip will allow dust to enter from the sides; depth of courts limited to 3A; both receive same protection.* (d) *Perimeter rectangular court provides some protection to maximum depth 3A but would be better situated on lee side of building.* (e) *Fully exposed space requires a barrier to provide protection from overhead dust and side swirls; protection is function of length and height of barrier and distance from face of building.*

Figure 28 Patterns of sand and dust pollution in courtyards (from Saini, 1980).



Barrier screens: (a) *Portion of dust stream enters sheltered space if barrier is less than A.* (b) *Amount of dust entering sheltered space increases as distance of screen from building face increases.* (c) *Little dust enters sheltered space if barrier height A is equal to height of building and distance does not exceed 20 ft.*

Figure 29 Protection from sand and dust by barrier screens (from Saini, 1980).

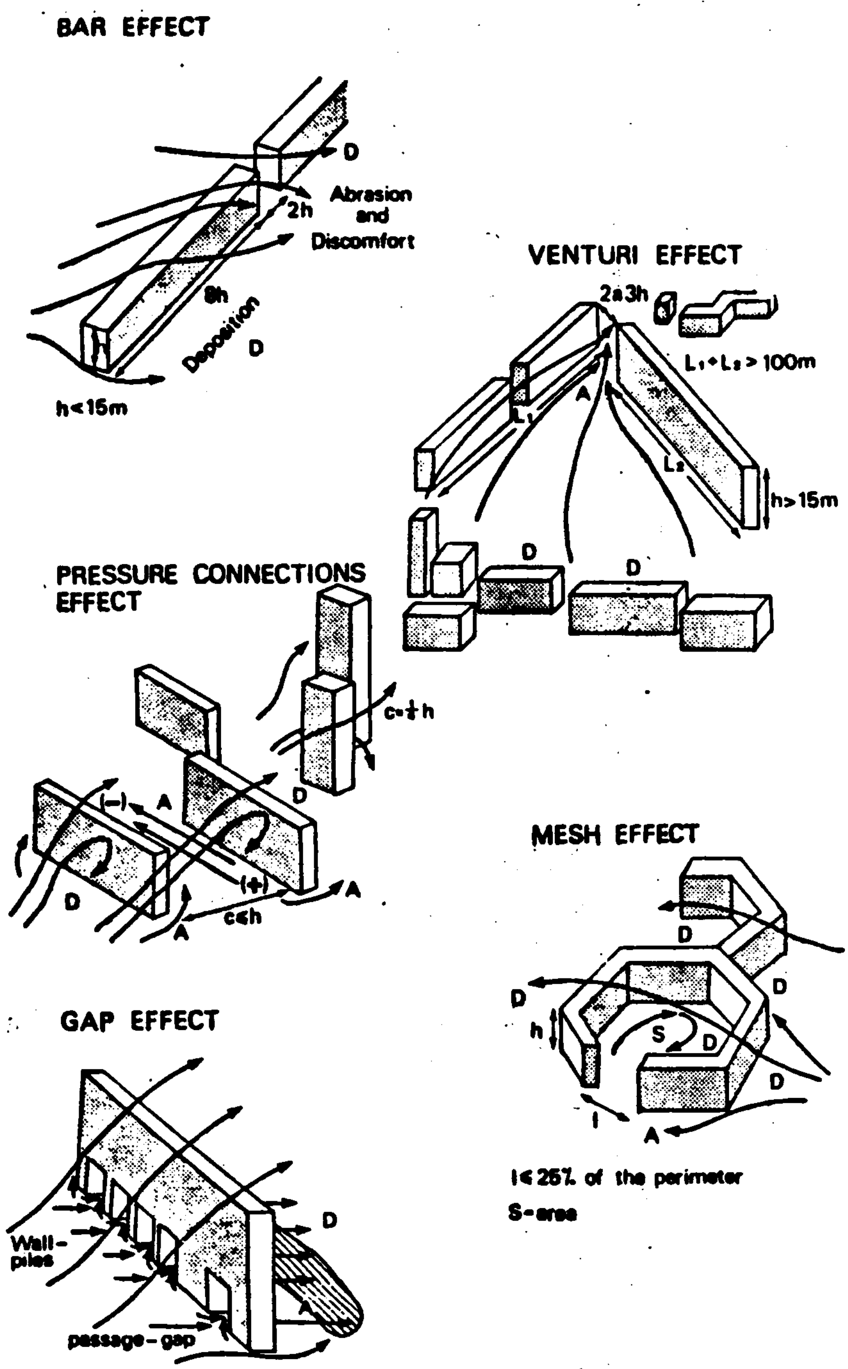


Figure 30 Effects of building arrangements on deposit of sand (D) and flying sand and dust (A), (from Cooke et al., 1982, modified from Gandemer, 1978).

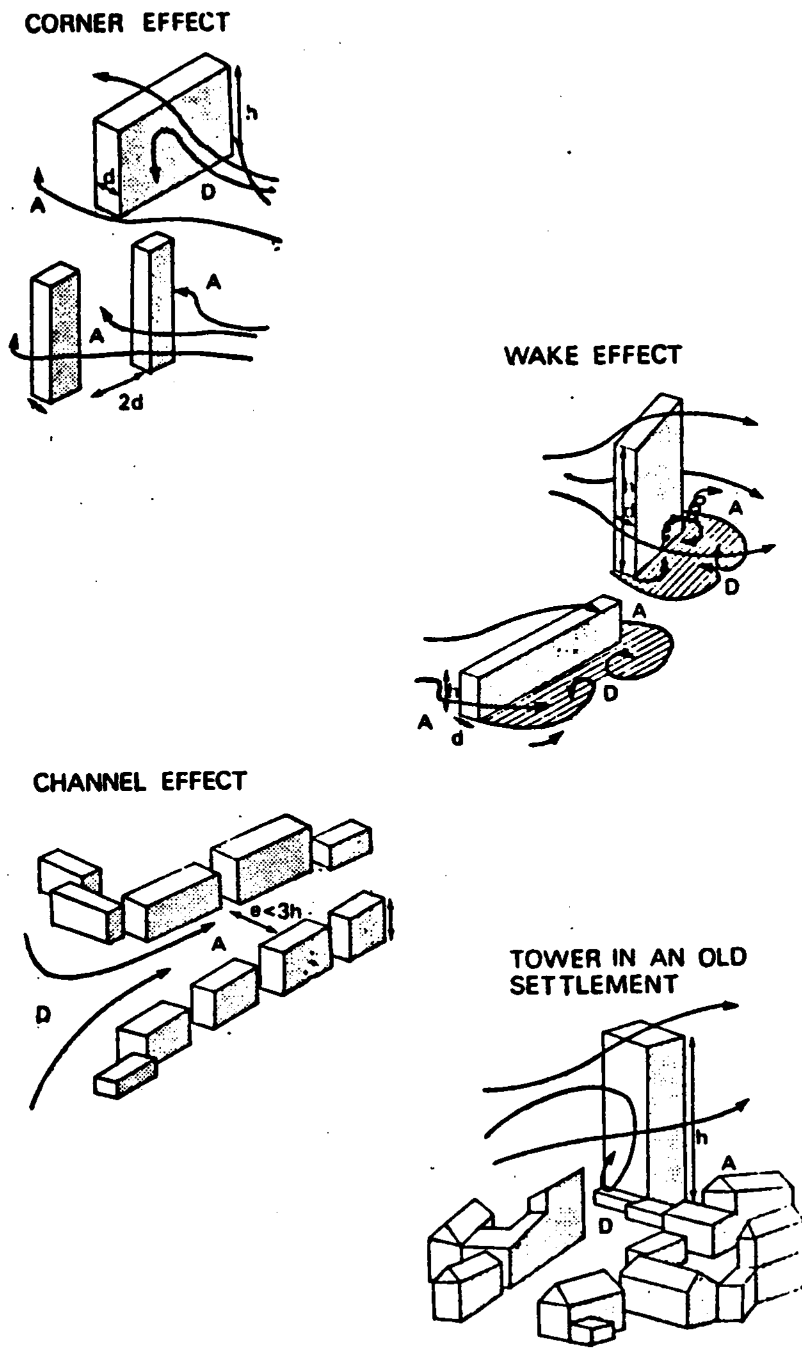
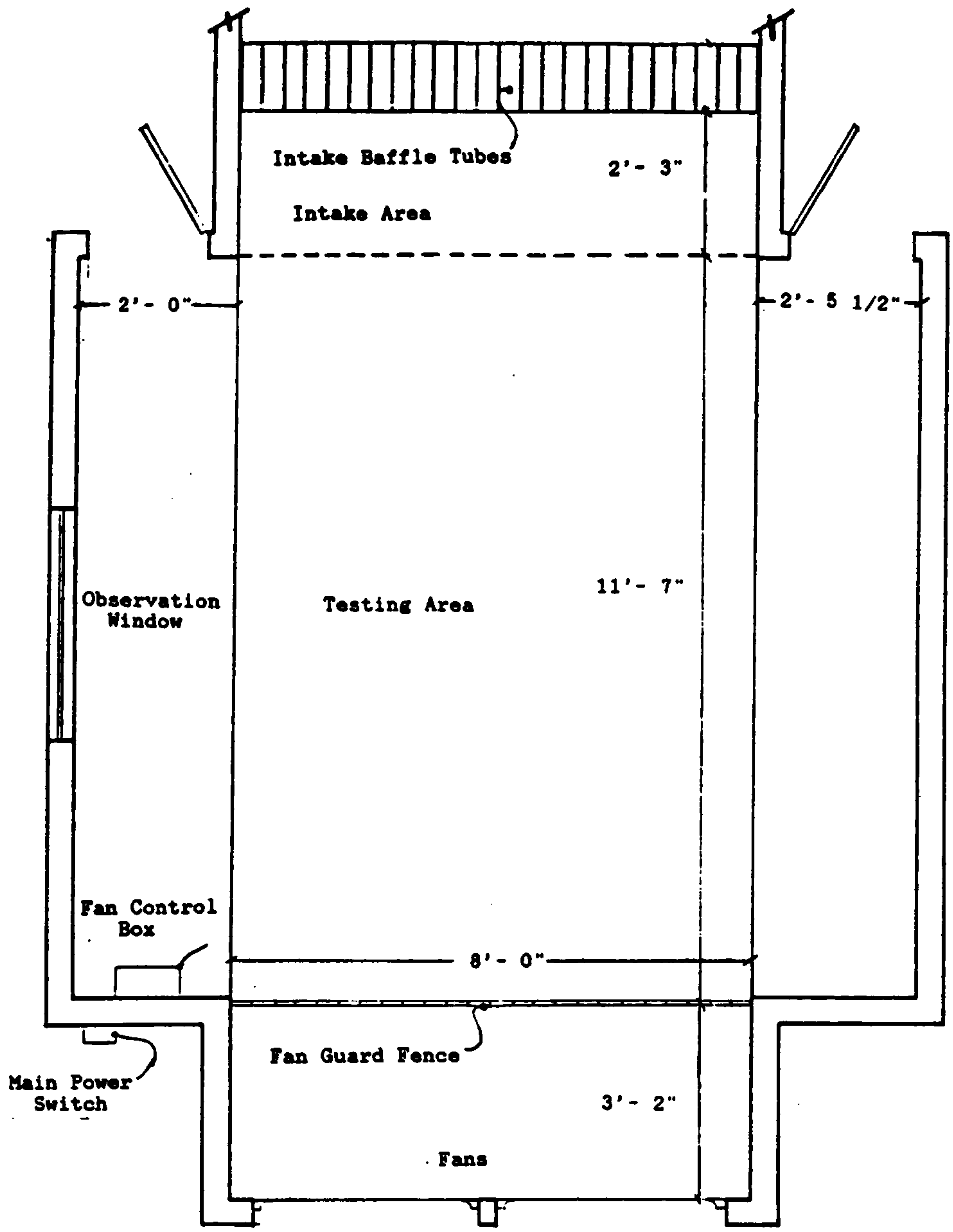


Figure 31 Effects of building arrangements on deposit of sand (D) and flying sand and dust (A), (from Cooke et al., 1982, modified from Gandemer, 1978).



<u>Figure 32</u> Plan of wind tunnel (from Tucker, 1985).

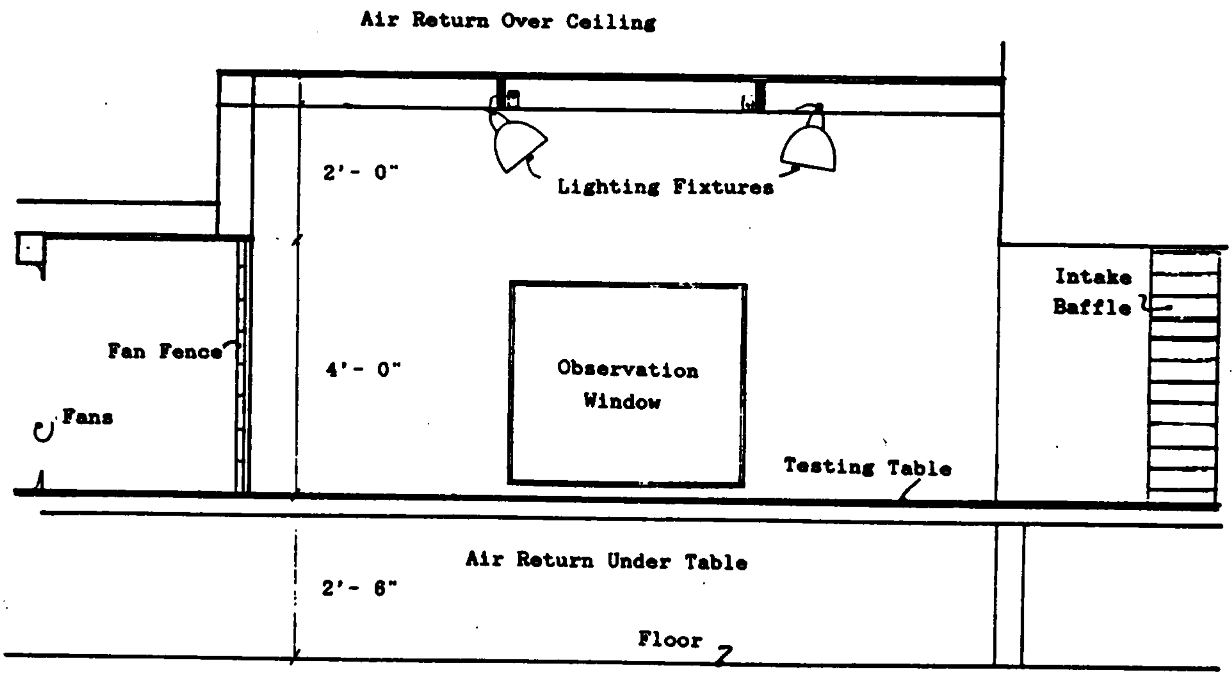
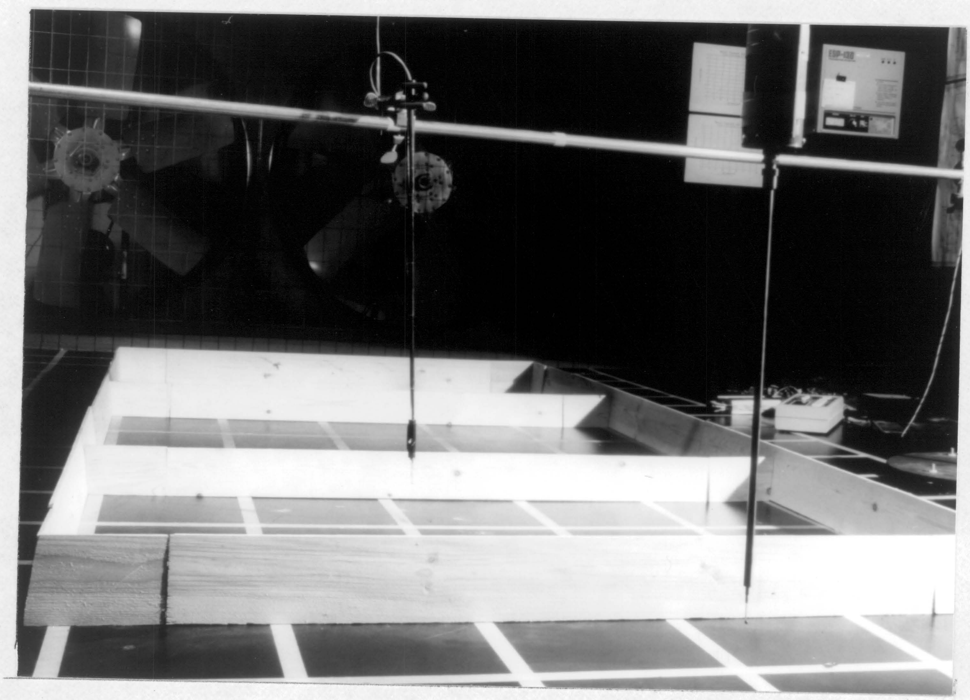


Figure 33 Side view of wind tunnel (from Tucker, 1985).



<u>Figure 34</u> Photograph of wind tunnel floor, full citadel model with internal walls, wind from the south. Upwind reference Probe 1 is in the foreground and data Probe 4 is inside the model in the background.

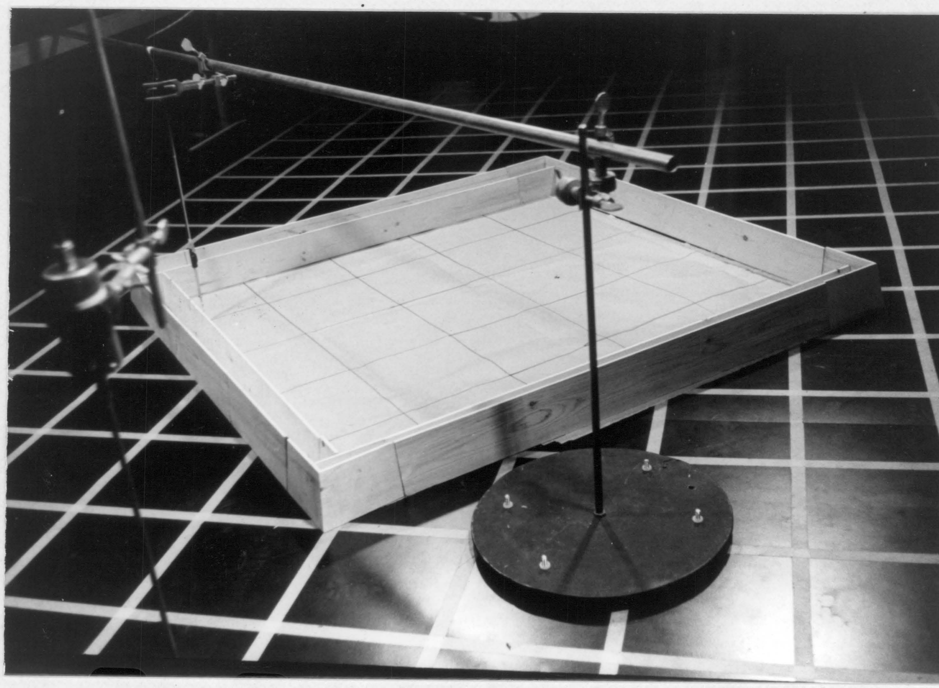


Figure 35 Photograph of wind tunnel floor, double walled single sector model, wind from the SE. Upwind reference Probe 1 is in the left foreground and data Probe 4 is inside the model in the left midground.

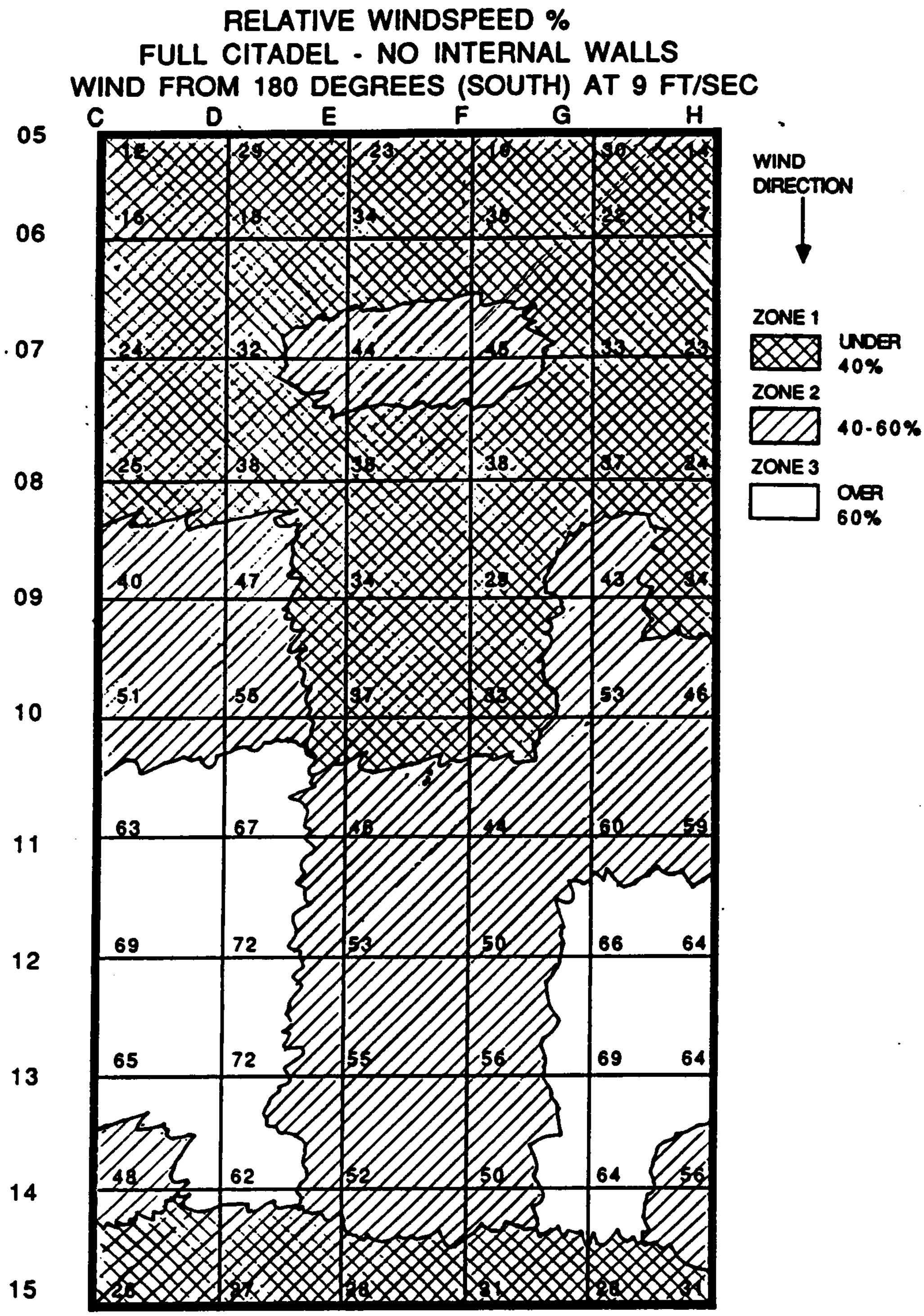
TABLE 1

EFFECTS OF A VARIATION IN UPWIND SPEED
FULL CITADEL, WITH INTERNAL WALLS, WIND FROM SOUTH

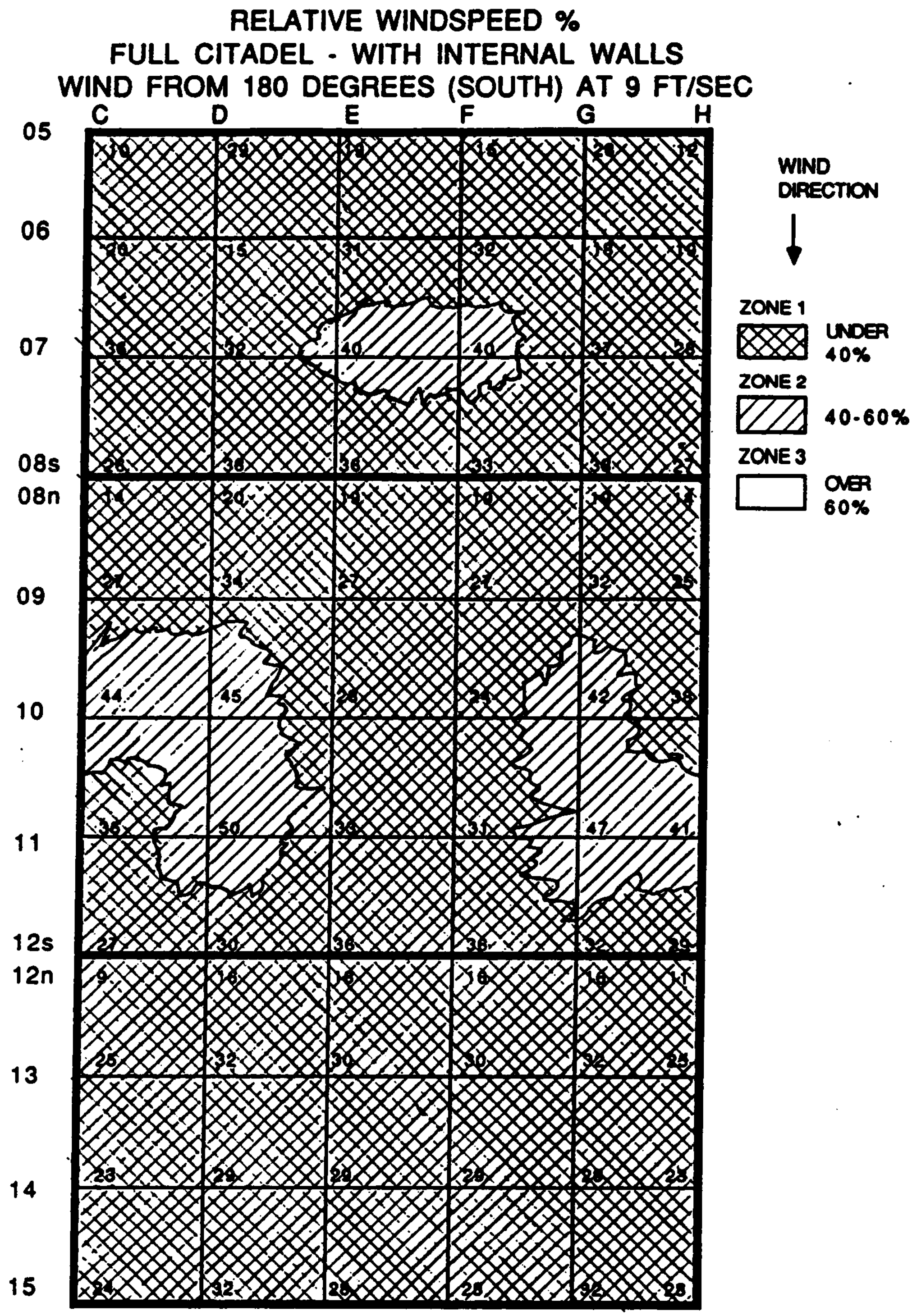
Experiment #1, variation in relative wind speed (%) that occurs at selected locations inside citadel model when the upwind speed is changed.

	COL. E			COL. F			COL. G		
ROW	50Hz	60Hz	80Hz	50Hz	60Hz	80Hz	50Hz	60Hz	80Hz
6	30	30	30	30	30	31	18	20	21
7	43	44	45	40	41	43	38	38	39
9	26	27	29	27	27	28	32	33	34
10	26	27	28	26	27	29	42	43	45
11	30	30	31	31	33	34	45	48	49
13	29	30	32	29	30	33	32	33	35
14	29	31	32	29	31	33	31	32	34

<u>Note.</u> Citadel walls normal to the wind are at rows 5, 8, 12, and 15.



<u>Figure 36</u> Experiment #2, distribution of relative wind speeds at pedestrian level by zones.



<u>Figure 37</u> Experiment #3, distribution of relative wind speeds at pedestrian level by zones.

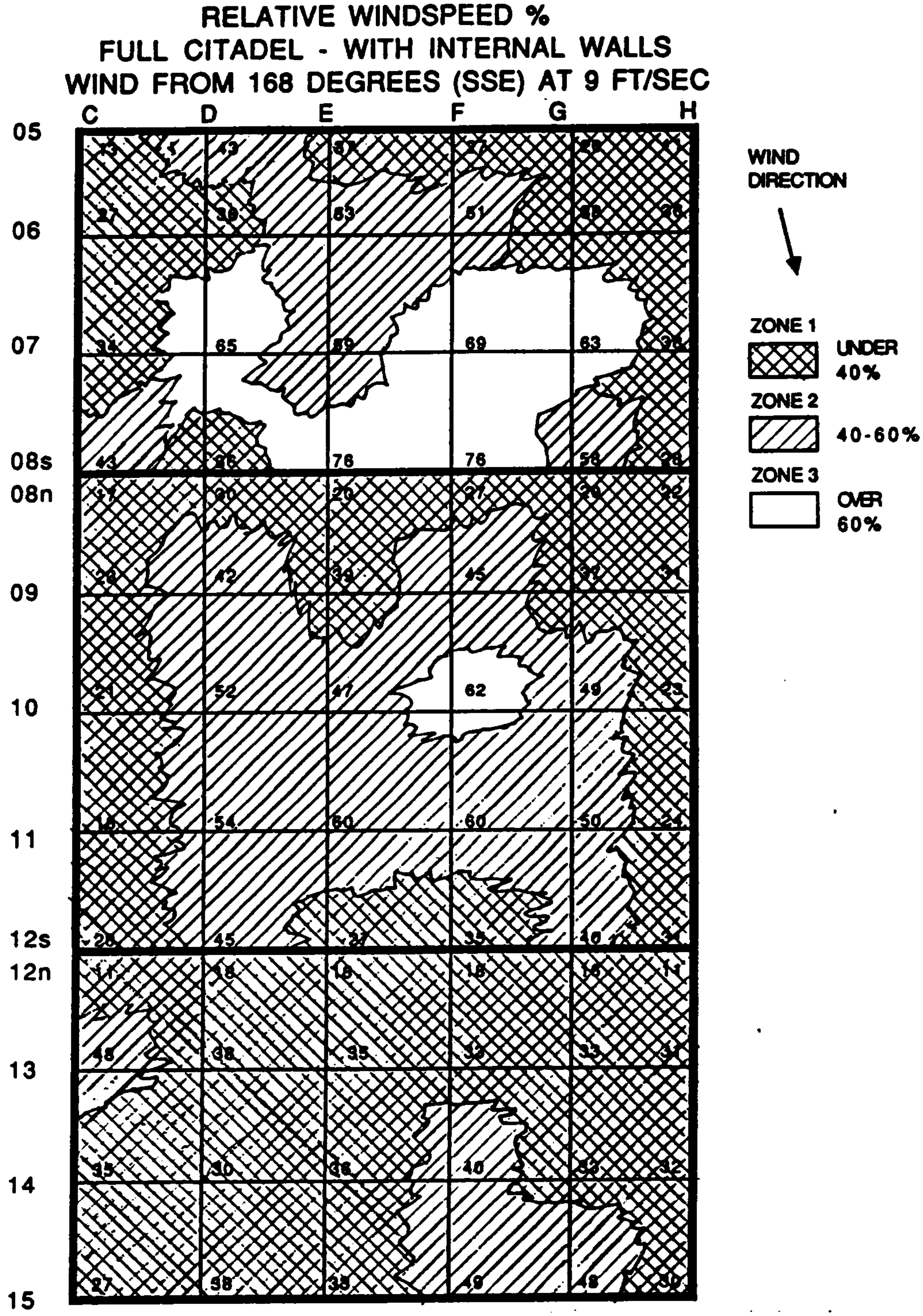
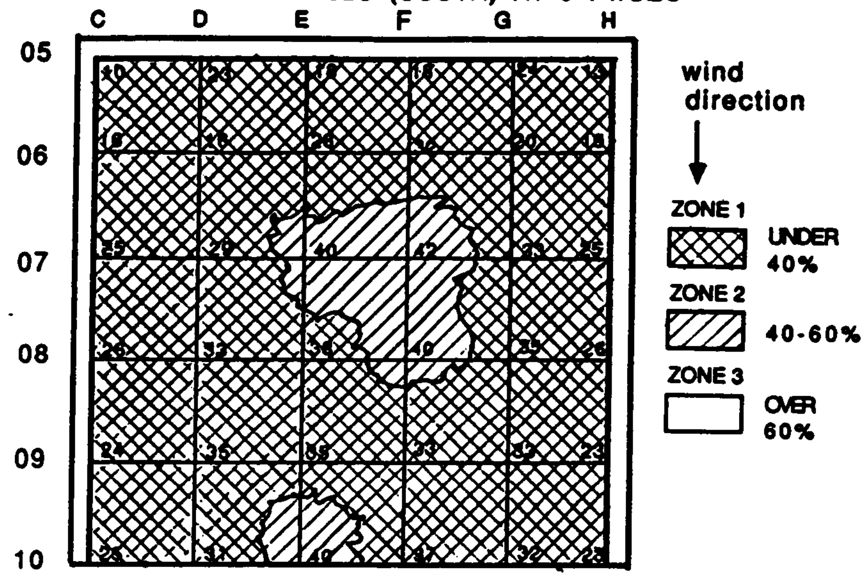
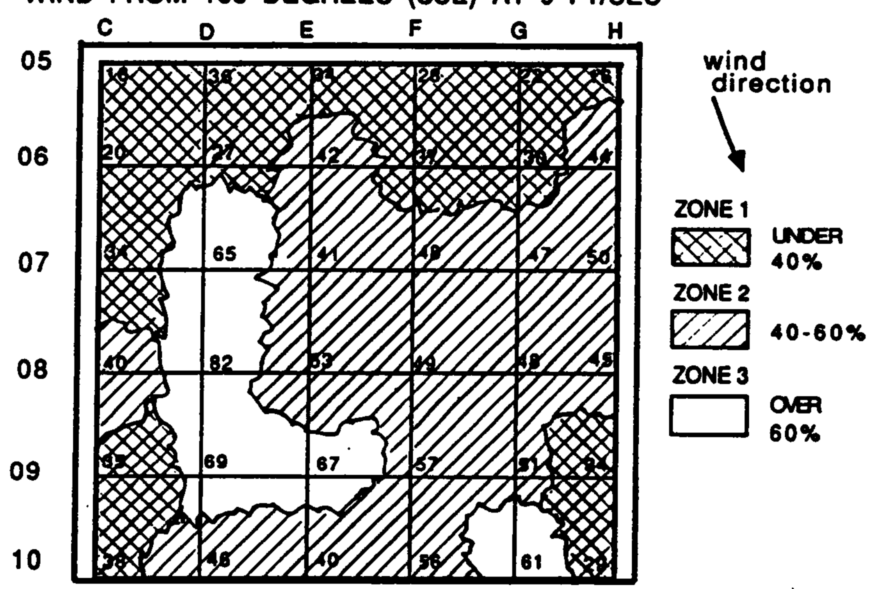


Figure 38 Experiment #4, distribution of relative wind speeds at pedestrian level by zones.

RELATIVE WINDSPEED %
ONE SECTOR - DOUBLE WALL ON 3 SIDES
WIND FROM 180 DEGREES (SOUTH) AT 9 FT/SEC



RELATIVE WINDSPEED %
ONE SECTOR - DOUBLE WALL ON 3 SIDES
WIND FROM 168 DEGREES (SSE) AT 9 FT/SEC



<u>Figure 39</u> Experiment #5 (above) and Experiment #6 (below), distribution of relative wind speeds at pedestrian level by zones.

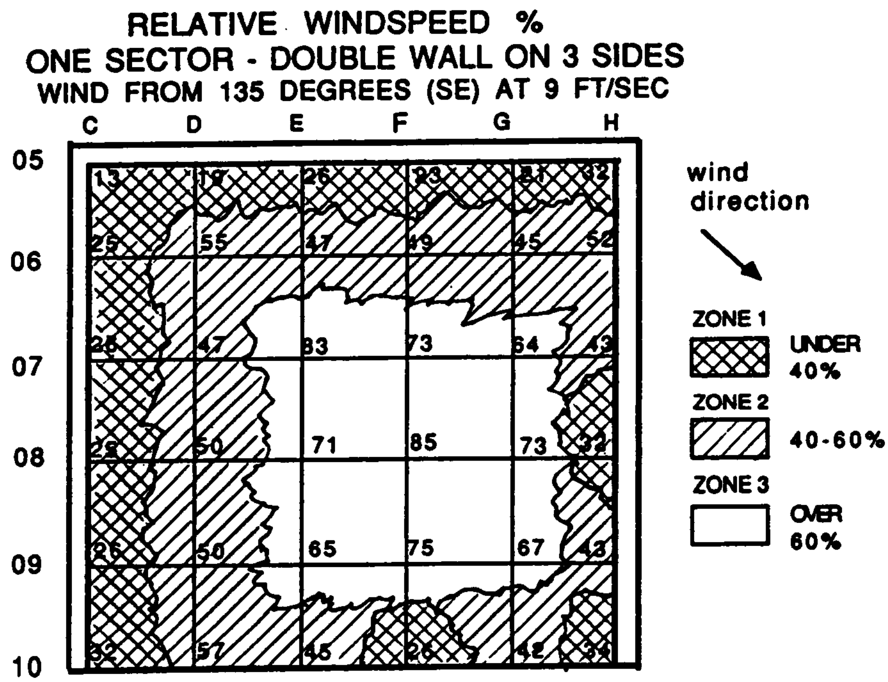
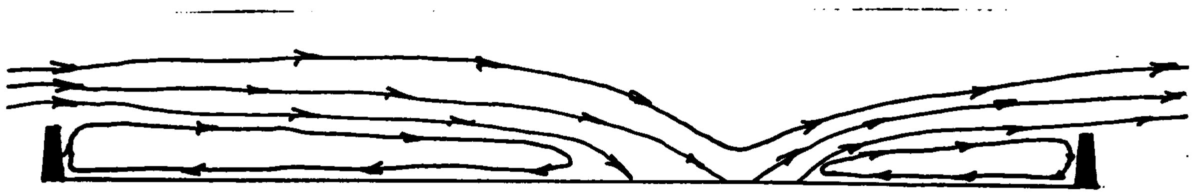
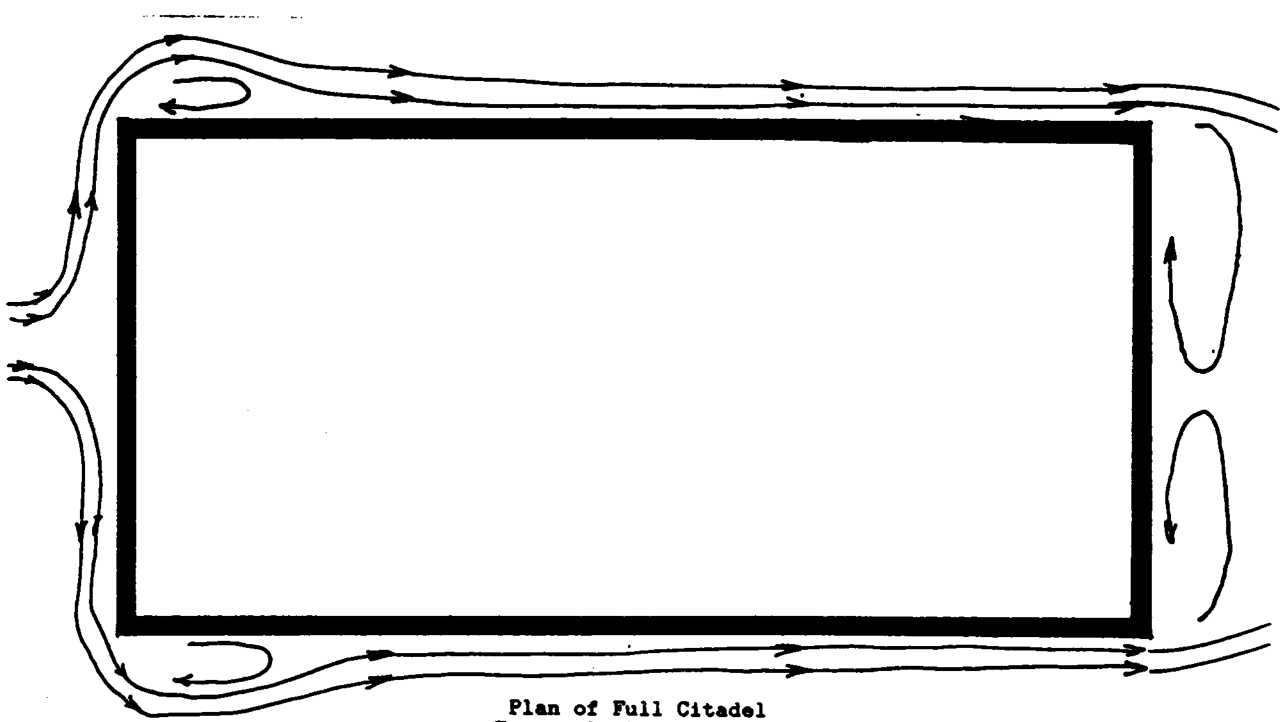


Figure 40 Experiment #7, distribution of relative wind speeds at pedestrian level by zones.



Section of Full Citadel, No Internal Walls
Internal Flow Pattern

Section of Full Citadel, With Internal Walls
Internal Flow Pattern



Plan of Full Citadel
External Flow Pattern

Figure 41 Schematics developed from the smoke and telltale airflow patterns generated in Experiments #8 and #9 (not to scale).

TABLE 2

DISTRIBUTION OF ZONES (%)

FULL CITADEL MODEL

Experiment #2, no internal walls, south wind

AREA	ZONE 1	ZONE 2	ZONE 3	TOTAL
south sector	90	10	0	100
central sector	49	33	18	100
north sector	22	45	33	100
full citadel	53	30	17	100

Experiment #3, internal walls, south wind

AREA	ZONE 1	ZONE 2	ZONE 3	TOTAL
south sector	90	10	0	100
central sector	71	29	0	100
north sector	100	0	0	100
full citadel	86	14	0	100

Experiment #4, internal walls, SSE wind

AREA	ZONE 1	ZONE 2	ZONE 3	TOTAL
south sector	36	33	31	100
central sector	45	52	3	100
north sector	80	20	0	100
full citadel	53	37	10	100

DOUBLE WALL MODEL, ONE SECTOR

EXPERIMENT	WIND	ZONE 1	ZONE 2	ZONE 3	TOTAL
#5	south	88	12	0	100
#6	SSE	33	50	17	100
#7	SE	27	40	33	100

NOTE. Zone 1 has under 40% relative wind speed, Zone 2 has 40 - 60%, and Zone 3 has over 60%.

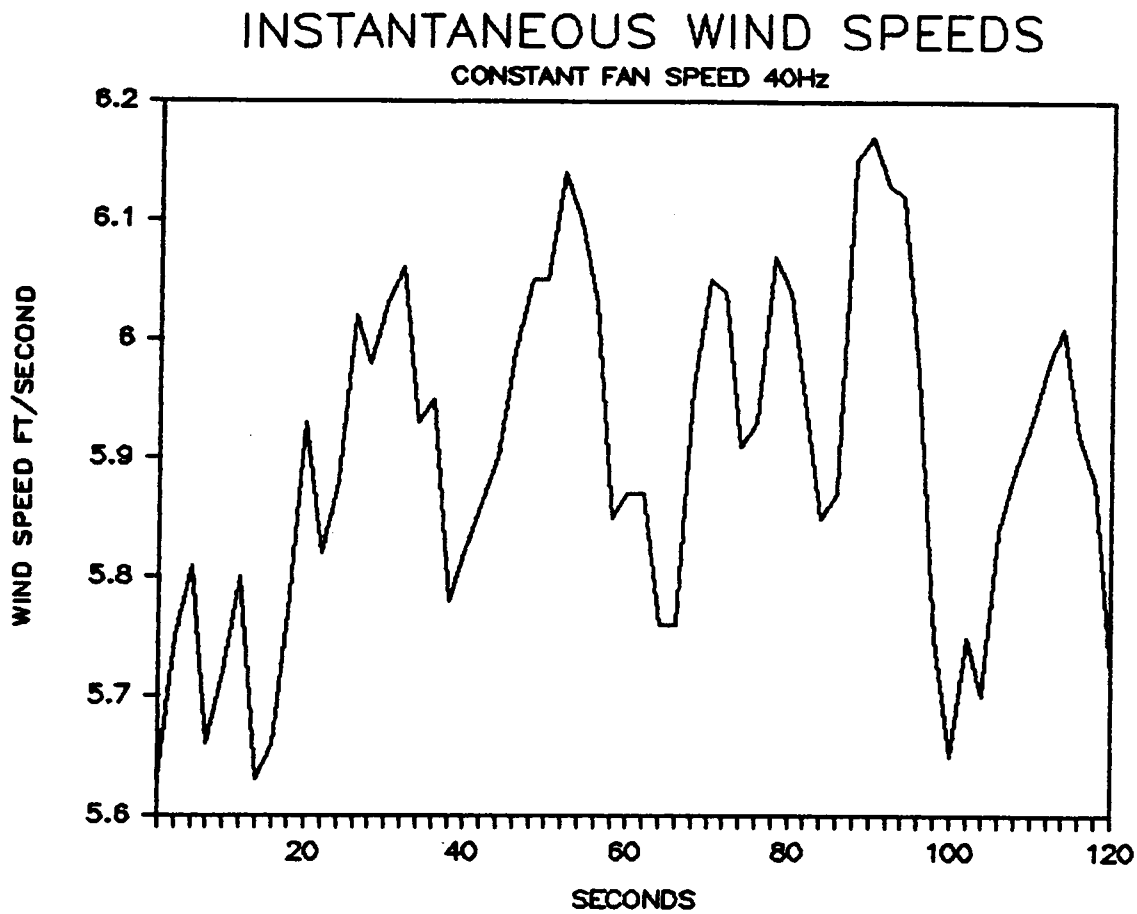


Figure 42 Fluctuations of wind speed in the Environmental Systems Laboratory wind tunnel, with constant fan speed and without model or other obstructions on the tunnel table.

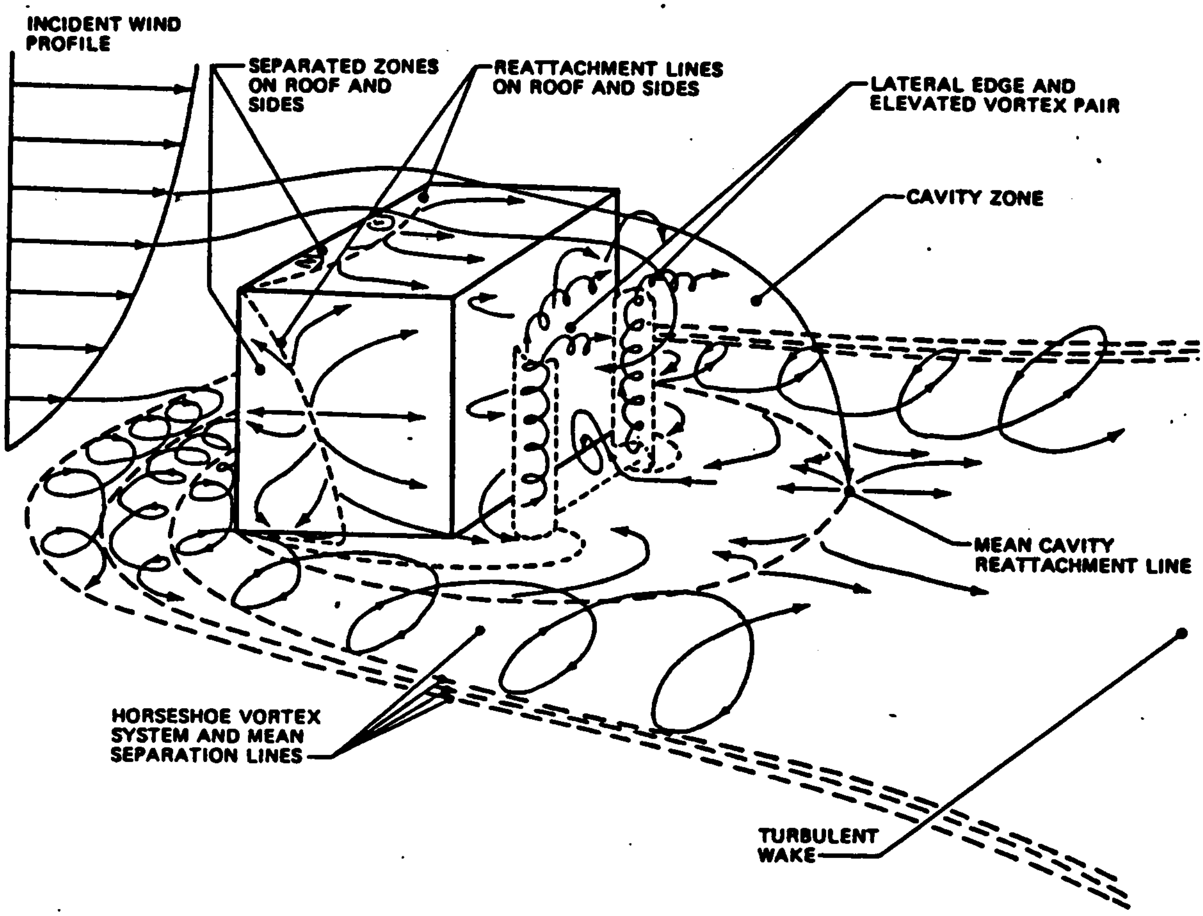


Figure 43 Model of airflow patterns near a sharp edged building (from Hosker, 1979).

JACKSON'S MODIFIED BEAUFORT SCALE

Mean speed meter/sec	Effects observed or detected
0	
	calm, no noticeable wind
2	wind felt on face
	clothing flaps, hair disturbed
4	
	hair disarranged, dust and paper raised
6	
8	control of walking begins to be impaired
	violent flapping of clothes, progress into wind slowed
10	force of wind felt on body, umbrella used with difficulty
12	blown sideways, inconvenience felt walking into wind
	difficult to walk steadily, appreciably slowed into wind
	noise on ears unpleasant
14	
	generally impedes progress
	almost halted into wind, uncontrolled tottering downwind
	difficulty with balance in gusts
16	
	unbalanced, grabbing at supports
18	people blown over in gusts
20	
22	cannot stand

Figure 44 Modified Beaufort scale. Effects of wind at standard conditions of 18% longtitudinal turbulence intensity at pedestrian level in rural terrain (adapted from Jackson, 1978).

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Appendix A

Conversion Table

Miles per Hour	Knots	Meters per Second	Feet per Second	Kilometers per Hour	Feet per Minute
1	0.9	0.4	1.5	1.6	88
2	1.7	0.9	2.9	3.2	176
3	2.6	1.3	4.4	4.8	264
4	3.5	1.8	5.9	6.4	352
5	4.3	2.2	7.3	8.0	440
6	5.2	2.7	8.8	9.7	528
7	6.1	3.1	10.3	11.3	616
8	6.9	3.6	11.7	12.9	704
9	7.8	4.0	13.2	14.5	792
10	8.7	4.5	14.7	16.1	880
11	9.6	4.9	16.1	17.7	968
12	10.4	5.4	17.6	19.3	1056
13	11.3	5.8	19.1	20.9	1144
14	12.2	6.3	20.5	22.5	1232
15	13.0	6.7	22.0	24.1	1320
16	13.9	7.2	23.5	25.7	1408
17	14.8	7.6	24.9	27.4	1496
18	15.6	8.0	26.4	29.0	1584
19	16.5	8.5	27.9	30.6	1672
20	17.4	8.9	29.3	32.2	1760
21	18.2	9.4	30.8	33.8	1848
22	19.1	9.8	32.3	35.4	1936
23	20.0	10.3	33.7	37.0	2024
24	20.8	10.7	35.2	38.6	2112
25	21.7	11.2	36.7	40.2	2200
26	22.6	11.6	38.1	41.8	2288
27	23.4	12.1	39.6	43.5	2376
28	24.3	12.5	41.1	45.1	2464
29	25.2	13.0	42.5	46.7	2552
30	26.1	13.4	44.0	48.3	2640
31	26.9	13.9	45.5	49.9	2728
32	27.8	14.3	46.9	51.5	2816
33	28.7	14.8	48.4	53.1	2904
34	29.5	15.2	49.9	54.7	2992
35	30.4	15.6	51.3	56.3	3080

Conversion factors:

mph × 0.44704 = m/s
mph × 0.868391 = knots
mph × 1.4667 = fps
mph × 1.609344 = km/hr
mph × 88 = fpm

(from 1984-85 catalog, Weathertronics, Division of Qualimetrics, Sacramento, CA.)

APPENDIX B

Natural Processes and Forces in Arid Zones

In the overall context of geological change, the geomorphology of a landscape can be transformed by wind, water, tectonic movement, earthquake, or man (Raikes, 1967:34). The character of the surface deposits and the underlying topography significantly determine the landscape. The same type of relief forming factors of erosion, aqueous deposition, deflation (depletion of sand by wind erosion), and eolian deposition occur in all deserts. The processes are governed by the laws of hydrodynamics and aerodynamics that are homogenous for all drylands. Landscape relief forms in arid zones or deserts with surface deposits of the same geology are, therefore, of the same type (Petrov, 1976:120).

Sand and dust are moved by wind in many different environments; they give the most problems in the hot dry zones. Extensive planning is necessary, if the buildings, cultivated areas, transportation networks, and irrigation systems of these drylands are to keep from being attacked and covered by sand and dust (Cooke, 1982:249). Control or amelioration of the effects of sand and dust requires that the process involved in their movement, determined by eolian and water activity, be investigated. This type of investigation, a central concern of contemporary arid zone urban studies, is useful in the exploration of the interaction between the natural and built environments.

Segments of selected contemporary studies have been summarized in this paper. More detailed descriptions of the physical aspects of wind and sand action and their effect on the landscape of arid zones are to be found in Bagnold (1941), Chepil and Woodruff (1963), Cooke and Warren (1973), Petrov (1976), and Mabbutt (1977). Definitive information on the deserts of southern Peru is available in Finkel (1959) and Lettau and Lettau (1978).

The Nature of Sand Movements

Deserts are, by definition, arid. They receive less than 25 cm of annual percipitation and have enormous evaporation rates, sometimes 15 to 20 times greater than precipitation (1). Desert landscapes contain a variety of depositional and erosional landforms on a diverse topography that ranges from flat plains to rugged mountains (Ritter, 1978:311). Sandy deserts account for only 25% to 33% of the worlds' desert lands.

Arid zones are dominated by mechanical rather than chemical processes. Wind is at times a powerful moving force, but water, although scarce, occasionally plays a more dynamic role. Change is usually slow, which makes the landscape seem immobile until these powerful forces are periodically activated over wide areas. This "stop and go" mechanism produces arid zones with dramatic topographical reliefs (Butzer, 1976:378).

Sand and dust are important factors in the desert eolian landshaping processes. Their movement is determined by the interaction of the velocity and turbulence of the wind, and the roughness, cohesion, and grain sizes of the particles being moved. It is the interaction between the erosivity of the wind and the erodibility of the surface that determines whether a given particle will move. Vegetation and moisture reduce particle mobility and therefore add complicating factors for sand movement (Cooke, 1982:250).

Sand is commonly defined as a loose cohesiveless aggregate of mineral or rock particles ranging from 2 mm (to 0.05 mm in diameter and is divided into very coarse (1-2 mm), coarse (1.0-0.5 mm), medium(0.5-0.25), fine (0.25-0.1mm) and very fine (0.1-0.05 mm) (Petrov, 1976:159). At the lower limit of the size grading, an eddy current in the average wind can carry the particles away in suspension as dust. At the upper size limit grains are rarely moved by wind pressure or by impact from other particles. Those sand particles sized between these limits have the distinctive property of ready surface movement by wind. The deposition or deflation of these particles give arid landforms (Mabbutt, 1977:218).

Sand (quartz based) has a density of 2.65 grams/cubic cm, while the smaller dust particle has a much lower density. Dust traveling as a suspended load in air can be carried to great heights. But, because of the dust particle's cohesive, platty, aerodynmaically smooth properties, it is difficult to start dust moving. Dust is usually moved only when there are high velocity winds and after it has been disturbed (Cooke, 1982:250).

Sand moves differently. Fine and medium sands travel by saltation and coarse sands move by rolling or sliding, motions collectively referred to as surface creep. When sand grains are first set in motion by pressure from a turbulent airstream, they are initially rolled along the ground. Later, as the process continues this becomes a bounding motion termed saltation. Grains bound a small distance into the air, and they are carried forward dislodging other particles by their impact. Most of this takes place within a few centimeters of the surface. The rate of saltation travel is about one-half the wind velocity at 1 m above the surface.

Saltation accounts for approximately 95% of the bulk transport of sand and occurs mainly with grain sizes of from 0.15 to 0.25mm with an upper limit of 0.5mm. The larger grain sizes between 0.25 and 2.0 mm are rolled or slid along the surface by the impact from the saltation to give the surface creep. Surface creep moves at a slower rate than saltation and accounts for only a small part of the bulk transport. Very fine sand is borne above the saltation level within about 2 m above the ground and is deposited with the saltation load when the wind speed decreases. The still smaller particles (0.084 mm), designated as dust, can remain suspended in turbulent air to form dust clouds or haze

(Mabbutt, 1977:220).

The force of gravity is omnipresent, pulling the particles down to the surface of the terrain. The downward speed of settlement, dependent on the size, shape, and density of the particle, is the terminal velocity. The heavier the material, the faster it falls. Because of this limiting velocity, sandstorms containing fine particles in a curtain of sand, are restricted to the lower layers of the atmosphere and are confined in a limited area. Dust storms made up of lighter, very fine, particles, cover much larger areas, at a higher level in the atmosphere and remain suspended for longer periods (see Figures B.1, B.2, and B.3).

Alluvial plains are often depleted by deflation, removing the sand and dust from between the larger particles of the surface leaving the coarser materials to form pebble or rock desert pavements with hardened surfaces. As long as the wind regime remains constant, the resultant is a wind stable desert with a flat winnowed terrain that is characteristic of the major portion of most of the world deserts. This deflation often supplies the sand for downwind deposition in the form of sand sheets and dunes.

The wind velocity at which sand is set in motion is the fluid threshold and the slightly lower velocity necessary to maintain the saltation motion is the impact threshold. The initial fluid threshold is set by the diameter of the surface particles. As the wind velocity and shear exerted by the wind at the surface (drag velocity) increase, the size particle that can be moved will also be increased. In dune sands, with their limited grain size distribution, it is common for all surface grains to be set in motion. Ultimate fluid threshold velocities are often altered by dune shape, vegetation, moisture content of the sand and by physical obstructions. Wind gustiness and turbulence, caused by eddy currents, are also important in intiating and altering sand movement (Mabbutt, 1977:220).

<u>The Nature of Wind</u>

Wind is a flow of air which tends to equalize the energy difference between pressure zones in the atmosphere. At low altitudes there is often significant agitation or turbulence when there are airflow changes and pressure differentials caused by obstructions in the path of the wind. As a result, at any given point, the velocity of the wind near the surface of the terrain will have instantaneous fluctuations in magnitude and direction (Gandemer, 1978:4) (see Figure B.4). The average speed at ground level in flat terrain, increases with height until it becomes constant at its gradient velocity. Below this height, in what is known as the boundary layer, the velocity is variable with the speed at the surface being the lowest. The time required for the wind to reach its gradient speed at the top of the boundary layer is controlled by the "drag velocity," a function of the obstructions on the terrain. An urban community with many obstructions has a higher drag velocity than an open field.

The quantity of sand that can be moved in any time period varies with the cube of the wind speed. Therefore, the occasional strong and gusty wind may be a more effective transport agent than a more gentle prevailing wind. A wind speed of 10 m/s (meters per second) will perform three times as much work as a wind with a speed of 5 m/s (Petrov, 1976:171).

In research, it is important to identify the most effective sand transporters in an environment based upon the analysis of the long term dominant wind patterns of the area. These patterns must be recorded in a uniform procedural manner so that they can be correlated with each other for particular time intervals. As a standard, meteorologists have established that wind speed be measured by an anemometer at 10 m above the surface at one hour intervals. Since the wind speed in a boundary layer varies with altitude, sand movement analysis requires a conversion of this 10 m standard to surface level speeds. Initially, scientists investigating sand movement used wind rose diagrams that indicated the frequency, strength, and direction of all winds at standard height. In current procedures, only those winds capable of transporting sand and considered meaningful for landform analysis are diagrammed.

Fine grained sand (0.25-0.1mm) requires a wind speed of close to 3.5-4.0 m/s at the ground surface to move. Since wind speed varies with height above the terrain, this corresponds to a wind force of 5-6 m/s (approximately 12 miles/hr or 20 km/hr) for open terrain at 10 m standard anemometer height. Thus, to process the data from wind stations or to evaluate the effects of wind in an area, only the direction and speed of those winds with a speed of 5-6 m/s or greater at standard anemometer height should be considered (Petrov, 1976:170-171).

A wind regimes' direction and speed can vary widely within each year or from one year to the next. A local variation with changes occuring every second is not unusual. Meteorologists use the wind speed averaged per hour (2) as the standard unit of record. These readings are then averaged again to give the daily, monthly or yearly winds of the location. Unfortunately, this process of averaging and reaveraging masks the higher, significant sand moving wind speeds. For sand movement analysis, it is imperative that the sand transporting winds be differentiated in the long term observations.

Eolian Landforms

Wind acts on surface sands and topography in a complex manner with different combinations of direction, force, and time. In the process it gives rise to different geomorphological forms (Petrov, 1976:174). Eolian sand deposition can take the form of sheets of sand or distinctive dunes. Dunes are found either "tied" on the downwind side of obstacles or completely free from obstacles. They can be active or immobile under vegetation.

The growth of dunes is influenced by the tendency for saltating sand to accumulate in areas already sand covered in preference to sand free surfaces. A strong sand laden wind will cause accretion or deposition on an existing sand patch, but a gentle wind may remove sand and extend the patch downwind. Sand accumulation is also influenced by the nature of the surface upwind and the supply of sand from it. A stony desert pavement upwind will trap sand at times of gentle wind and will release it to a strong wind (Mabbutt, 1977:223).

Dunes are found where there is a source of sand, such as a dry lake or stream bed in the desert, or a sandy beach on the coast. The location, size, and shape of dunes are largely controlled by the interaction of the location of the sand supply, sand grain size, roughness of the surface across which the sand moves, the wind regime, moisture, obstacles, and topography (Butzer, 1976:388). The dune configurations attributed to sand and wind action on the upwind and downwind sides of obstacles and topographic barriers are detailed in the illustrations (see Figure B.5). Any urban obstructions that are introduced into a sandy desert environment present an interference to sand movement and affect the airflow and deposition patterns in the same manner.

<u>Sand Movement in Water</u>

The mineral and rock deposits that supply the sand to the coast can originate from the alluvial plains, the upper river basins, or from the wearing action of the ocean forces. In the river system, the fine grained sediment is transported in the water by the flow turbulence. This load of suspended grains can stay suspended and move downstream without deposition. Coarser materials can also move in suspension, but they will be deposited more quickly and stored within the river channel. Coarse materials usually travel as bed load with either a rolling, sliding, or bouncing action. The length of time the coarse material stays as bed load depends on the size of the material and the flow characteristics of the river. The quantity of material that a river will entrain, transport or deposit depends on the river velocity, depth, and slope and the resistance to flow by channel configuration, particle size, and sediment concentration. The amount of discharge and load it must handle is determined by the geological and climatic character of its drainage basin (Ritter, 1978:255).

Rivers on the coast of Peru obtain their sediment loads high in the Andes in easily eroded drainage basins that contain vast sand and gravel deposits. These rivers rapidly descend down steep slopes to the ocean's continental shelf and deposit sediments at the rivers mouth. Here the silt, clay, sand, gravel, and rocks become part of the larger oceanic sediment system dynamics. The river sediments often influence the sand deposition patterns on distant beaches.

The location of major beach landforms depends to a large degree on the availability of sand from the ocean. The primary source of beach sand is the material load delivered to the coast by major river systems. Most large beaches are created from the river sand by the drifting of material load in the longshore transport process called littoral drift. Although longshore currents generated by winds or other factors can move sand, littoral drift due to wave action is the most effective. The volume of sediment being transported along the shore is largely the consequence of height, period, and direction of waves.

Changes in coastal sand landforms are at times the result of a changing sand supply. Erosion or depletion results if the volume of sand which leaves the coast exceeds that which enters. Deposition and accretion occur if there is a sand surplus. When a coast is stable in form, it is in equilibrium (Duane, 1976:514).

Changes in the coastal sand supply can also result from tectonic uplift, sea level change, or from variations due to eroded geological features. Any of these will change the littoral drift permitting deposition or increased sand supplies for some areas, depletion or sand starvation for others. Modern day shore protective devices projecting into the ocean, known as groins, (also known as moles), are currently being built along coasts to maintain and protect beachs. Erosion is prevented and beaches are maintained by changing the configuration of the shoreline and trapping the littoral drift. However, problems usually develop downcurrent where other beaches are starved of sand and equilibrium is upset. The sand supply parameters can remain stable for extended periods or change rapidly in the same "stop and go" type of mechanism that influences sand movements on land.

Airflow Patterns

Wind control is an essential ingredient for effective design in an arid community. The reduction or adjustment of wind speed and its direction can have a major influence on the microclimate of the surrounding area. Uncontrolled wind can be an annoying and destructive element in the urban environment.

Airflow is classified into laminar or smooth, separated or turbulent (see Figure B.6). Laminar flow is the most predictable and the easiest to control, while turbulent flow is the most unpredictible and also the most difficult to control. Air flows freely when unobstructed, but obstacles in its path will generate forces between the air layers that can cause pressure differentials, separation, and turbulence. If the obstacles have smooth, streamlined surfaces the air will flow freely around them with little change in the flow characteristics. The air layer next to the surface will increase in speed but there will probably be no turbulence. If the wind strikes an obstacle that is not streamlined, the air layers cannot easily follow the contours and separation and turbulence may result. The rougher the surface and the greater the resultant change in the direction of airflow, the greater the turbulence (Miller, 1980:17).

With the proper design and location, the effects of winds can be effectively controlled by the built environment. Interception and diversion with obstructions such as earth forms, vegetation, walls, fences, and buildings are effective. Landforms can also be used to channel or deflect air movement. If the critical wind velocity is attained, sand and dust will move with the wind in the eolian manner previously described. It becomes evident, when wind controls are improperly designed or located, the results can easily cause intolerable environmental changes.

When wind blows at right angles to the vertical face of a building or obstruction, the wind at about two thirds of the way up from the ground goes up and over the building. The lower part of the wind comes down and forms a vortex in front of building. At the upwind corners and along the downwind side and roof a low pressure area of suction is created by an increased velocity. In this same location there is a separation from laminar to turbulent airflow at these corners and part way down the sides. Buildings or obstructions that are downwind will be affected by the attendant change of wind pattern, airflow intensities, airflow directions, and pressure differentials that add to the complexity of the environment. Even a single building can bring about a marked change in the wind flow. The wind direction can easily be diverted by an obstacle and made to flow from any direction of the compass.

Additional complexities are encountered due to the building height, width, length, material of construction, color, general configuration, and orientation. The arrangement of other structures in the area and the patterning of the streets also make a difference. There are many varibles to be considered. The best design approach for determining airflow patterns has been to develop scale models that can be tested in a wind tunnel. Recent publications describing wind tunnel studies provide visualizations of wind flow around a wide variety of building configurations. These illustrations give indications of wind behavior around buildings that are useful for the interpretation of wind patterns and deposition of sand and dust around any obstruction.

<u>Windbreaks</u>

The reduction in wind speed caused by a wind barrier can have considerable influence on the microclimate of the surrounding area. A steep upwind slope causes a compression of the air, resulting in wind speeds as much as twenty percent greater. It also causes increased turbulence downwind. A gradual slope will lift and deflect air masses more efficiently and give a greater zone of downwind protection (Miller, 1980:31) (see Figure B.7).

Vegetation shelterbelts are commonly used windbreak devices for control of microclimate. Plants with varying heights, width, and densities can be planted individually or in groups in conjunction with landforms and structures to give solutions to wind problems. Walls and fences are also effective as windbreaks.

The amount of protection offered by the windbreak depends on the parameters of the barrier, the distance between the barriers and the orientation to the prevailing wind. The porosity or density of the windbreak is probably the most decisive factor in determining wind speed reduction (Yao, 1981:268). Windspeeds on the downwind side of the shelterbelts may be reduced by as much as 50% for a distance of 10-20 times the height of the barrier. The total influence may extend as much as 25-35 times its height, depending on the overall characteristics of the barrier.

Modifying the microclimate with windbreaks can greatly influence the growth of plants in the protected area. Barriers reduce the impact of destructive winds, reduce evaporative and evapotranspiration demands of high velocity dry winds, and protect against sand and dust deposition. The decrease in evaporation on the downwind side of the barrier has been shown to be about 40, 60 and 80% of open field evaporation at the points of a distance of 1, 5, and 10 times barrier height respectively (Yao, 1981:269). The influence of the windbreak on evaporation is felt for a distance of 20-25 times the height of the barrier. Windbreaks provide a very significant water conservation method for arid zone agriculture.

Solar Radiation

Solar radiation is the driving force of our biosystem. It is the single most influential climatic factor that powers global weather systems. It influences the circulation patterns and turbulence of the wind and is an important element in the investigation of the wind, sand, and dust.

Radiation from the sun provides the energy for evaporation and circulation of atmospheric moisture. It supplies the radiation necessary for photosynthesis, the biological process for converting radiant energy into food and fiber. The sun can be helpful or destructive. Therefore, the design of our physical environments must be responsive to solar radiation and the important role it plays in human comfort and stress in arid zones (Miller, 1980:19).

The high sun angles of the tropical latitudes concentrate solar radiation and the long summer days give irradiated surfaces more time to absorb the energy. The summer nights have short periods of surface cooling. As a result, there is a daily excessive heat gain during the summer. In the winter when the days are shorter and the sun angle is lower, there is a daily heat loss (Miller, 1980:19). The effect of incoming solar radiation on the heating of a surface depends on the height of the sun, the length of the day, cloud cover, turbidity of the air, and the heat absorbing capacities of the material.

Local winds are often generated by the differences in the thermal properties of surface materials in the vicinity. The greatest wind activity with turbulence can be expected in those environments where large temperature variations exist in the air layer immediately above ground level. The temperature gradients caused by these variations often change from daytime to nighttime because of differences in rates of cooling and heating inherent in the surface materials. Such conditions are common in deserts, along seacoasts, or in areas with diversity in elevation, such as the juncture of mountain ranges and low plains (Ritter, 1978:315).

Vegetation can be used effectively for solar radiation control. Trees, shrubs, vines, and ground covers will reduce direct and reflected radiation and absorb heat. They also provide the cooling effect of evapotranspiration, direct air movement, and act as a buffer to abrupt temperature changes. Temperatures in planted areas remain cooler through most of the day and will retain warm air at night. Since evaporation and evapotranspiration are effective cooling agents in an arid climate, habitation sites downwind from large bodies of water and irrigated fields will have the benefit of cooler winds.

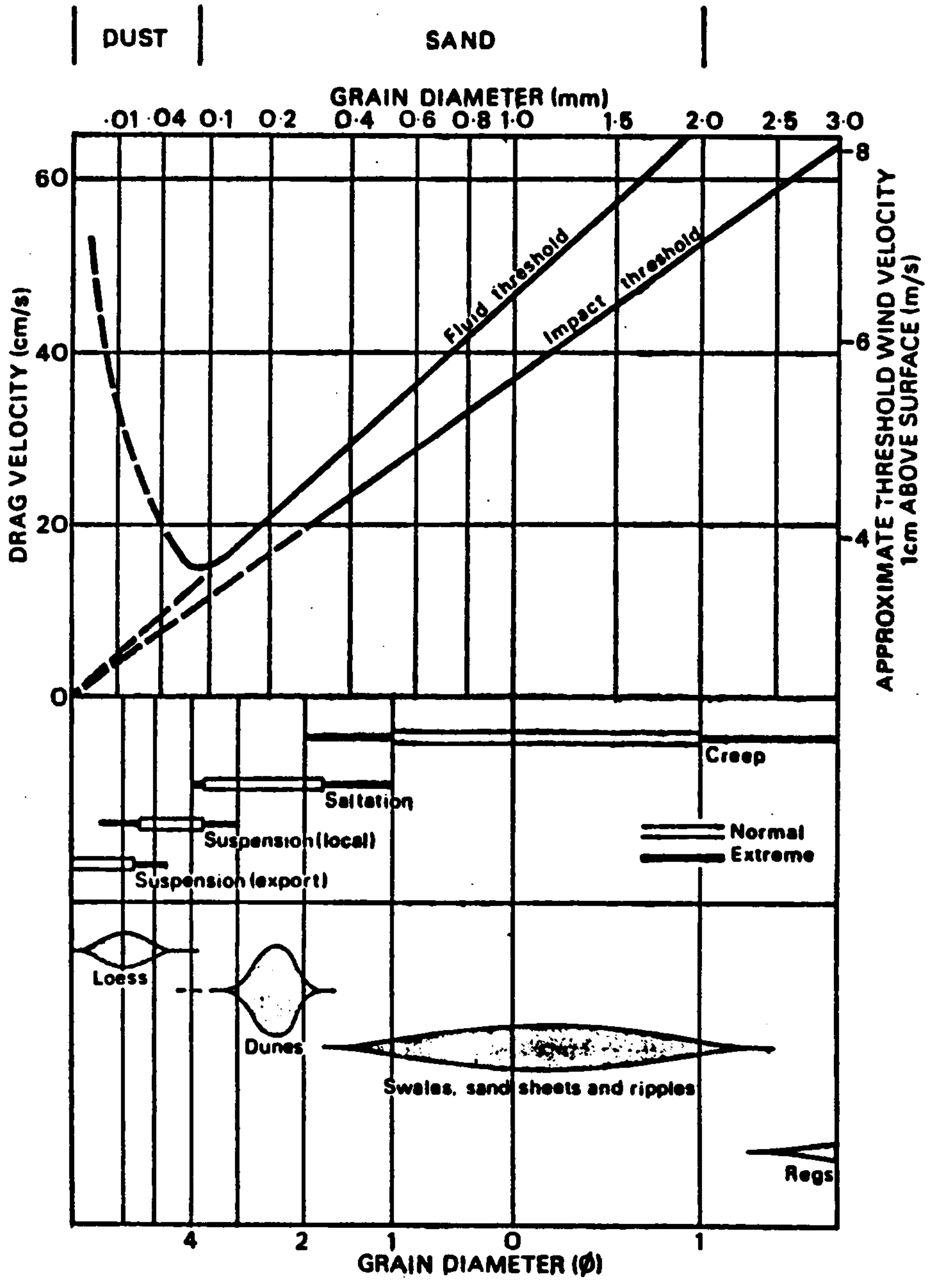
The site orientation, with respect to solar radiation, determines the degree of heat gain, heat loss, and light during each day of the year. Differential shading gives each area of a site pockets of microclimate which will differ from those of other sections. East and west exposures will give shadows on one side of a structure and leave the other side exposed to radiation all day. A northeast to southwest or southeast to northwest direction for orientation of the walls or streets is suggested by Golany (1983:12).

The configuration of the sites structures and street network also act to change microclimates. A dense or compact site with common building walls and narrow, winding streets loses temperature very slowly in the evening but also gains it very slowly during the day. This compact form, so prevelant in the Mid-East, can break the force of the hot day time winds, reduce the effect of dust and sand storms, build in cool air and shadow by reducing direct radiation and evaporation, and minimize heat gain during the day and heat loss at night. For high density areas, structures can be situated to shade one another as well as outdoor living spaces and circulation ways, especially if buildings are close, walkways are narrow and open spaces are small. Long broad straight streets or alleys oriented in the same direction as the prevailing wind will channel and increase the airflow and should be avoided (Golany, 1978:195).

Endnotes

1. More complex methods for defining arid zones were devised by Koppen in 1931, Thornthwaite in 1948, Meigs in 1953, and by a revision of Thornthwaite's original method, in collaboration with Mather, in 1962 (Adams et al., 1978:16). All the methods define the Moche Valley as desert.

2. Caution should be exercised in using the United States National Oceanic and Atmospheric Administration (NOAA) wind data. These data are termed as "hourly wind speeds" but are actually the average of a series of wind speed measurements taken during a one minute interval, once an hour (Arens, 1982:15).



<u>Figure B.1.</u> Relationships between grain size, fluid, and impact threshold wind velocities, characteristic modes of eolian transport, and resulting size grading (from Bagnold, 1941).

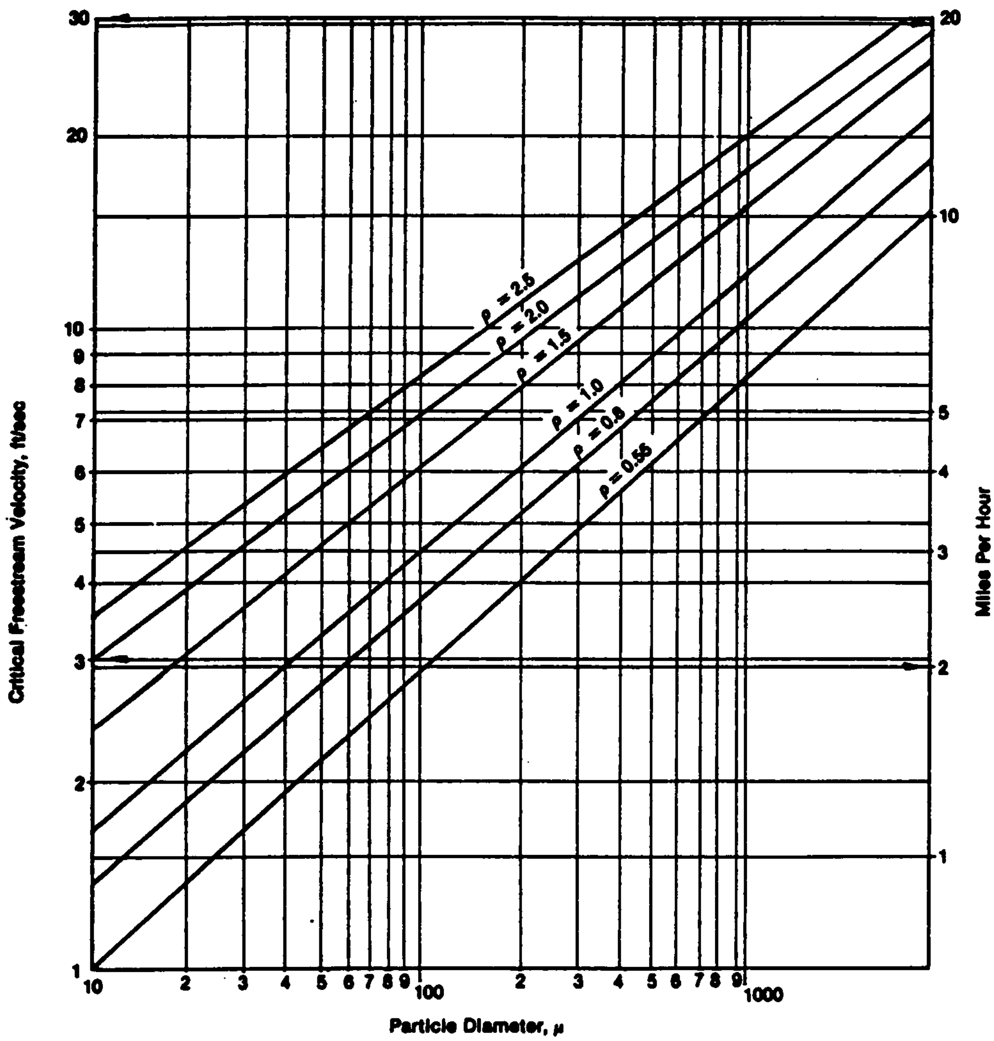


Figure B.2. Critical freestream velocities required to suspend regular particles of different densities in neutral atmosphere (from Hesketh & Cross, 1983).

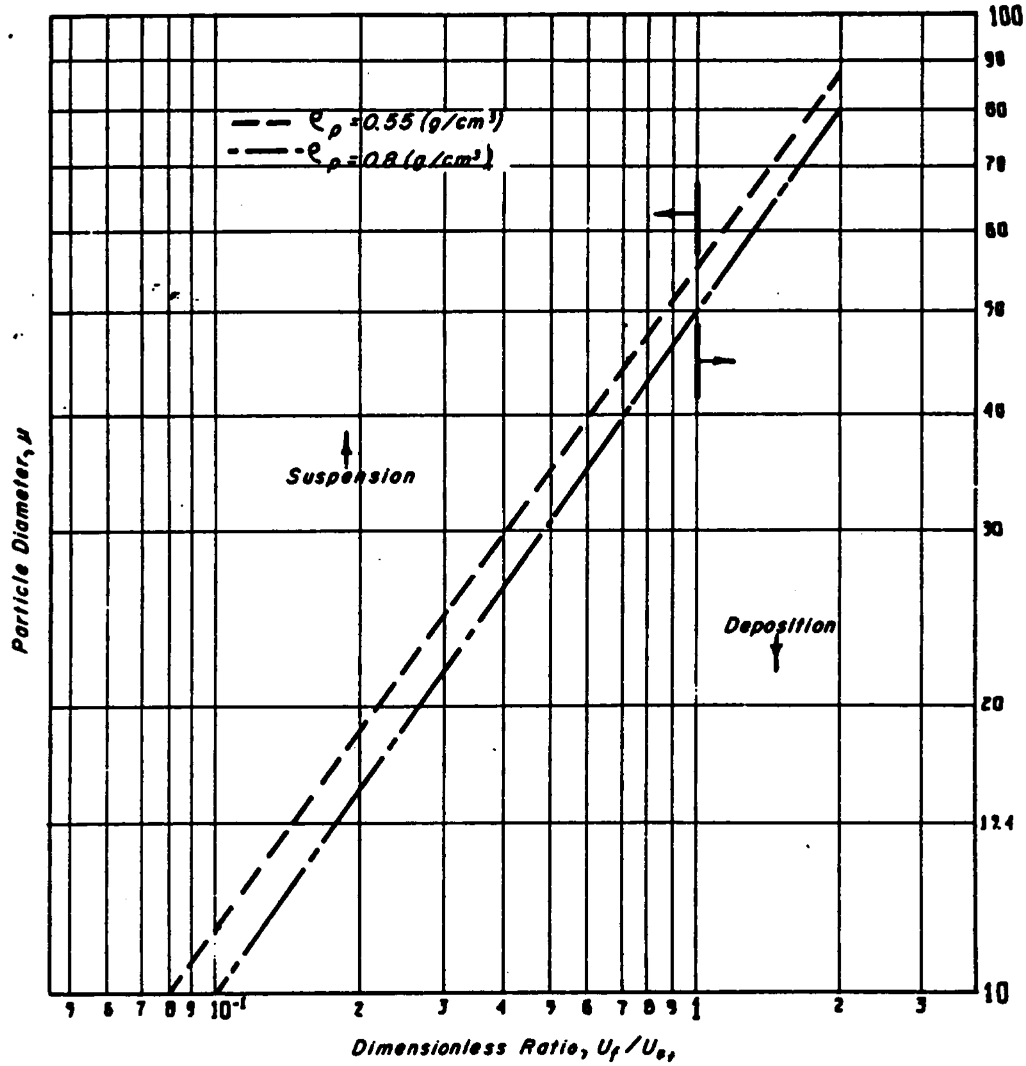


Figure B.3. Particle diameter vs. ratio of terminal velocity to threshold velocity at different densities (from Hesketh & Cross, 1983).

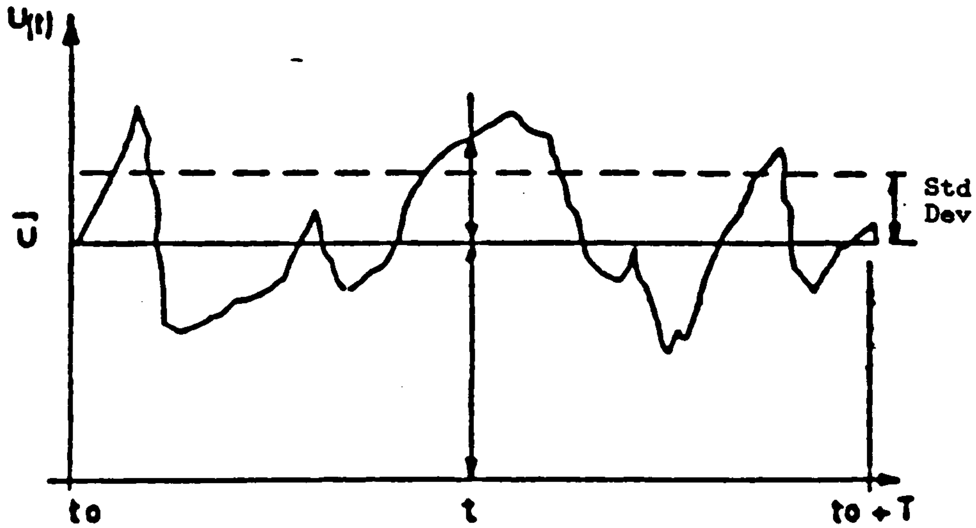


Figure B.4. Variation of velocity (U) with time (T) for instantaneous recording of wind in nature (from Gandemer, 1978).

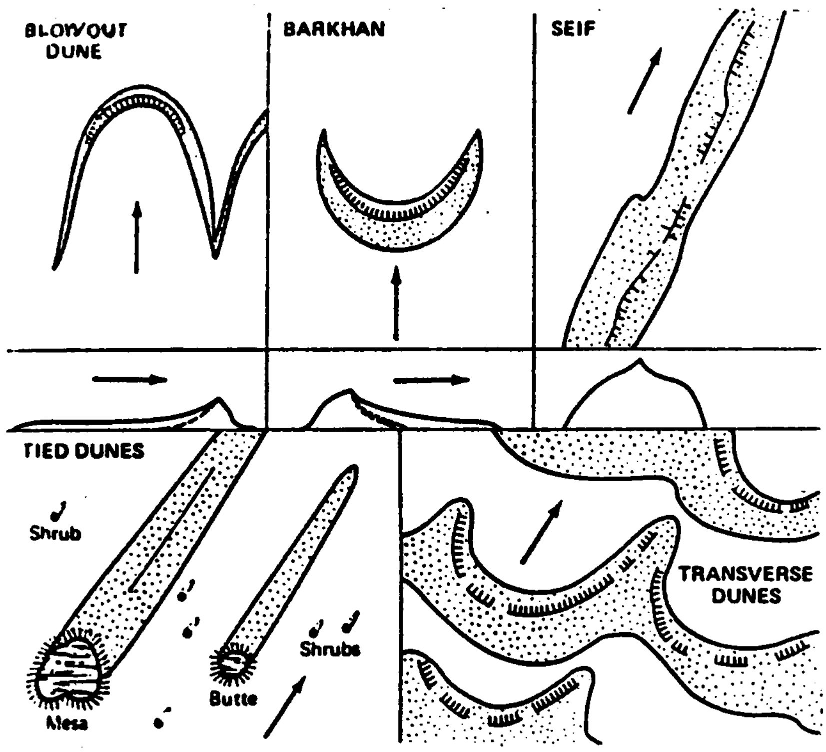
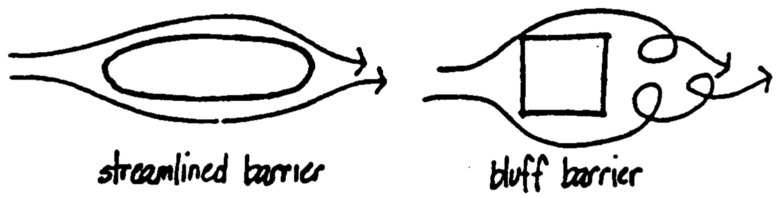
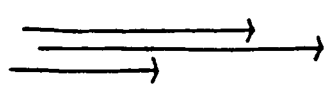


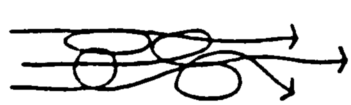
Figure B.5. Dune types (arrows indicate wind directions)(from Butzer, 1976).





laminar airflow, where parallel layers of air flow smoothly one on top of another in a predictable pattern

separated airflow, where a separation of layers may result in some turbulence between layers



turbulent airflow, where air masses travel in the same direction but with a random pattern and with unpredictable velocities

Figure B.6. Airflow patterns (from Miller, 1980).

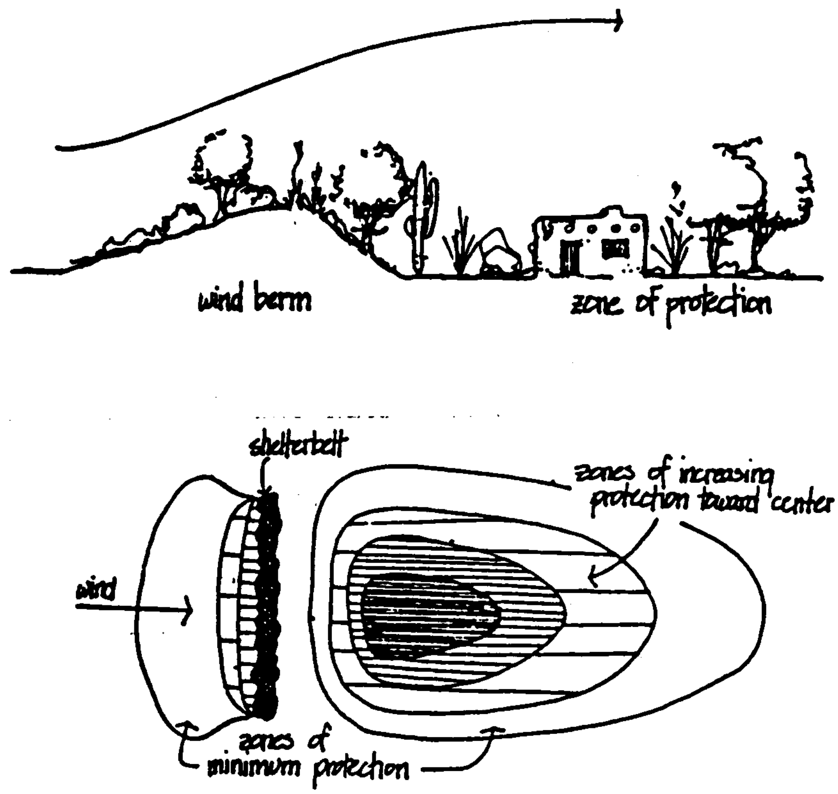


Figure B.7. Zones of protection resulting from a wind berm and a shelterbelt (from Miller, 1980).

APPENDIX C

Equipment

1. One low speed, closed circuit, wind tunnel with two variable speed suction fans operating from 0 to 80Hz (Hz indicates fan rotation speed in revolutions per minute)(top wind speed at 80Hz approximately 14 ft/s). Speed controlled by an ESP-130, type form 10FS-203080 transistor inverter, manufactured by Toshiba International Corporation. The tunnel floor or table is approximately 8 ft wide by 12 ft long. The tunnel inlet and outlet are approximately 8 ft wide by 4 ft high (see Figures 32 & 33).

2. Three hot wire omni-directional anemometers manufactured by TSI, powered by external source (modified with 10 ohm variable resistors across output lines to give a maximum of 5 volts to match maximum input of Data Logger.)

    1-Model 1620-12 serial # L727 (Probe 1)

    1-Model 1620-12 serial # M439 (Probe 2)

    1-Model 1620-12 serial # M440 (Probe 3)

3. One hot wire omni-directional anemometer model 1640F serial # 141 (Probe 4) manufactured by TSI, powered by internal rechargeable battery, with analog scale and connection for voltage outputs.

4. One nine volt D.C. power supply Model 1605 serial #1102, manufactured by TSI.

5. One Data Logger Model 714, serial #1183 with maximum 5 volt input, manufactured by Metrosonic.

6. One photographic timer manufactured by Gralab.

7. One portable Propane Insect Fogger, Model 1443, manufactured by Burgess using Johnson's Baby Oil to generate smoke.

8. Two model citadels, scale 1:120, fabricated from wood with the following scale wall dimensions:

a. External wall cross section

Height	10 m
Top	50 cm wide
Base	3 m wide

b. Internal wall cross section

Height	8 m
Top	50 cm wide
Base	2.5 m wide

The full citadel model is 120 m by 240 m in plan and is divided into three sectors by transverse internal walls at 72 m and 168 m from the south end wall. The double wall sector model is 120 m by 120 m at the external walls. The internal walls of the double wall sector were positioned parallel to the external walls with a 4 m space between them.

9. One pitot tube manufactured by Dwyer.

10. One telltale rack with alternating 11.5 cm and 25 cm lengths of yarn on 10 cm centers (for visualizing wind flow patterns).

11. Various support stands and fixtures to hold instruments and telltales.

12. One IBM PC XT computer.

13. One terminal bus to connect:

a. The D.C. power supply to 1620 anemometers

b. The 1640 and 1620 anemometers to the Data Logger (by means of coaxial wires with telephone jack connectors).

14. One standard voltmeter.

Software Utilized

1. LSF (Least Squares Fit) by Sumar Corporation (determined anemometer calibration curves and equations).

2. Data Logger proprietary internal program (recorded data).

3. ProComm communications program in public domain (transfered the data from Data Logger to the PC computer).

4. Lotus 123 spreadsheet and graphics by Lotus Development Corporation (processed the recorded data).

Calibration Procedures

1. To check accuracy, all anemometers were initially calibrated with a voltmeter and pitot tube at 5Hz fan rotation speed increments from 5 to 55Hz and the measurement from the anemometers were compared to the manufacturers calibration curves. The 1640 had the closest match to the manufacturers curve and was therefore considered to be the most accurate and was selected as the data probe to be used

inside the citadels. Of the 1620s, Probe 1 followed the manufacturer's calibration curve the closest and was selected as the upwind reference probe.

The operating voltage output of the 1640 was less than 5 volts and did not require adjustment to match Data Logger input requirements. Because of the 1640's accuracy, analog scale, voltage range, and independent power supply, it was used to recalibrate the 1620 anemometers.

2. Before recalibration of the 1620 anemometers, the complete electrical circuit, including the Data Logger, was connected and the fan rotation speed adjusted to give 10 ft/s on the 1640 analog scale (maximum wind speed recommended by the anemometer manufacturer). The input D.C. power supply to the 1620 anemometers was then adjusted to 9 volts (recommended by the manufacturer of the anemometers). At this same wind speed each of the 1620 anemometers was adjusted using the variable 10 ohm resistors to give a 5 volt output that would be within the maximum range of the the Data Logger.

3. The 1620 anemometers were then recalibrated at fan settings from 5 to 55Hz in 5Hz increments using the 1640 anemometer as the standard. The voltage from the 1620's and analog readings from the 1640 were utilized in the LSF computer program to develop curves and cubic equations that would later be used to calculate wind speeds from the Data Logger voltage readings. The equation given by the

manufacturer for the 1640 curve was recalculated for use in the Lotus 123 computor software (using factory data) so that it would provide the wind speed, rather than the voltage, as the dependent variable.

4. The tunnel floor was checked (at 2m, 8m, and 14m scale heights) at each grid location, using fan rotation speeds from 25Hz to 55Hz to ascertain how the wind speeds were distributed close to the tunnel floor. This information was instrumental in developing the size of the models and the best tunnel floor location for the experiments.

5. Initial experiments showed that the anemometers were not actually omni-directional and that the probes must remain oriented in the same direction (as used for the calibration) to give the most consistent readings.