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Degradation Of An Arid Environment: Earth Fissures In Central Arizona

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DEGRADATION OF AN ARID ENVIRONMENT:
EARTH FISSURES IN CENTRAL ARIZONA

A Dissertation

Presented to

The School of Graduate Studies

Indiana State University

Terre Haute, Indiana

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

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by

Leonard H. Alger

December 1982

APPROVAL SHEET

The dissertation of Leonard H. Alger, Contribution to the School of Graduate Studies, Indiana State University, Series III, Number 273, under the title Degradation of an Arid Environment: Earth Fissures in Central Arizona is approved as partial fulfillment of the requirements for the Doctor of Philosophy Degree.

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ABSTRACT

The surficial desertification and degradation characteristics of major elements of the natural environment (vegetation, drainage, and morphology) associated with the development of earth fissures were investigated. Three appropriate fissure sites within a general study area located southeast of Phoenix, Arizona were carefully selected to minimize cultural influences.

Data for analysis were collected from satellite imagery and aerial photography, and from ground level surveys. Traditional remote sensing analysis techniques were employed to identify degradational characteristics which appear on the various remotely-sensed data bases. Remote sensing techniques were incorporated into the investigation to provide an overall, comprehensive view to enhance the spatial arrangement of anomalies suggestive of degradational characteristics. On-site data collection involved taking calculated transects across the various fissures to provide micro-scale information suggestive of degradational characteristics. These ground surveys involved the collection of physical measurements of individual fissures; apparent plant stress information; gross thermal characteristics; erosional characteristics and anomalies; and apparent surficial changes in the natural drainage, morphology, and vegetation.

The results of analysis indicate that the occurrence of true desertification does not exist, but that degradation clearly exists, primarily in the form of erosion, and is the result of earth fissure development. Erosion was found to occur in two ways: that which is commonplace beginning at fissures and migrating up-slope, and that which washes soil from around plant roots. In addition, minor selective changes in the vegetation, drainage, and morphology were clearly identified and proven to be the result of earth fissure development. It is concluded that erosion can not be effectively halted and, as a result, will spread widely resulting eventually in desertification.

PREFACE

This dissertation topic was undertaken as a result of the researcher's interest in worldwide desertification and, in particular, degradation of arid lands in the American Southwest. Obtaining sufficient water supplies for agricultural and urban needs is a real-life problem that must be correctly addressed and solved in the Southwest. Just as important is the understanding of environmental consequences that result when water supplies are mismanaged. Such mismanagement is occurring in areas of Arizona as groundwater supplies are being grossly over-pumped.

Thus, this dissertation is designed to serve as a preliminary investigation of environmental damage resulting from earth fissures which are, in turn, a result of groundwater mismanagement. Since no other studies are available explaining the degradational consequences related to earth fissures, it must be stressed that this study is a beginning, a foundation, for future research.

It is appropriate here to acknowledge two individuals in particular. First, Dr. Paul Mausel served as advisor and director of the dissertation. In this capacity he was exceptionally helpful, patient, and understanding. Second, my wife Pam served as editor and typist, and provided that necessary, dedicated assistance to make this dissertation possible. They will always have my deepest thanks.

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INTRODUCTION

Desertification

Investigations of the world's desert environments and the way in which man affects the various deserts have greatly increased in recent years. Studies of so-called "waste lands" are becoming extremely important as the world's human population increases, because less and less arable land is available to support more and more people. Full realization of the extent to which man occupies desert regions has come about in the last few years. For example, it has been just within the last decade or so that published conference proceedings have documented research conducted by scientists interested in the problems associated with arid environments.[1]

The primary concern of these various scientists is the rate at which arid lands are degrading. Degradation is best explained in terms of climatic fluctuations and the various activities of man.[2] The latter is commonly thought by scientists to be the primary cause for desert expansion or desert degradation (intensification).[3]

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[1]Gene Penick, Arid Lands in a Changing World, Abstracts of Contributed Papers, an international conference sponsored by the American Association for the Advancement of Science and the University of Arizona, Tucson, Arizona, June 1969.

[2]Michael Glantz, ed., Desertification, with a Foreword by Viktor A. Kovda (Boulder, Colorado: Westview Press, 1977).

[3]Ibid.

This spatial phenomenon of desert expansion and/or the physical and biotic degredation of deserts are termed desertification. Various other, perhaps more precise, definitions of desertification exist. For example, Grove suggests that desertification means ". . . a laying waste of land associated with diminishing surface water and increasingly sparse vegetation."[4] Another definition of desertification, and one that seems to include all pertinent considerations, is that proposed by Dregne. He writes:

> Desertification is the process of impoverishment of arid, semi-arid, and some subhumid ecosystems by the combined impacts of man's activities and drought. It is the process of change in these ecosystems that can be measured by reduced productivity of desirable plants, alterations in the biomass and the diversity of the micro and macro fauna and flora, accelerated soil deterioration, and increased hazards for human occupancy.[5]

One other definition, that proposed by McGinnies, states that, "desertification is the product of processes leading toward impoverishment of biota, soil depletion, and the establishment of altered erosional surfaces."[6] The occurrence of desertification is found worldwide in all warm desert regions.[7] Figure 1 shows that desertification on a

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[4]A. T. Grove, "Desertification in the African Environment," report presented at the symposium on Drought in Africa, Centre for African Studies, School of Oriental and African Studies, Cambridge University, London, 1973, p. 1.

[5]Harold E. Dregne, "Desertification: Symptom of a Crisis," <u>Desertification: Process, Problems, Perspectives</u>, ed. Patricia Paylore and Richard A. Haney, Jr. (Tucson, Arizona: University of Arizona, 1976), p. 12.

[6]William G. McGinnies, "Ecology of Desertification," <u>Desertification: Process, Problems, Perspectives</u>, ed. Patricia Paylore and Richard A. Haney, Jr. (Tucson, Arizona: University of Arizona, 1976), p. 40.

[7]Ibid.

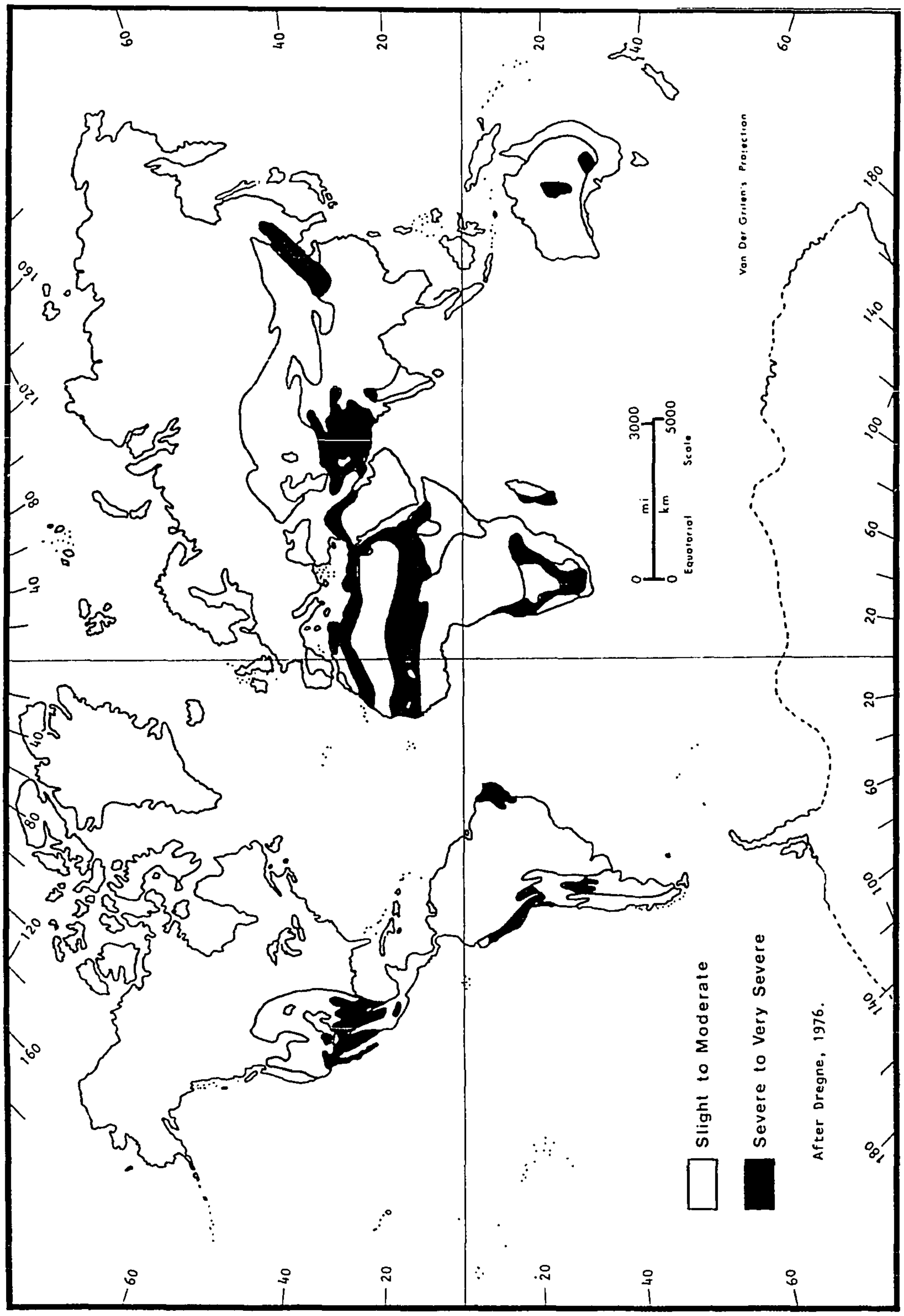

Fig. 1. Worldwide desertification

worldwide basis is not only wide-spread but also varies from slight to very severe.

Of the 124 million square kilometers (48 million square miles) of arid and semiarid land on the earth's surface, 78 million square kilometers (30 million square miles), or 19 percent, of the earth's land surface are threatened by desertification.[8] This is significant because one-sixth of the world's population, 600 to 700 million people, occupies dry land regions.[9] Approximately 50 million people (8 percent) of the total arid lands population are threatened by desertification.[10]

Perhaps most severely affected is the African continent, where the southern side of the Sahara Desert is moving south 48 kilometers (30 miles) every year. The northern side of the Sahara loses nearly 100,000 hectares (247,000 acres) to desertification each year.[11]

The Peoples' Republic of China (China) is also losing land to desertification. Verbal communications with Chinese geographers from Peking suggested that China is attempting to halt the expansion of the Takla Makan Desert through reforestation measures along the current periphery of the desert.[12] Documentation of a tree-planting campaign indicates that areas in southern China are experiencing denudation problems because past practices called for the clearing of trees to

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[8]Kenneth Brower, "The Ungreening," Omni, December 1980, p. 70.

[9]Ibid.

[10]Douglas L. Johnson, "The Human Dimensions of Desertification," Economic Geography 53 (October 1977):318.

[11]Dregne, "Desertification," p. 13.

[12]Interview with Yang Shih-gen and Ch'eng Chi' Ch'eng, Geographers, Peoples' Republic of China, Terre Haute, Indiana, 9 October 1978.

plant grains for the rapidly increasing population. As a result, more land is lost from agricultural production because of severe erosion than if forested areas were left standing.[13]

The degradation of arid lands in North America (figure 2), more precisely, the Sonora Desert of Mexico and Arizona, is not as apparent as degraded lands in, for example, Africa or China. The reasons for this are not yet clear. Several factors appear to be contributing to the differences in desertification between North America and Africa or Asia. For example, these differences may result from technological differences, conservation practices, climatic factors, varied population rate increase, or any combination of these. Perhaps too, more arid land research interests have centered on the African environment rather than on the American Southwest.[14]

Causes of Desertification

The causes of desertification generally are multiple. A review of the literature has indicated that desertification is a result of either climatic or cultural factors or both.[15]

During periods of deficient precipitation most vegetation types tend to be under more stress than normal. This, in turn, restricts soil development, although soil degradation tends to be minimal assuming

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[13]Jay Mathews, "China Proposes Huge Tree-Planting Campaign to Save Land," Arizona Republic, 30 March 1980, Sec. AA, p. 2.

[14]The Periodical Economic Geography 53, no. 4, October 1977, contains many references to desertification, most of which are directed toward the African environment.

[15]Dregne, "Desertification," p. 14.

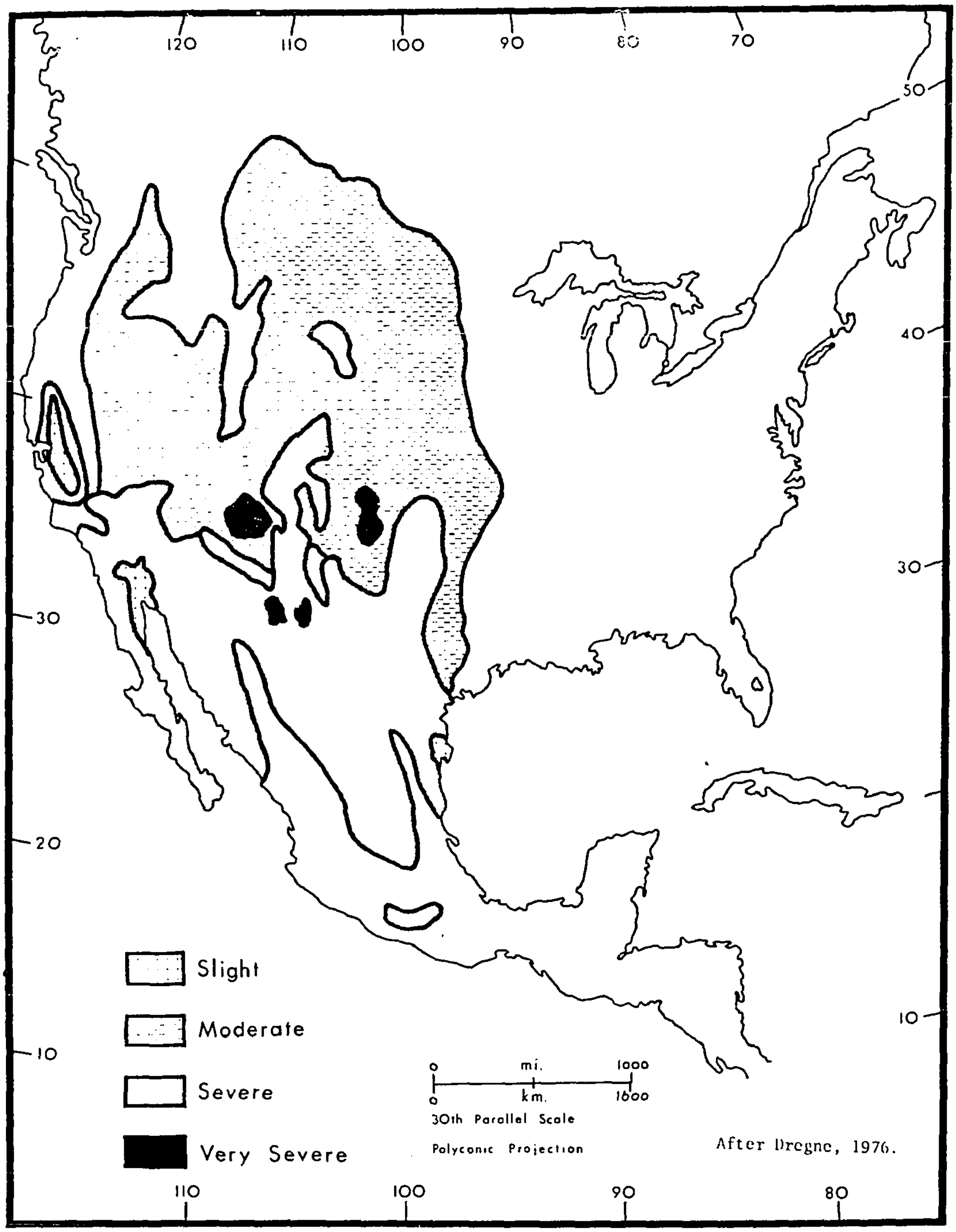

Fig. 2. Desertification in North America

non-interference by man.[16] A specific explanation of climatological desertification appeared in a recent article suggesting that 20,000 years ago Saharan sands were approximately 400 kilometers (667 miles) north of the present limit.[17]

The occurrence of desertification in recent years along the southern boundary of the Sahel might, from a climatological standpoint, be best explained by synoptic climatology. The movement of the Intertropic Convergence Zone (ITC), corresponding with seasonal change in the southern Sahara, tends to control the amount of precipitation received in this intensely desertified area. In winter months, the dominant Azore high pressure cell works contiguously with a broad, but weak, low pressure belt across central Africa. Together these pressure systems bring hot, dry air from the northern Sahara region insuring dry conditions. Summer months experience essentially a reversal of the winter season but precipitation to the southern Sahara, however, results primarily from convective activity when the ITC moves up over this region. In addition, if the ITC fails to move north to its normal 18° north latitude point, then drought conditions may begin in regions which are not accustomed to prolonged dry spells.[18]

This concept of climate influencing the occurrence and spread of desertification is valid, but it must be stressed that desertification is ". . . an inevitable encounter between human livelihood systems

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[16]Ibid.

[17]Brower, "Ungreening," p. 108.

[18]J. F. Griffiths, ed., Climates of Africa (New York: Elsevier Publishing Company, 1972), p. 76.

and the physical environment from which they must extract a living."[19] This fact is agreed upon by virtually all researchers of desertification.

It is also the concensus of researchers of desertification that human influences, more than climate, are the principal agents responsible for desertification. For example, one writer suggests four ways in which people help to expand or intensify desert regions: the expansion of agriculture into rainfall-deficient areas, poorly-planned irrigation, overgrazing, and the collection of wood for fuel.[20]

Perhaps the problem is not this simple. Hare, Kates, and Warren suggest two major patterns of change in human society as being causal in desertification. The first is population dynamics and the second involves changes based on the interaction of society at varying scales.[21]

Population change tends to have the most dramatic effect on desert landscapes by causing increased pressures to be placed on the resource base. The effect of social change on desertification manifests itself in three ways: the onset of more complicated socioeconomic systems, new versus old technologies, and the capability and consistency for local governments to manage marginal lands.[22]

Land Subsidence

Because almost all publications on desertification focus on environments in other parts of the world, various causes of land

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[19] Johnson, "Human Dimensions," p. 319.

[20] Brower, "Ungreening," p. 108.

[21] F. Kenneth Hare, Robert W. Kates, and Andrew Warren, "The Making of Deserts: Climate, Ecology, and Society," Economic Geography 53 (October 1977):339.

[22] Ibid., p. 340.

degradation in North America seem to go unnoticed. It is also difficult to apply the previously-referred-to human influences to the occurrence of desertification in the American Southwest. In fact, technological advances and the American socioeconomic system are combining to help the spread of land degradation in ways different from the rest of the world. Wilson, for example, suggests that the key to desertification in the American Southwest is groundwater overdraft.[23]

Groundwater overdraft, which is the result of the mining of groundwater, is the chief cause of land subsidence. Land subsidence is now the most apparent aspect of a changing desert landscape in the southwestern United States. It should be noted here that overgrazing is also quite apparent, but it is a problem that can be, and is being, managed. Land subsidence, on the other hand, is very difficult to control.[24]

Greater technological capabilities for drilling deep wells in North America have resulted in the drilling of many deep wells throughout much of the southwestern United States to supplement surface waters.[25] For example, one deep well located in northwestern Phoenix, Arizona is 520 meters (1707 feet) deep and withdraws 3778 liters

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[23]Andrew W. Wilson, "Technology, Regional Interdependence and Population Growth: Tucson, Arizona," Economic Geography 53 (October 1977):389.

[24]Arizona Department of Water Resources, Water Resources Center, and Office of Arid Land Studies, Arizona Water Resources Project Information (Tucson, Arizona: University of Arizona, August 1980), p. 3.

[25]R. L. Laney, Richard Raymond, and Carl C. Winikka, Maps Showing Water-Level Declines, Land Subsidence, and Earth Fissures in South-Central Arizona, Open-File Report of the U.S. Geological Survey, Water Resources Investigation 78-83 (Tucson, Arizona: U.S. Geological Survey, 1978).

(1000 gallons) a minute. Few deep wells (traditionally hand-dug) have been utilized in the arid African environment. Instead, the capturing and channeling of rainwater has been the most important source of water.[26] The result is that land subsidence and associated problems are not as significant a problem in arid Africa as in some of the agricultural communities of Arizona. This difference manifests itself in the large quantities of water required by large, modern farming practices, while nomadism and subsistence farming are still common on the African continent.

The best known areas of land subsidence in the United States are those in California.[27] For example, the most intense area of subsidence may well be in the San Joaquin Valley where it is estimated that the land surface has subsided as much as 9.2 meters (30 feet) because of groundwater mining to meet irrigation needs. Another area of publicized subsidence in California is the Long Beach region. Here subsidence has occurred because of the pumping of subterranean oil resources.[28]

Less notice and concern exist for land subsidence in Arizona compared with regions such as California. In fact, records of land subsidence exist since 1925[29] in California, while subsidence in Arizona was not noted until 1934 by the U.S. Geological Survey and the National

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[26] KAET Television Station Channel 8, "Desertification," Public Broadcasting System (Tempe, Arizona: Arizona State University, 8 April 1980).

[27] State of California Resources Agency, Landslides and Subsidence--Geologic Hazards Conference (Los Angeles, California: The Resources Agency, 1965), pp. 90-169.

[28] Thomas Y. Canby, "Water: Our Most Precious Resource," National Geographic, August 1980, p. 171.

[29] Ibid.

Geodetic Survey while surveying an agricultural valley of central Arizona. The land surface subsidence correlated with declining groundwater levels in that area. Although little data have been made available for land subsidence in the Phoenix area[30] (the general area of this research) other than the simple mapping of selected fissures, recognition of the severity of the problem is exemplified by a 311 square kilometer (120 square mile) area near Eloy. This region, about 67 kilometers (40 miles) south of Phoenix, has subsided between 2.13 meters (7 feet) and 3.8 meters (12.5 feet) since 1952.[31] At another site, Winikka and Wold indicate surficial subsidence of over 1.16 meters (3.5 feet) has occurred near the tiny community of Queen Creek, which is adjacent to the study area.[32]

Causes of Land Subsidence

The causes of land subsidence are multiple. The rated authority on land subsidence, Joseph F. Poland, has indicated that subsidence can be caused by

> . . . withdrawal of fluids, the application of water to moisture deficient deposits above the water table (hydrocompaction), drainage of peat lands, extraction of solids in mining operations, removal of solids by solution, application of surface loads, and tectonic movement.[33]

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[30]Arizona Department of Water Resources, Water Resources Center, and Office of Arid Land Studies, Arizona Water Resources Project Information, p. 2.

[31]Laney, Raymond, and Winikka, Water-Level Declines, sheet No. 1.

[32]Carl C. Winikka and Paul D. Wold, "Land Subsidence in Central Arizona," Proceedings of the International Association of Hydrological Sciences 121 (Anaheim, California: International Association of Hydrological Sciences, 1976), pp. 95-103.

[33]Joseph F. Poland, "Land Subsidence in Western United States," Conference Proceedings Geologic Hazards and Public Problems, Office of Emergency Preparedness (Santa Rosa, California: Office of Emergency Preparedness, Region Seven, Federal Regional Center, 1969), p. 77.

In the western United States the withdrawal of fluids, primarily water, is the most intense of the various factors causing subsidence.[34]

The withdrawal of water reduces the fluid pressure in the aquifer and increases the effective stress (grain-to-grain load) which is dependent upon buoyant support. For every foot of saturated sediments, the effective stress increases by 0.6 as water is lost from those sediments. The effect of this increase in stress is immediate.[35]

As the ground water is mined and the aquifer depleted, compaction of sediments increases because the buoyancy factor previously available is lost. The result can be observed at the surface in the form of subsidence when leveling across suspected subsidence valleys is taken and recorded. It is this subsidence (or compaction of sediments) that is hypothesized to be the cause of fissures.

The effects of land subsidence are basically twofold. First, the gradient of the surface is changed thus affecting natural drainage, erosion, irrigation systems, and flood-control projects. Second, earth cracks, or fissures appear at the surface and, as they enlarge over time, they alter surface runoff and erosion, transportation networks, utilities, and other cultural features.[36]

The term "earth fissure" is defined as a narrow vertical crack in alluvial deposits. Fissures, which are the focal point of this investigation, may first appear as very narrow cracks along the surface, as a series of holes, or even as abrupt gorges several meters wide.

[34] Ibid.

[35] Thomas L. Holzer and Earl H. Pampeyan, "Earth Fissures and Localized Differential Subsidence," Water Resources Research 17 (February 1981):223.

[36] Laney, Raymond, and Winikka, Water-Level Declines, sheet No. 1.

The depth of fissures is also variable; from a few centimeters to a few meters is common. Their occurrence is always adjacent to desert mountains where support of alluvium by underlying bedrock is greatest. Usually there is no vertical offset.[37]

Causes of Earth Fissures

The cause of earth fissures is thought to be man-induced through the mining of groundwater, in turn causing subsidence, although the specific mechanism of earth fissure formation has not yet been demonstrated.[38] Other hypotheses regarding the formation of fissures, such as desiccation, horizontal seepage forces, and rotation of rigid slabs of overburden responding to regional differential subsidence, have not been as strongly accepted as has the idea of differential subsidence because of groundwater withdrawal. It should be noted that to date no definite cause of fissuring has been proven, but research strongly suggests that earth fissuring is a result of differential subsidence caused by differential compaction as fluids are withdrawn from the sediments.[39]

As groundwater is depleted and compaction of sediments occurs, compaction is greatest in areas where distance to the water table is greatest. But where bedrock lies closer to the surface, compaction of sediments, and thus subsidence, is negligible. As a result, tensile stress is applied to that point where subsiding sediment in the alluvial valley meet those sediments that are not subsiding and which lie over

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[37]Ibid.

[38]Holzer and Pampeyan, "Earth Fissures," p. 223.

[39]Ibid.

the buried bedrock. Figure 3 illustrates this effect. The result is the development of a shear zone caused by the subsidence which, in turn, causes pulling from one side while stationary, nonsubsiding sediments on the other side resist pulling.[40]

Surficial changes associated with earth fissures are becoming increasingly apparent to many scientists; however, research on the effects which fissures exert upon their surrounding natural environments has not been conducted. Thus, an investigation to determine if earth fissures cause degradation of major elements of the surrounding natural environment (within 16.5 meters, 50 feet) seemed warranted.

Dissertation Hypothesis

This investigation was conducted under the hypothesis that earth fissures, resulting from groundwater depletion and the corresponding land subsidence, cause isolated areas of surficial degradation of major elements of the natural environment immediately adjacent to fissures within the selected study area. Degradation is defined by this researcher as the initial visible stage of desertification, not yet regional in scope, and refers to the decrease in quality of biotic communities and destruction of surface and subsurface soils.

Study Area

The study area for this research is located in eastern Maricopa County, Arizona near the small agricultural community of Chandler Heights. This area lies approximately 32.6 kilometers (20 miles) southeast of the greater Phoenix metropolitan area. The fissure field

[40]Ibid.

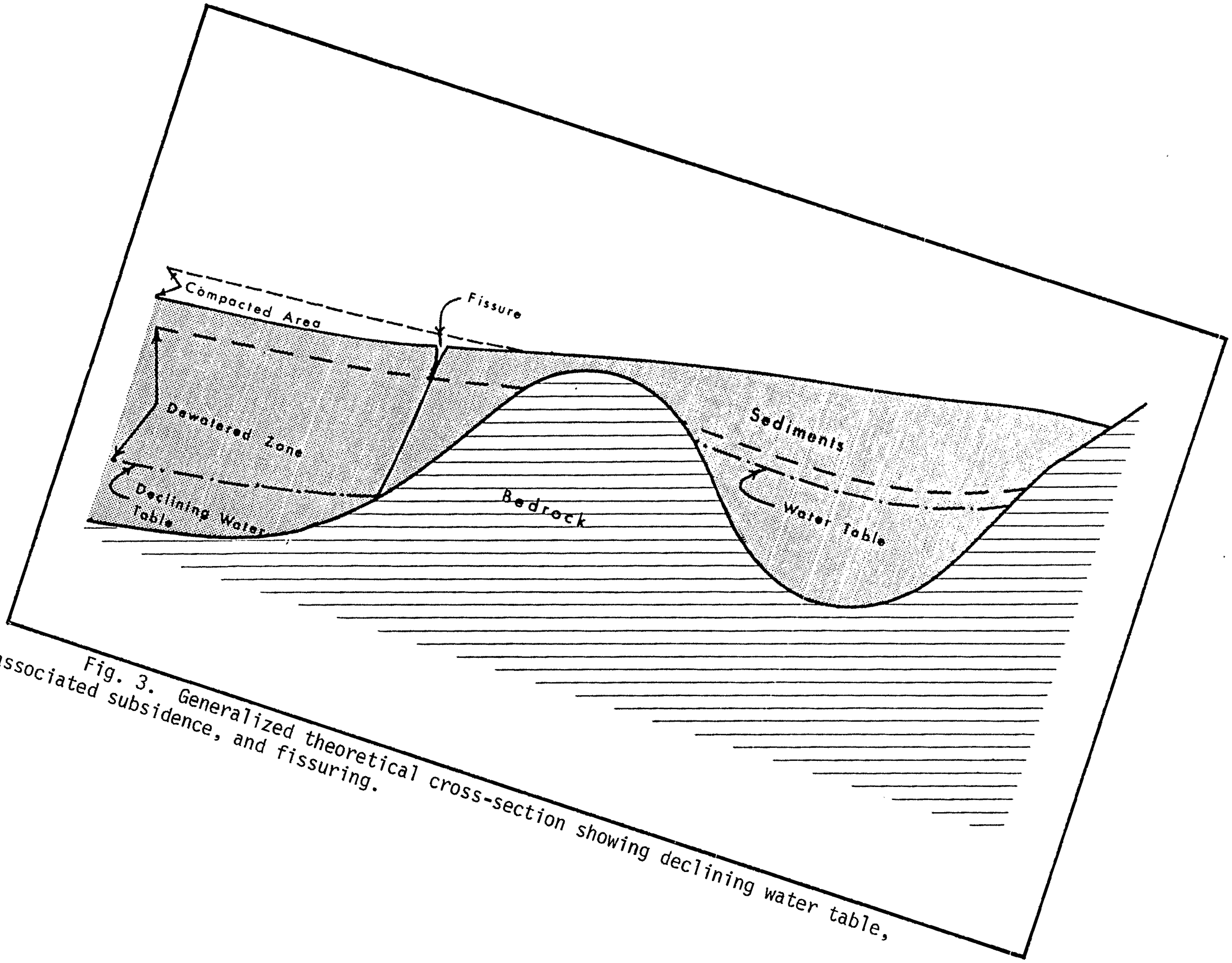

Fig. 3. Generalized theoretical cross-section showing declining water table, associated subsidence, and fissuring.

of interest stretches approximately 8.15 kilometers (5 miles) in an east-west direction. Figure 4 delineates this study area fissure field, and three specific sites of interest within it, as the area parallels the northern boundary of the Santan and Goldmine Mountains.

This study area is not located within housing developments or agricultural fields, nor does this area have major transgressing transportation routes. The natural desert setting surrounding the fissure field may well be one of the very few in arid North America. There are, however, a few homes and citrus groves in the general area. It is expected that the fissures will expand into the nearby agricultural and residential areas as they have done in several other locations in central Arizona.[41]

Geologically, the study area contains a water bearing unit of alluvial sediments approximately 244 to 366 meters (800 to 1200 feet) thick.[42] It is these sediments that compact as groundwater is removed. It is estimated that almost all of the mined and yet unmined groundwater was accumulated during previous geologic periods of wetter climates.[43]

The climate of this area is typical of warm deserts. Winters tend to be mild since the average maximum temperature for the six winter months (October through March) is 22.7°C (72.9°F), as indicated by Phoenix temperatures. The average minimum temperature for the corresponding time period is 6.6°C (43.9°F). The six summer months (April

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[41]Winikka and Wold, "Land Subsidence," p. 98.

[42]M. E. Cooley, Map Showing Distribution and Estimated Thickness of Alluvial Deposits in the Phoenix, Arizona Area, U.S. Geological Survey, 1973.

[43]Thomas Clark, Phase 1 Arizona State Water Plan--Inventory of Resource and Uses (Phoenix, Arizona: Arizona Water Commission, 1975), p. 45.

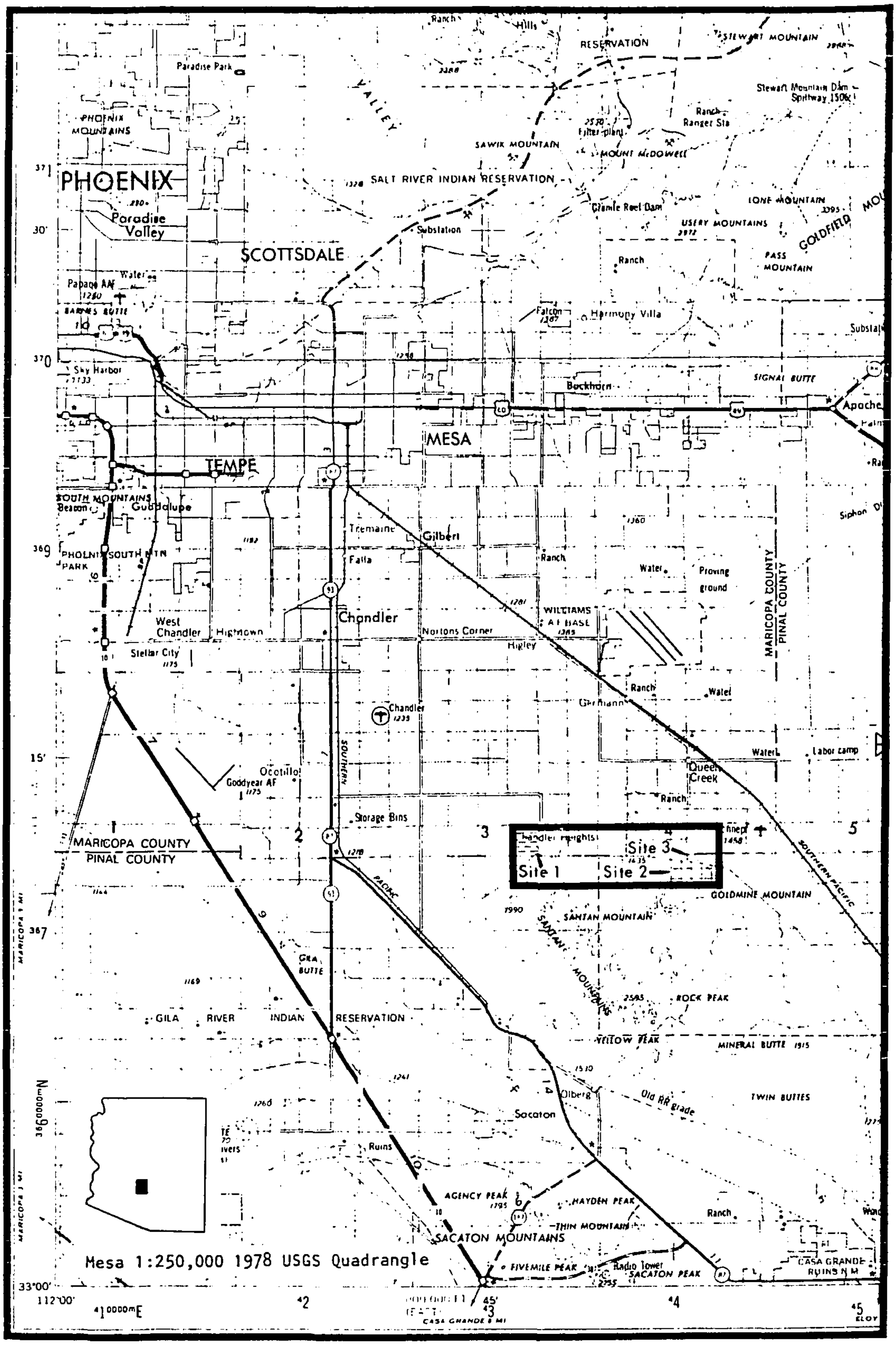

Fig. 4. Study area within Arizona

through September) tend to be much warmer. The average maximum temperature for these summer months is 36.2°C (97.2°F), while the average minimum temperature for the corresponding time period is 19.4°C (67.0°F).[44]

The potential evaporation of the general study area exceeds the average annual precipitation of 17.63 centimeters (7.05 inches) by a factor of approximately 6.[45] Most moisture is received during midwinter frontal activity and occasional tropical storms. Convective summer storms, although few, begin in midsummer as the controlling thermal low pressure system helps to bring in moist tropical air. Nevertheless, it is probable that groundwater replenishment from precipitation and runoff is insufficient to keep pace with the rate of groundwater withdrawal.

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[44]Valley National Bank of Arizona, Arizona Statistical Review, 35th ed., Economic Research Department (Phoenix, Arizona: Valley National Bank, 1979), p. 56.

[45]Interview with Dr. Anthony Brazel, Office of State Climatology, The Laboratory of Climatology, Arizona State University, Tempe, Arizona, 19 June 1980.

Chapter 2

REVIEW OF RELATED LITERATURE AND RESEARCH

The Office of Arid Land Studies (OALS) at the University of Arizona is a world center for the study of desertificaton and desert degradation and, consequently, has much of the available literature on world desertification. The subject matters reviewed focused on desertification, land subsidence, and earth fissures. Brief discussions of some of the more prominent and appropriate literature follow.

A. T. Grove prepared an excellent study on desertification entitled Desertification in the African Environment for the 1973 Symposium on Drought in Africa. There are four separate discussions within the article. Grove first presents a historical description of climatic change over the last twenty thousand years for the entire African continent and a discussion of climatic change on a regional basis.[1] The second section focuses on man's role in desert encroachment. Again, a historical perspective is placed on such topics as burning of vegetation, overgrazing, cutting of wood for fuel, and cultivation.[2] The third section describes past and present methods used for locating and measuring the rate of desert encroachment. Grove suggests that remote sensing techniques can be of great value, especially infrared photography; and since comparative remote sensing studies have not been

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[1]Grove, "African Environment," pp. 1-23.

[2]Ibid.

widely exploited in the study of desertification, they are, therefore, encouraged.[3] The fourth section describes methods of combating desert encroachment. Because Grove focuses on the African environment, his discussion is limited to reclamation associated with pastoral cultures.[4]

One of the more recent works on desertification is the publication Desertification, edited by Michael H. Glantz.[5] This book is a contribution of articles by various authors knowledgeable in various phases of desertification. It is a comprehensive and basic source of information on desertification focusing primarily upon the African continent.[6]

The article by Bahre and Bradbury, "Vegetation Change along the Arizona-Sonora Boundary," does not refer to desertification as such, but incorporates the ideas of desertification.[7] A comparative analysis of vegetation change along boundary markers using photographs taken in 1892, 1969, and 1976 revealed drastic changes in the vegetation cover over time. In the late 1800s drought and overgrazing destroyed much of the vegetation in the area. Subsequently, vegetation cover has returned and the grass cover is now quite dense. A pronounced difference of surficial vegetation cover has developed since the construction of the fence line marking the border between Mexico and the United States.

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[3]Ibid.

[4]Ibid.

[5]Glantz, Desertification.

[6]Ibid.

[7]Conrad J. Bahre and David E. Bradbury, "Vegetation Change along the Arizona-Sonora Boundary," Annals of the Association of American Geographers 8 (June 1978):145-65.

Management of grazing lands on the U.S. side has been more successful than on the Mexican side, as can be attested to by higher abundance of grass cover.[8]

Kharin has published an article describing the general techniques remote sensing can contribute to the monitoring of desertification processes.[9] He cites examples of climatic desertification (such as deficient precipitation), anthropogenic desertification (the location and movement of cultural features and centers), and desertification which is the result of natural events (severe flash flooding and fires). This article provides insights into remote sensing of desertification in the Soviet Union.[10] Much more research involving remote sensing of desertification has been conducted in the Soviet Union than in the United States.

A publication of maps and associated text by Laney, Raymond, and Winikka provides indirect evidence that the mining of water in central Arizona is contributing to the occurrence of desertification.[11] Since 1923, groundwater recharge has not equaled the amount pumped from the ground for agricultural and municipal uses. This, in turn, has caused compaction of alluvial materials such that the surficial slope of the land has been changed, increasing the gradient of drainage channels and causing accelerated erosion and gullying. This erosion has the

[8] Ibid.

[9] N. G. Kharin, "Remote Sensing Techniques and the Monitoring of Desertification Processes in Arid Areas," report presented to the Turkmen Academy of Sciences, Institute of Deserts, Moscow, U.S.S.R., 1977.

[10] Ibid.

[11] Laney, Raymond, Winikka, Water-Level Declines, sheet No. 1.

effect of washing away soil from around the already sparse vegetation and diverting water away from needed areas, and the resulting vegetation stress may be the primary key to the identification of desertification in North America.[12]

Other corresponding maps are those by Ross[13] and Laney, Ross, and Littin.[14] These maps illustrate, and the text briefly describes, groundwater conditions in eastern and western Maricopa County, Arizona. In the area representing the main water-bearing unit, contours show water level altitude above sea level and other contours indicate depth to groundwater. Although a few isolated areas have depths to groundwater of over 213 meters (700 feet), the average depth is in the range of from 91 to 152 meters (300 to 500 feet). Generalized directions of groundwater flow are also indicated.[15]

One other map of direct importance to this study is that by Schumann which indicates the distribution and amounts of subsidence in a large, somewhat irregular, area around Phoenix, Arizona. Also indicated on the map are earth fissures of 1970. Although Schumann's

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[12] Ibid.

[13] P. P. Ross, Maps Showing Ground-Water Conditions in the Western Part of the Salt River Valley Area, Maricopa County, Arizona--1977, U.S. Geological Survey Water-Resources Investigation 78-40 (Tucson, Arizona: U.S. Geological Survey, 1978).

[14] F. L. Laney, P. P. Ross, and G. R. Littin, Maps Showing Ground-Water Conditions in the Eastern Part of the Salt River Valley Area, Maricopa and Pinal Counties, Arizona--1976, U.S. Geological Survey Water-Resources Investigation 78-61 (Tucson, Arizona: U.S. Geological Survey, 1978).

[15] Ibid.

research was comprehensive, it is apparent that many new fissures have appeared in the last decade.[16]

Raymond, Winikka, and Laney designed a field-trip/road-log guide to selected earth fissures along the southeastern boundary of Maricopa County.[17] The log briefly describes the characteristics and facts about existing earth fissures. Included are several photographs showing some fissures as large gullies. Other fissures mentioned, but not quite as large, are still of importance because many are beginning to cross highways causing cracks in the asphalt.[18]

Winikka and Wold give a brief account of land subsidence in central Arizona.[19] They suggest that land subsidence has been an ongoing process since the 1940s because of groundwater withdrawal. For example, subsidence for an area near Eloy, Arizona between 1948 and 1967 was 2.29 meters (7.4 feet). Another area east of Mesa, Arizona has subsided approximately 1.13 meters (3.6 feet). Subsidence seems to be a renewed process since intensive groundwater mining began in the 1960s.[20]

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[16]H. H. Schumann, Land Subsidence and Earth Fissures in Alluvial Deposits in the Phoenix Area, Arizona, Map 1-845-H (Washington, D.C.: U.S. Geological Survey, 1974).

[17]Richard H. Raymond, Carl Winikka, and R. L. Laney, "Earth Fissures and Land Subsidence, Eastern Maricopa and Northern Pinal Counties, Arizona," Bureau of Geology and Mineral Technology, Guidebook to the Geology of Central Arizona, edited by D. M. Burt and T. L. Pewe (Tucson, Arizona: University of Arizona, 1978), pp. 107-14.

[18]Ibid., p. 107.

[19]Winikka and Wold, "Land Subsidence."

[20]Ibid., p. 95.

Wilson focused on a city in Arizona and its influence on desertification.[21] It was claimed that although desertification has been observed in the Tucson area, the local population had been shielded from the rather harsh realities of desertification by modern technology. Wilson suggested that the agricultural activity in the area is essentially expendable because it only employs 1 percent of the population but uses most of the mined water. It is further suggested that agriculture requiring irrigation should be eliminated since Tucson receives virtually all of its food from more humid regions of the United States. The underground water could then be mined for municipal purposes thereby allowing greater population growth.[22]

A frequently referenced article on land subsidence is that by Poland.[23] The author describes three types of subsidence: organic deposits due to drainage, application of water (hydrocompaction), and withdrawal of fluids. The problem created by subsidence and explorations of subsidence in the southwestern United States and remedial actions, such as repressuring operations and the importation of water, are discussed.[24]

The only study found to date that is an actual analysis of land subsidence rather than the typical descriptive discussion is that by McCauley and Gum.[25] Their intent was to investigate a fissure area for

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[21]Wilson, "Tucson, Arizona."

[22]Ibid., p. 389.

[23]Poland, "Land Subsidence," pp. 77-96.

[24]Ibid., pp. 84-85.

[25]Charles McCauley and Russell Gum, "Land Subsidence: An Economic Analysis," American Water Resources Association, Water Resources Bulletin 11, no. 1 (Minneapolis: American Water Resources Association, 1975), pp. 148-54.

economically-related problems caused by subsidence. The authors concluded that there was little or no economic change exerted by land subsidence upon the selected study area.[26]

One of the earliest published articles about earth fissures is that by Leonard.[27] His 1929 article described one of the first-discovered earth fissures in Arizona. The site was near Picacho and crossed the main railroad right-of-way. A search for the cause revealed three possibilities: a saturation of sediments following a torrential downpour; tectonic disturbances in the underlying rock structure; and earth vibrations originating many miles away. The latter, a distant earthquake, was thought to be the actual cause of the earth fissure.[28]

In 1965, Kam described earth cracks (fissures) as an important cause of gullying.[29] He suggested that fissures result from subsidence caused by differential compaction of unconsolidated sediments. These fissures can take on any shape regardless of the drainage pattern. Where fissures cross drainways lower base levels are established, resulting in a more rapid erosion rate and the consequential formation of gullies upstream. Research indicates that if drainways are not crossed by fissures, gullies tend to form upstream. Where the material beneath the fissures does not absorb the water carried by the gullies, streams

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[26]Ibid., p. 153.

[27]R. J. Leonard, "An Earth Fissure in Southern Arizona," Journal of Geology 37 (1929):765:74.

[28]Ibid., p. 774.

[29]William Kam, "Earth Cracks--A Cause of Gullying," U.S. Geological Survey, U.S. Geological Survey Professional Paper No. 525 (Washington, D.C.: U.S. Government Printing Office, 1965), pp. B122-25.

diverted along the fissures may lead to changes in the drainage pattern.[30]

An article by Lofgren on the analysis of stresses causing land subsidence suggested that subsidence is related directly to effective stress changes resulting from changes in the groundwater level.[31] Even though stress changes are often difficult to calculate, these changes can occur in two major ways. Water table fluctuations change the buoyant support of grains in the zone of change, and a change of the water table may induce hydraulic gradients and seepage stresses in the deposits. The author claims that these changes are additive in their effect, and together cause compaction.[32]

A study by Charney and others investigated the effects of albedo change on the amount of rainfall received at six selected sites.[33] Two sites each in Africa, Asia, and North America were selected with one site in each case on the desert/non-desert boundary and one site within the non-desert region. Those desert sites having high evaporation and an albedo change of from 0.14 to 0.35, for example, caused large decreases in rainfall. At the low evaporation sites (non-desert) an increase in albedo was not an efficient predictor of rainfall as in the high albedo sites. Overall results indicated that changes in evaporation are as

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[30]Ibid., p. B122.

[31]Ben E. Lofgren, "Analysis of Stresses Causing Land Subsidence," U.S. Geological Survey, U.S. Geological Survey Professional Paper No. 600 (Washington, D.C.: U.S. Government Printing Office, 1968), pp. 219-25.

[32]Ibid.

[33]J. Charney, W. J. Quick, S. H. Chow, and J. Kossinfield, "The Comparative Study of the Effects of Albedo Change on Drought in Semi-Arid Regions," Journal of the Atmospheric Sciences 34 (September 1977): 1366-85.

important as changes in albedo, although albedo proved to be the better predictor of desert conditions.[34]

Dregne presents a succinct view of desertification, on a worldwide basis, and suggests that desertification will ultimately lead to an increase in human misery.[35] If land degradation or the spread of desert environments are not halted, then human suffering will continue to increase. The author presents a careful, well though-out definition of desertification. He also suggests rates and the severity of desertification for affected areas around the world. Maps are utilized to convey this information. Other considerations confronted by Dregne are factors contributing to desertification, the impact of desertification, combatting desertification through governmental action as part of broad national development efforts, the extent of desertification, and criteria for estimating desertification hazard.[36] Although specific ideas on worldwide desertification are discussed, the author does not indicate groundwater overdraft as a factor in influencing the intensity of land degradation or the spread of desert environments.

One article that does discuss the relationship of groundwater overdraft to land degradation is that by Matlock.[37] His approach to land degradation resulting from the mining of deep groundwater does not include the occurrence and consequential effect of earth fissures on

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[34]Ibid.

[35]Dregne, "Desertification."

[36]Ibid.

[37]W. Gerald Matlock, "Segments of a Vicious Circle: Land Degradation and Water Resources," Desertification: Process, Problems, Perspectives, ed. Patricia Paylore and Richard A. Haney, Jr. (Tucson, Arizona, 1976), pp. 45-50.

the land; rather, the author suggests that previous areas of intense agriculture have now become idle lands because the expense of pumping deep underground water has become uneconomical for farmers. Farm lands, essentially abandoned, are now isolated "dust-bowl" pockets because deficient moisture supplies prevent a meaningful vegetation cover from becoming established.[38]

Only the most appropriate and pertinent publications have been reviewed in this chapter. A few of these mention earth fissures but only from the standpoint that they exist and that they pose a potential hazard to man. No article has yet been found which relates earth fissures directly to land degradation (or desertification).

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[38]Ibid., p. 50.

Chapter 3

AREA AND SITE ANALYSIS

Several methodological steps were involved in this research project. These steps included locating an acceptable study area; collecting ground level data; collecting remotely-sensed data; and analyzing, synthesizing, and classifying these data for the purpose of understanding degradational processes as they relate to the occurrence of earth fissures within the study area. Figure 5 charts the various procedural steps.

Site Selection

Prior to data collection it was necessary to select a study site which satisfied certain requirements. Chief among these requirements was a natural desert environment, free of man-made features, and one which contained several well-developed earth fissures. Also, guaranteed site accessibility (i.e., not Indian reservations or posted lands) was needed for proper data collection. Of the various areas evaluated during preliminary investigations and the literature review, only the Chandler Heights area met the stated criteria (figure 4).

The study area was divided into three sites, as indicated in figure 4, corresponding to fissure groupings. Each grouping consists of more than one fissure and has its own characteristics of vegetation surface morphology and natural drainage.

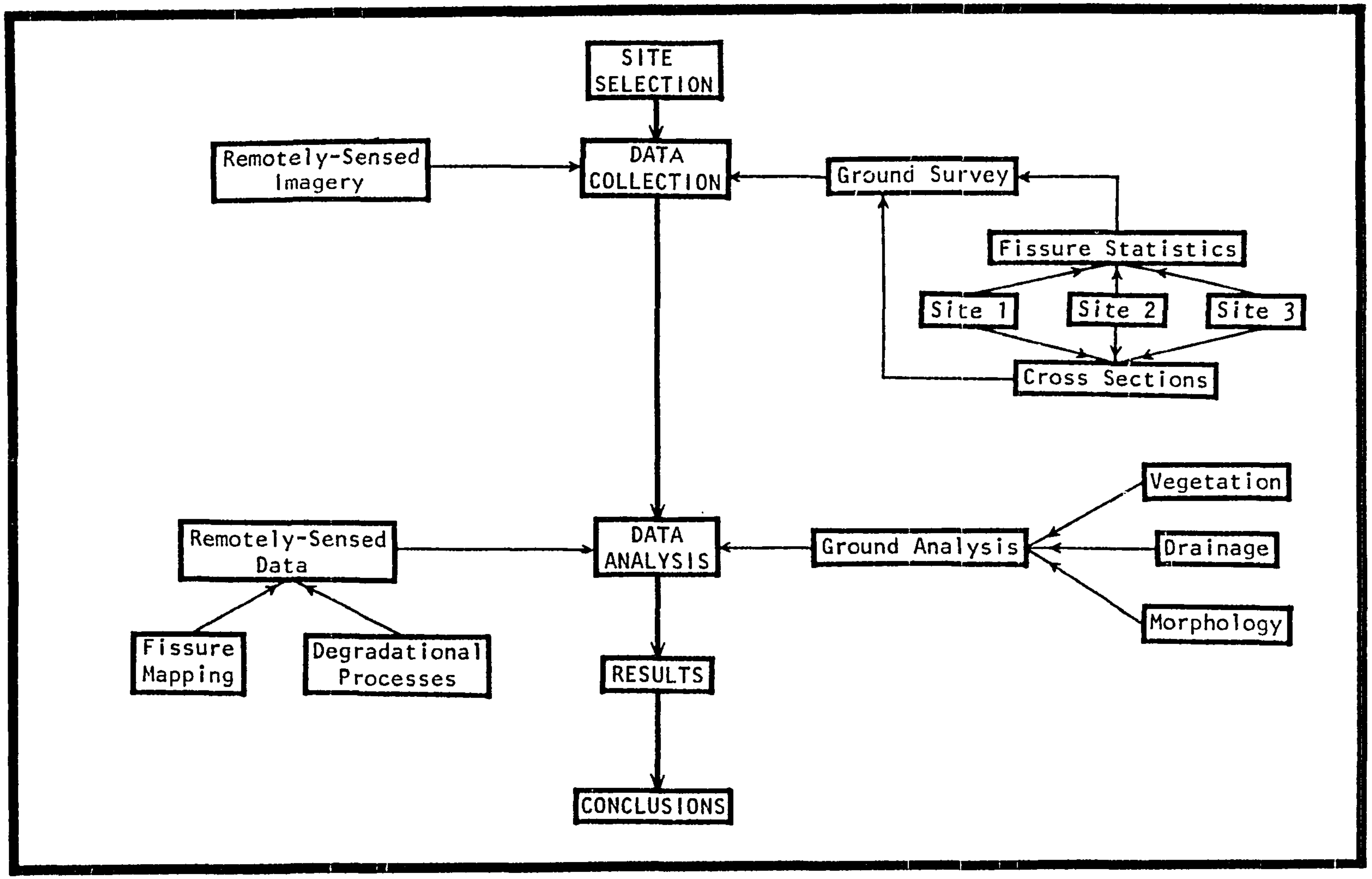

Fig. 4. Flow Chart of procedural steps

Data Collection and Analysis

Two forms of data were collected for this investigation. Remotely-sensed data were collected from aircraft and spacecraft platforms to help understand fissure patterns and characteristics through an overall view. Ground level data were collected for precise, large-scale information extraction to facilitate an understanding of degradation and vegetation stress as they are caused by the occurrence of earth fissures within the study area. The term stress is utilized by this writer to categorize those plants not exhibiting normal existence characteristics. The list of degradation and stress characteristics in Table 1 is the result of ground level observation in conjunction with analysis of low altitude, infrared photographs. Aside from naturally deficient precipitation, there are two causes of stress: lack of water because of altered drainage channels and erosion of soil from around plant roots. To better understand the causes of plant stress it is necessary to investigate drainage and morphological characteristics as influenced by earth fissures.

Prior to detailed data collection, it was necessary to evaluate the study area in terms of fissure locations, vegetation characteristics, general drainage patterns and characteristics, and locations of man-made features. After defining the study area boundary, fissures were located from information in publications, field investigation, and corresponding high altitude photography. Some fissures were easy to identify because scarce plant cover made them clearly visible, and/or because plants growing in the more eroded gullies delineated the linear fissure pattern. Other fissures were very difficult to locate because they either were not well-developed or because they were hidden by plant cover. The full

TABLE 1

DEGRADATION AND STRESS CHARACTERISTICS

Type	Characteristics
Erosion of Soil	Gullying Undermining Up-Slope Erosion
Vegetation Stress	Exposed Root Systems Loss of All Leaves Dried Limbs Losing Leaves Leaves Recently Dropped Low Reflectivity in the Green and Near Infrared

extent of fissuring in the study area was not determined until the low altitude aerial photography was analyzed.

Ground Level Survey

Three extended visits to the study area were made for the purpose of collecting ground data in the categories of vegetation, drainage, surficial morphology, fissure gully temperatures, soil characteristics, and selected physical measurements of fissures. The first trip was in June 1980 to locate fissures, obtain an overall understanding of the area, and collect selected data related to plant stress during the warmest season. In addition, discussions were conducted with individuals considered experts in land subsidence.[1] Air temperatures during the June visit approached 37.8°C (100°F) by mid-morning.

Two more visits made for data collection in December 1980 provided the opportunity to collect data during the cooler season (for comparison with data collected during the warm season). Temperatures during December approached 26.7°C (80°F) by mid-afternoon.

One purpose for collecting ground level data during the warmer and cooler seasons was to attempt to identify differences caused by seasonal precipitation. Unfortunately, drought conditions prevailed during both seasons of field work. The desert environments of Arizona generally receive precipitation during the winter months rather than during the hot summer months. The average annual precipitation for this environment is less than seven inches, as evidenced by the study area receiving virtually no precipitation between June and December 1980.

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[1]Personal conversations with Dr. Carl C. Winikka, Arizona Department of Transportation, and Dr. H. H. Schumann, U.S. Geological Survey, Phoenix, Arizona, 18 June 1980, concerning the degradational effects of earth fissures on the natural environment.

This is because a strong high pressure system was positioned over the entire western United States. As a result, jet stream paths were changed significantly northward taking with them storm tracks and thus lessening the chances for precipitation. Also, because of the high temperatures of the region, much of the precipitation that fell evaporated before reaching the surface.

Soil temperatures at selected locations and fissure depths were collected to provide an insight into subsurface moisture pockets. Equipment utilized for this step in data collection consisted of an electric thermometer and a portable radiometer. The collection of temperatures was accomplished in two phases.

First, the electric thermometer was used to collect air temperatures at 1.5 meters (5 feet) above the surface and at selected depths within the various fissures. Such temperatures were 24.0°C (75.2°F) air temperature on 21 December 1980 at 11:00 A.M.; 19.0°C (66.2°F) at approximately 92 centimeters (36 inches) deep in Fissure A of Site 1; and 21.5°C (70.7°F) at approximately 140 centimeters (55 inches) deep in the same fissure. These temperatures along various fissures varied little except for temperatures collected at depths approaching 140 centimeters (55 inches). Variable fissure depths prevented the recording of numerous temperatures at consistent depths along fissures.

The second phase of collecting temperatures involved a portable radiometer commonly used in measuring terrestrial radiation. Measuring the radiation from soils with the radiometer proved to be unreliable because solar heating effectively masked terrestrial radiation which may have given indications of subsurface patterns. Soils were very dry and temperatures bore no indication of moisture pockets. Thus, ground temperatures could not be considered as a major data source for understanding desert degradation.

Site 1

Site 1 is located in the SE 1/4 of Section 34, Township 2 South, Range 6 East. The major fissure trend direction is east-west. The eastern one-half of Site 1 has the appearance of once having been denuded of vegetation, perhaps for agricultural purposes, but now annual grasses, creosote, and palo verde trees are common over the entire site. The soil at Site 1 is Antho sandy loam (AnA) with a 0 to 1 percent slope, which is resistant to surface flow and erosion.[2] In fact, it is probable that when sufficient precipitation is received, surface flow is more in the form of sheet wash than channel flow, although a few minor drainage channels may exist. Other than drainage channels, the only surficial expressions found in these soils are related to fissuring.

Fissure statistics

Because numerous branch fissures exist, it was decided to collect measurement information from the three most dominant fissures. These fissures (Fissure A, Fissure B, and Fissure C) have the greatest length, width, and depth, and correspond with the general trend directions.

Fissure A (east-west orientation) is approximately 209 meters (682 feet) long (figure 6). The width tends to be quite narrow, from a surface due to erosion. An average width is virtually impossible to

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[2] U.S. Department of Agriculture Soil Conservation Service, _Soil Survey: Eastern Maricopa and Northern Pinal Counties Area, Arizona_ (Washington, D.C.: U.S. Department of Agriculture, 1974), p. 62.

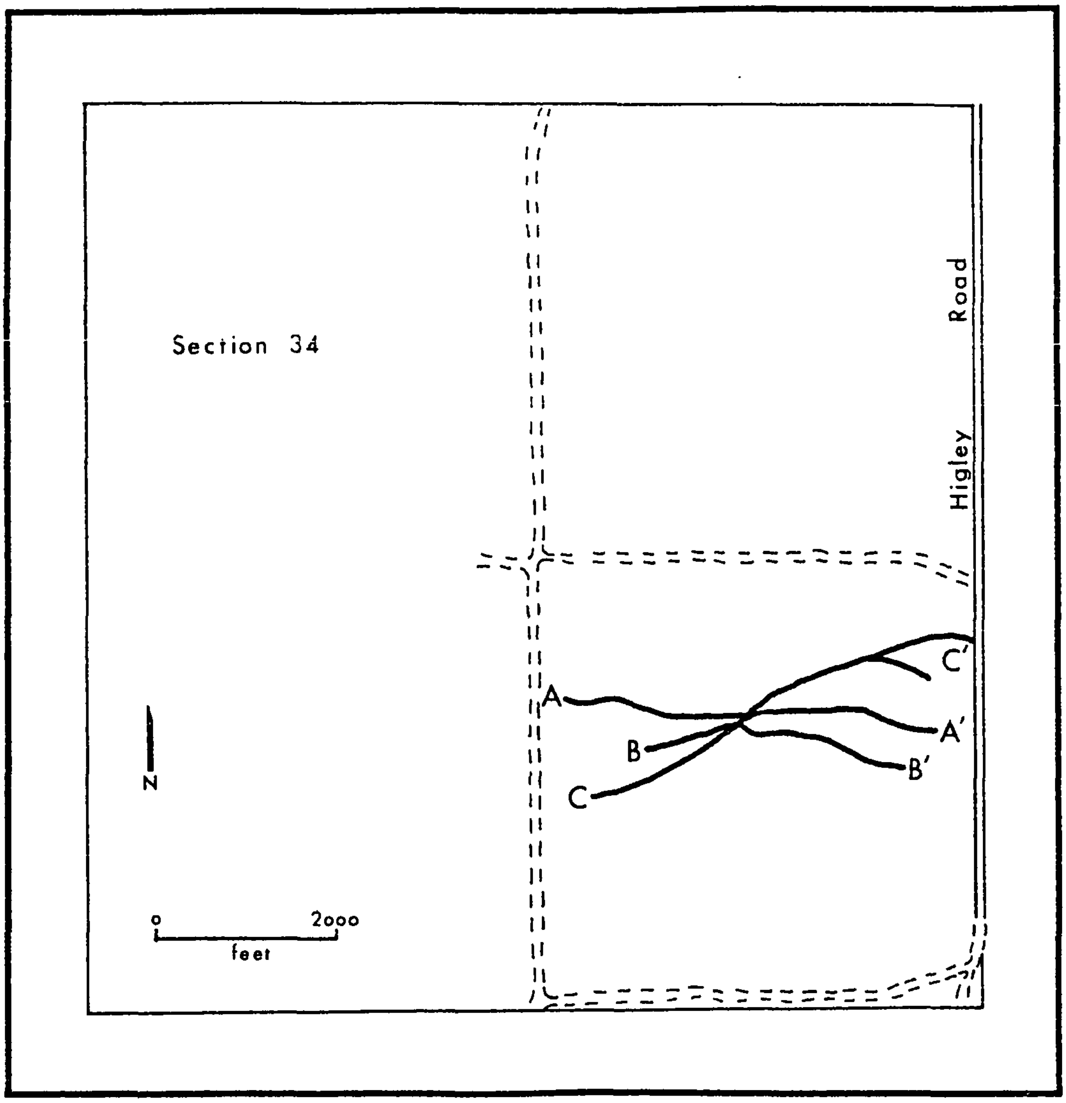

Fig. 6. Generalized fissure configuration January 1981 at Site 1, T2S, R6E, Chandler Heights Quadrangle, Arizona.

calculate, but it can be said that widths tend to be less than 1 meter (3.3 feet) except where erosion of fissure sides has been more prominent.

Depths are variable because alluvium has been deposited in most fissures. Also, differential erosion within the fissures helps to cause depth variation. Drainage of water into, and through, the fissure shear zone often results in deep holes rather than a single, linear opening into subterranean alluvium. Selected hole depths were measured, with the greatest depths measuring approximately 150 centimeters (60 inches).

Fissure B follows the same general orientation of Fissure A (figure 6). The overall length of Fissure B was measured at approximately 197 meters (640 feet), and the width was found to be similar to Fissure A, generally less than 1 meter (3.3 feet). The depth along Fissure B was inconsistent. In some instances the bottoms of holes within the fissure could not be seen because the holes often did not follow a vertical path, but, rather, angled downward so that it was impossible to obtain reliable measurements. Selected fissure depth measurements were in the general area of 150 centimeters (60 inches).

The third major fissure at Site 1, Fissure C, was found to be the longest of all the fissures at this site. It measured approximately 543 meters (1810 feet) in length in a northeast-southwest orientation before disappearing when meeting the western side of an unpaved road (figure 6). The surficial expression of the fissure reappeared on the eastern side of the road and continued for approximately 18 meters (60 feet).

The width of Fissure C can only be estimated because erosion along fissure openings has effectively masked the fissure shear zone width. Because of this, the erosional width along fissure openings varied from approximately 0.5 meters (1.65 feet) to 3 meters (10 feet).

The depths of holes in this fissure are characteristic of other fissures. Measurements were collected to approximately 150 centimeters (60 inches) deep, at which point the holes changed course and standard measuring devices were no longer useful.

Age

Comparison of the 1970 high altitude photography with the recent low altitude photography yielded interesting results. At Site 1, Fissure C is the longest and has some of the more intense areas of erosion around fissure openings; however, although this fissure appears on the low altitude photography taken in January 1981, it does not appear on the high altitude photography taken in February 1970 or March 1971 as do Fissures A and B. As a result, Fissure C is less than ten years old making it the youngest of the major fissures at Site 1. The oldest may be Fissure B since it has the most intense erosion, but the true ages of these fissures have not been established.

Comparison among fissures

The surficial relationship of fissures suggests that those fissures trending in the same general directions might be associated with the same subsurface shear zone. In many cases, these fissures tend to join one another as they are viewed at the surface.

Many fissures are separated by only a few meters. Fissures A and B, for example, are separated at the western side of the road (figure 6) by a physical distance of approximately 36 meters (120 feet). The distance between Fissures B and C, again at the road, is about 43.6

meters (142 feet); and the distance between Fissures A and C, using the road as a reference point, approaches 78.6 meters (262 feet).

Distance alone may not be indicative of direct fissure relationships, but if distance apart and directional orientation among fissures are considered together, then patterns emerge suggesting fissure relationships. For example, the smaller, often shorter, fissures generally are found close to a major fissure and take on the same general directional pattern.

Cross sections

A pattern of cross sections was designed to collect data for determining the effect various fissures have on the surrounding vegetation, drainage, and morphology. At Site 1, cross sections were taken at right angles to the three prominent fissures (A, B, and C). Cross sections were taken for a distance of 15 meters (50 feet) and at intervals of 7.5 meters (25 feet) along each fissure.

Table 2 catalogs the findings along each cross section at Site 1. Where no apparent effect of fissuring on either the surficial morphology, natural drainage, or natural vegetation for any cross section could be identified, it was left blank in the tables. In the case of Site 1 and 2 little meaningful data were collected related to the surface morphology; as a result, that category does not appear in the tables. The relationship of the cross sectional observations to the occurrence of degradation are discussed in chapter 4.

Site 2

Site 2 is located 9.4 kilometers (5.9 miles) east of Site 1 (figure 4). It has considerably more vegetation cover consisting

TABLE 2

CATALOG OF FINDINGS AT SITE 1

Cross Section	Fissure	Vegetation	Drainage Channels
1	A	. . . . .	deposition
2	A	healthy plant 35 cm below surface	deposition
3[a]	A	. . . . .	side erosion rechanneling into fissure
4	A	. . . . .	side erosion w/ rechanneling
5	A	dead plant	deposition w/ caving of side walls, rechanneling
6	A	3 creosote bushes, 1 dead	deposition
7	A	. . . . .	deposition
8	A	. . . . .	deposition
9[b]	A	. . . . .	. . . . .
10[b]	A	exposed roots	side erosion
11	A	. . . . .	headward erosion 3 m erosion finger perpendicular to fissure
12[c]	A	. . . . .	side erosion has created a drainage channel into fissure 5.5 m long w/ .3 m tributaries
13	A	. . . . .	intense headward erosion
14[d]	A	exposed creosote roots	side erosion

TABLE 2--Continued

Cross Section	Fissure	Vegetation	Drainage Channels
15	A	exposed mamosa tree root	side erosion
16	A	exposed creosote roots	side erosion
17	A	. . . . .	caving of fissure walls
1	B	. . . . .	. . . . .
2	B	. . . . .	side erosion
3	B	healthy plant	deposition
4	B	healthy plant	side erosion
5	B	healthy creosote	. . . . .
6	B	exposed creosote roots plant under stress	side erosion
7	B	vegetation growing in fissure	side erosion
8	B	vegetation growing in fissure	side erosion
9	B	vegetation in fissure exposed creosote root	. . . . .
10	B	live & dead vegetation in fissure	side erosion
11	B	large live bush in fissure	side erosion
12[e]	B	exposed creosote root	deposition
13[f]	B	exposed grass & creosote roots	intense headward erosion

TABLE 2--Continued

Cross Section	Fissure	Vegetation	Drainage Channels
14[g]	B	. . . . .	. . . . .
15[b,h]	B	. . . . .	side erosion
16[e]	B	exposed roots	. . . . .
17	B	. . . . .	. . . . .
18	B	vegetation under stress subsided w/ surficial soils to 92 cm	side erosion
19	B	. . . . .	. . . . .
20	B	stressed vegetation in hole	. . . . .
21	B	stressed vegetation in hole	side erosion
22	B	non-healthy annual grasses in area of fissure only	. . . . .
23	B	. . . . .	gullying side erosion
1	C	. . . . .	side erosion
2	C	. . . . .	. . . . .
3	C	. . . . .	side erosion
4	C	. . . . .	side erosion
5	C	. . . . .	side erosion
6	C	dead bush in fissure	side erosion
7	C	. . . . .	. . . . .
8	C	. . . . .	side erosion w/ deep hole

TABLE 2--Continued

Cross Section	Fissure	Vegetation	Drainage Channels
9	C	. . . . .	2 holes 1.2 m from main fissure
10	C	. . . . .	side erosion
11	C	live plant exposed roots	erosion slumping of fissure side
12[i]	C	. . . . .	. . . . .
13[i]	C	. . . . .	. . . . .
14	C	palo verde tree in fissure, 1.8 m tall, started in fissure	erosion washing soil from tree roots
15	C	dead grasses and plants within 1 m of fissure only, nothing beyond	. . . . .
16	C	. . . . .	side erosion
17	C	dead grasses and plants within 1 m of fissure only, nothing beyond	. . . . .
18	C	. . . . .	side erosion
19	C	palo verde growing in fissure	. . . . .
20	C	creosote growing in fissure	. . . . .
21	C	plants in fissure	side erosion
22	C	. . . . . .	. . . . .
23	C	healthy plants in fissure	. . . . .

TABLE 2--Continued

Cross Section	Fissure	Vegetation	Drainage Channels
24[j]	C	. . . . .	. . . . .
25	C	dying creosote	. . . . .
26	C	. . . . .	holes with side erosion
27	C	. . . . .	holes with side erosion
28	C	. . . . .	holes with side erosion
29	C	. . . . .	holes with side erosion
30	C	concentration of dead grass in and around old fissure hole	. . . . .
31	C	. . . . .	. . . . .

[a]Fissure 137 cm deep

[b]Fissure 152 cm deep

[c]Drainage channels drop 14 cm sharply into fissure

[d]Temperature 21.5°C at 140 cm and 19°C at 92 cm

[e]Fissure 102 cm deep

[f]46 cm drop-off

[g]Fissure B and C cross

[h]Subsiding along surficial fissure expression

[i]Folding 3.7 m away on north side and a minor crack is the only surficial fissure expression

[j]Holes on each side of fissure with no surficial expression between

Site 2

Site 2 is located 9.4 kilometers (5.9 miles) east of Site 1 (figure 4). It has considerably more vegetation cover consisting primarily of creosote bushes, mesquite, palo verde, annual grasses, saguaro cacti, and cholla cacti. The soil type is slightly different from Site 1. Antho gravelly sandy loam (AoB) with a slope of from 1 to 3 percent dominates. It is moderately alkaline, and occupies the upper parts of alluvial fans bordering the Santan and Goldmine mountains. The gravel content varies from 15 to 35 percent by volume.[3]

Drainage channels adjacent to Site 2 have dissected more deeply than those found in the vicinity of Site 1 because of the greater slope. For example, channel dissection can be found up to 30 centimeters (1 foot) deep, whereas channel depths at Site 1 average about 3.75 centimeters (1.5 inches).

Fissures statistics

Two separate fissures, referred to as Fissure A and Fissure B, were found at Site 2 (figure 7). Fissure A is 361 meters (1184 feet) in length and lies in an east/west direction, perpendicular to the natural drainage. This fissure was not as well developed as those fissures at Site 1 because less erosion has occurred at Site 2.

Depth measurements within exposed fissures were less than 30.5 centimeters (12 inches). Initially, this appeared correct, but undermining by water has caused certain portions of fissures to become deeper than realized. The researcher found this to be the case when the ground gave way beneath him while he was investigating depths along Fissure A.

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[3]Ibid.

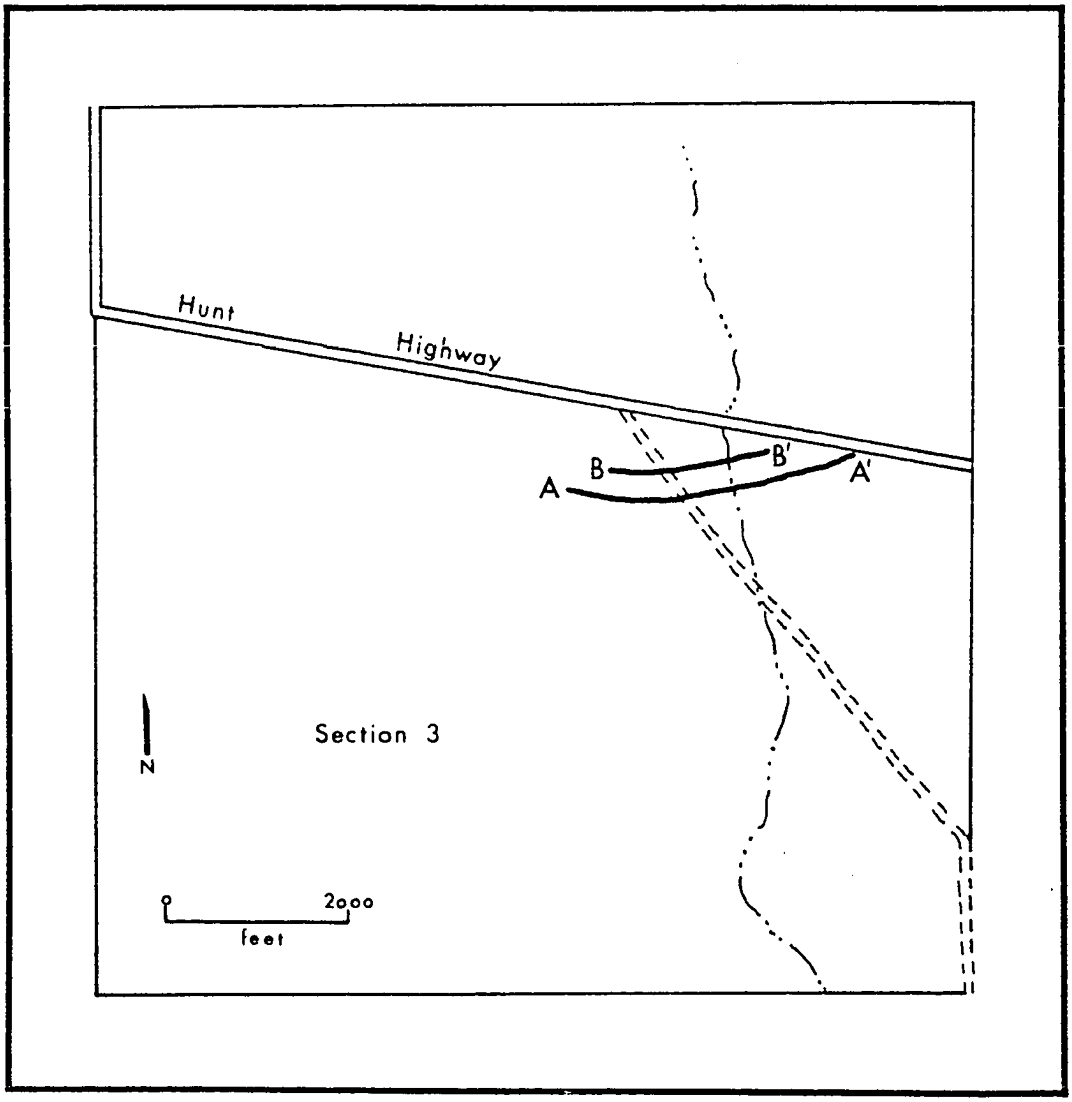

Fig. 7. Generalized fissure configuration January 1981 at Site 2, T3S, R7E, Sacaton NE Quadrangle, Arizona.

A small subsurface cavern approximately 1.2 meters (4 feet) deep was revealed and appeared to be the result of water percolating downward along the fissure shear zone.

This information is significant because there was no apparent indication of surficial fissure expression where the surface gave way. It is difficult to estimate how extensive subsurface undermining is because surficial expressions do not always exist; however, undermining was found to be more prevalent at Site 2 than at Sites 1 and 3.

The width of Fissure A was found to be quite narrow, rarely more than 15 centimeters (6 inches). On occasion, however, minor fissure branches were apparent at the surface and the total distance across measured approximately 61 centimeters (2 feet). These narrower widths have not yet been eroded to the same degree as those at Site 1, perhaps due to larger, more stabilized soil particles even though the surface slope is 2 percent steeper here.

Another measurement taken at Site 2 is the offset from one fissure side to the other. Offset along Fissure A varies from 0 to 15 centimeters (6 inches). These offset areas, in essence, are creating nick points where drainage channels cross, thus renewing the base level. This facilitates up-slope erosion by water.

Fissure B was measured and found to be 178 meters (584 feet) in an east-west direction. Although this fissure is much shorter than Fissure A, the widths, depths, and offsettings are all very similar. Widths do not exceed 30.5 centimeters (12 inches) with very little side erosion. Depths were rarely measured over 15 centimeters (6 inches). Variable offsetting also occurred along Fissure B, normally less than

10 centimeters (4 inches). No areas of undermining along this fissure were identified.

Age

The ages of these two fissures cannot be verified from publications. Visible evidence from the 1967, 1970, and 1971 aerial photography, however, suggests that fissuring in the area of Site 2 has been present for at least the past fourteen years.

Comparison among fissures

Surficial relationships between the various fissures were the focus of this study. It is suspected that the two fissures at Site 2 are associated with the same subsurface shear zone, primarily because of their trend directions and because of their proximity. These fissures, at the surface, vary from 4.6 meters (15 feet) to 7.6 meters (25 feet) apart.

Cross section

The same procedures for ground level data collection were applied at Site 2 as were applied at Site 1. This procedure involved studying a series of cross sections approximately 7.5 meters (25 feet) apart. Each cross section focused on the vegetation, drainage, and morphology.

Vegetation

The primary vegetative types found at Site 2 were creosote bushes, annual grasses, palo verde trees, mesquite, saguaro cacti, and cholla cacti. Unlike Site 1, there was no apparent tendency for vegetation to occupy the fissure openings. Site 2, as compared with Sites 1 and 3, had a higher vegetation density, but no apparent density patterns from ground level were associated with the occurrence of the fissures. Table 3 summarizes the data collected along each cross section at Site 2.

Site 3

Site 3 is located .32 kilometers directly south and slightly east of Site 2 (figure 8). It is on the southern part of the same alluvial slope where Site 2 is located. Site 3 may have at one time been under cultivation as suggested by the denuded appearance and the level surface.

Two different soil types have been differentiated in the vicinity of this site. Antho sandy loam (AnA), with a slope of from 0 to 1 percent, and Antho gravelly sandy loam (AoB), with a slope of from 1 to 3 percent, are present. Both are moderately alkaline.[4]

Fissure statistics

There are two surficial fissures at Site 3, but it is believed that they connect to the same shear zone at an unknown depth. The resulting surface formation is graben-like. Fissure A is 240 meters (789 feet) long and Fissure B is 168 meters (552 feet) long.

Age

The literature indicates that the fissures at Site 3 are post-1975. The interpretation of the various photographs, however, revealed that these fissures could be seen on the 1967 Soil Conservation Service photography. Thus, these fissures have been in existence for at least fourteen years, but records on their growth have not been kept.

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[4]Ibid.

TABLE 3

CATALOG OF FINDINGS AT SITE 2

Cross Section	Fissure	Vegetation	Drainage Channels
1	A	. . . . .	. . . . .
2	A	. . . . .	termination of drainage channel
3	A	. . . . .	. . . . .
4	A	exposed roots	rechannelization
5	A	. . . . .	. . . . .
6	A	. . . . .	. . . . .
7	A	no vegetation	. . . . .
8	A	. . . . .	. . . . .
9	A	6 dead creosote bushes in 13.4 m^2 area	. . . . .
10	A	. . . . .	new micro channels leading into fissure
11	A	. . . . .	new micro channels leading into fissure
12	A	. . . . .	. . . . .
13	A	. . . . .	. . . . .
14	A	. . . . .	. . . . .
15[a]	A	. . . . .	. . . . .
16[b]	A	. . . . .	undermining
17	A	. . . . .	crosses channel but no effect
18[b]	A	. . . . .	. . . . .
19[b]	A	. . . . .	. . . . .

TABLE 3--Continued

Cross Section	Fissure	Vegetation	Drainage Channels
20	A	dead plant undermining caused plant to fall in fissure exposed root	. . . . .
21	A	. . . . .	interruption of minor drainage
22[b]	A	. . . . .	undermining
23	A	. . . . .	headward erosion
24[c,d]	A	exposed roots in hole	undermining
25[a]	A	severed roots	undermining
26	A	. . . . .	stream capture
27[d]	A	exposed saguaro roots	erosion and rechanneling
28	A	. . . . .	. . . . .
29	A	. . . . .	termination of channel
30	A	. . . . .	. . . . .
31	A	. . . . .	rechanneling of drainage into fissure
32	A	. . . . .	rechanneling of drainage into fissure
33	A	dead cactus skeleton in hole	. . . . .
1	B	. . . . .	termination of drainage
2[e]	B	plants fall in hole as caving occurs	micro-channels form and drain into hole

TABLE 3--Continued

Cross Section	Fissure	Vegetation	Drainage Channels
3[e]	B	plants fall in hole as caving occurs	micro-channels form and drain into hole
4[e]	B	plants fall in hole as caving occurs	micro-channels form and drain into hole
5	B	undermining of creosote bush	. . . . .
6[a]	B	exposed roots 7 dead plants within 1.5 m	. . . . .
7[a]	B	. . . . .	. . . . .
8[a]	B	down-side plants under more stress than up-side plants	termination of major drainage channel
9	B	. . . . .	channel termination
10[a]	B	. . . . .	. . . . .
11[a]	B	. . . . .	. . . . .
12[f]	B	exposed saguaro root saguaro root truncated	channel termination
13	B	. . . . .	minor erosional hole
14[a]	B	. . . . .	channel termination
15[b]	B	. . . . .	. . . . .
16	B	exposed roots	. . . . .
17	B	. . . . .	termination of major channel
18	B	dead creosote	. . . . .
19	B	. . . . .	rechannelization
20	B	. . . . .	no effect no major channel

TABLE 3--Continued

Cross Section	Fissure	Vegetation	Drainage Channels
21	B	undermining of plants	. . . . .
22[b]	B	. . . . .	. . . . .
23	B	exposed roots	. . . . .
24	B	. . . . .	. . . . .
25	B	. . . . .	rechannelization

[a] 15 cm offsetting

[b] Slight surficial folding

[c] Point where earth surface gave way underfoot

[d] Temperature 10°C in fissure hole at .6 m deep

[e] Subsidence noted

[f] Exposed cemented, unconsolidated material of subsurface soil layer

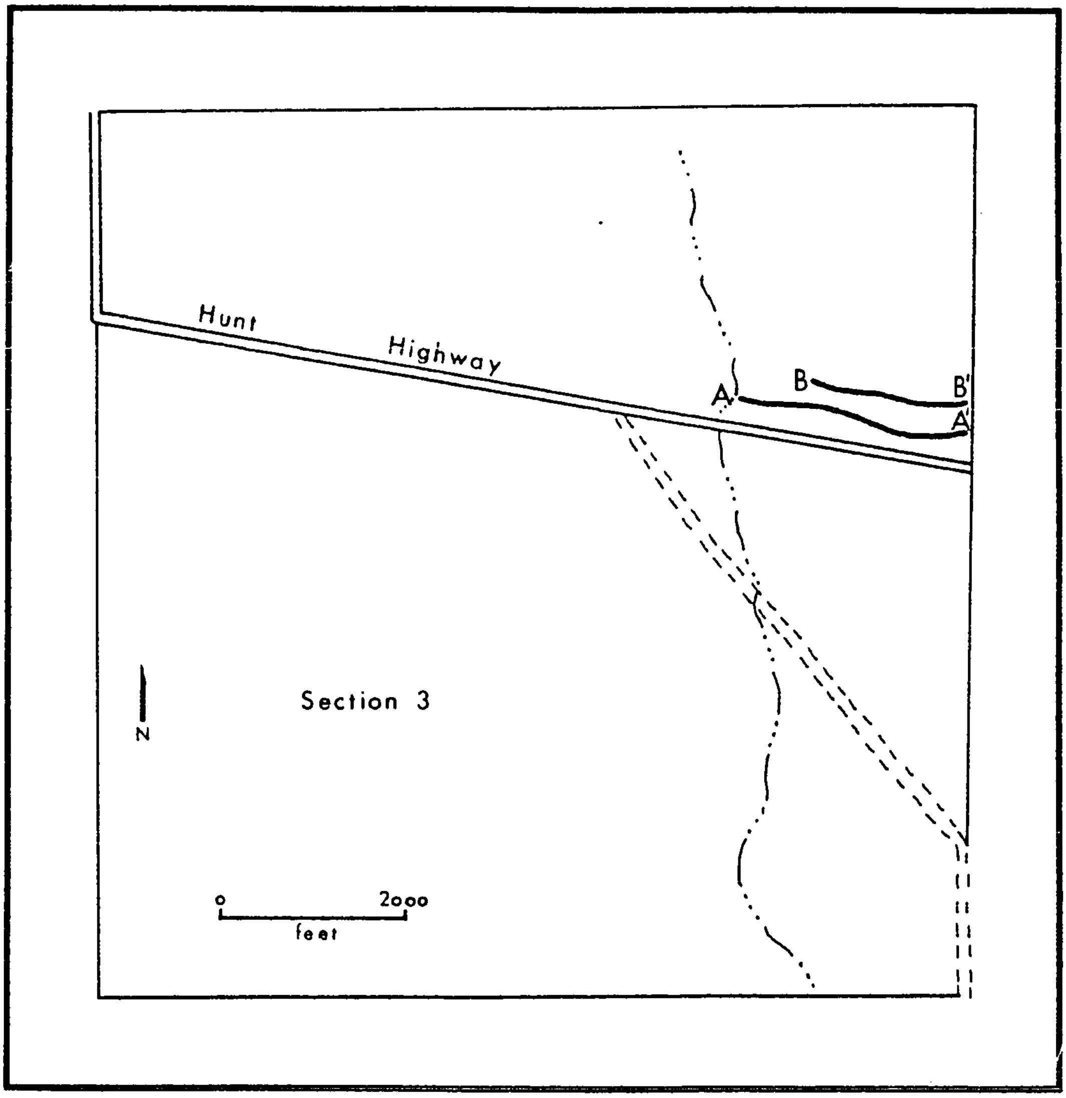

Fig. 8. Generalized fissure configuration January 1981 at Site 3, T3S, R7E, Sacaton NE Quadrangle, Arizona.

Cross sections

Procedures for ground level data collection at Site 3 were identical to those used at Sites 1 and 2. These procedures involved examining a series of cross sections approximately 7.5 meters (25 feet) apart. Each cross section focused on the vegetation, drainage, and morphology. Table 4 summarizes the cross section findings at Site 3. Because of the existing surficial characteristics, no problems were encountered involving either drainage or vegetational characteristics.

Remotely-Sensed Data Collection

Table 5 lists the various types of aerial photography and imagery utilized during data collection and analysis. Remote sensing was incorporated into the study in an attempt to facilitate the identification of degradation along fissures.

Various dates, scales, and types of photography and imagery were selected to provide information regarding the ages of fissures as well as indications of vegetation stress. Conventional visual photographic analysis techniques were utilized. All photography, except the black and white, was utilized in positive transparency form. Analysis of the photography required a light table, optical magnifiers, and various cartographic tools.

Analysis of remotely-sensed data

The actual analysis of the study area for fissure-related surficial changes and the mapping of fissures required larger scales than Landsat and Skylab (spacecraft platforms) imagery and photography were capable of providing; thus, the high altitude National Aeronautics and

TABLE 4

CATALOG OF FINDINGS AT SITE 3[a]

Cross Section	Fissure	Morphology
1	A	offsetting 30 cm
2	A	offsetting 30 cm
3	A	offsetting 30 cm
4	A	offsetting 30 cm
5	A	offsetting 30 cm
6	A	offsetting 25 cm
7	A	offsetting 25 cm
8	A	offsetting 20 cm
9	A	offsetting 8 cm
10	A	offsetting 15 cm
11	A	offsetting 15 cm
12	A	offsetting 15 cm
1	B	offsetting 46 cm
2	B	offsetting 46 cm
3	B	offsetting 46 cm
4	B	offsetting 41 cm
5	B	offsetting 36 cm
6	B	offsetting 23 cm
7	B	offsetting 15 cm
8	B	offsetting 12 cm
9	B	offsetting 15 cm
10	B	. . . . .
11	B	. . . . .
12	B	. . . . .

[a]No change in vegetation or drainage was identifiable at this site

TABLE 5

REMOTELY-SENSED IMAGERY AND PHOTOGRAPHY
USED IN ANALYSIS

Type	Agency	Platform	Angle	Date	Scale
Black & White	SCS[a]	Aircraft	Vertical	1967	1:20,000
Color	NASA[b]	Aircraft	Vertical	3/3/71	1:113,500
Color IR[c]	NASA	Aircraft	Vertical	2/8/70	1:113,500
Color IR	NASA	Aircraft	Vertical	2/8/70	1:55,200
Color IR	NASA	Aircraft	Vertical	3/7/78	1:51,000
Color	NASA	Skylab	Vertical	8/-/73	1:1,200,000
Color IR	NASA	Landsat	Vertical	11/15/75	1:1,000,000
Color	Researcher	Aircraft	Oblique	1/17/81	183 meters (600') AMT[d]
Color IR	Researcher	Aircraft	Oblique	1/17/81	183 meters (600') AMT
Color	Researcher	Aircraft	Oblique	1/17/81	366 meters (1200') AMT
Color IR	Researcher	Aircraft	Oblique	1/17/81	366 meters (1200') AMT

[a]SCS = Soil Conservation Service

[b]NASA = National Aeronautics and Space Administration

[c]IR = Infrared

[d]AMT = Above Mean Terrain

Space Administration (NASA) photography proved more helpful during analysis and mapping.

Mapping of fissures

Without sophisticated equipment, the most efficient means of mapping fissures was to delineate the various fissures on an overlay of transparent tracing paper with a light table as the illuminating source. This resulted in maps showing site boundaries and fissure configurations only. The information was then easily transferred to base maps. Figure 6 shows the fissure configuration as Site 1; figure 7 shows the fissure configuration at Site 2; and figure 8 shows the fissure configuration at Site 3.

Analysis of remotely-sensed data for degradational processes

Analysis of the imagery and photography for evidence of desertification characteristics began with the imagery and photography collected from the highest platform altitudes. This was, first, Landsat imagery, which has an altitude of 940 kilometers (570 miles), and then Skylab photography, which had an altitude of 430 kilometers (270 miles). The Landsat imagery (scene ID E-22970171 95) was available as a color composite in transparency form. The Skylab photography was in the form of a color transparency.

Optical magnifiers were utilized with imagery and photography over a light table source of illumination. This technique proved sufficient for locating those fissures with significant plant growth in fissure openings.

The ability to locate fissures by the corresponding plant growth was dependent upon resolution capabilities of the various forms of remotely-sensed data. Resolution for the Landsat multispectral scanner (MSS) system is an actual instantaneous field of view (IFOV) of 79 x 79 meters (260 x 270 feet) which, because of the sampling rate, has a nominal resolution element size of 79 x 56 meters (260 x 184 feet). As a result the resolution of Landsat MSS images is considerably greater than the width of fissures. The factor, then, that allowed the few vague fissure patterns to be identified on the Landsat imagery was vegetation. This is because all surficial features contained within one resolution unit have an averaged spectral signature and, in the situation here, the fissure pattern identified as such has the vegetation as the dominant reflector of energy (in this case, near infrared energy) causing the resolution elements to have signatures characteristic of moderately vegetated areas. When the Landsat color composite transparency is viewed, the result is a lineation of several resolution elements having a light, pinkish-purple hue.

Vegetational reflectance patterns from only one fissure were identified. This fissure was identified as Fissure C at Site 1 (figure 6). Because of resolution constraints, no other information extraction was possible; thus, no indications of degradation were noticed on the Landsat imagery.

The resolution capabilities of Skylab's Earth Terrain Camera are approximately 50 meters (164 feet), somewhat better than Landsat's MSS resolution capabilities. Nevertheless, the identification of fissures through optical magnifiers proved difficult. The Skylab photography utilized for analysis was color and not color infrared; consequently, minor areas of vegetation were much more difficult to identify and delineate because of the lower intensity of vegetation reflectivity in the visible region as compared with the reflectivity in the near infrared region.

The next set of photography selected for analysis was the NASA high altitude color and color infrared photography. The smaller-scale (1:113,500) set of color infrared information was collected with a Zeiss 5L camera having a 30.5 centimeter (12 inch) focal length from a platform altitude of 17,983 meters (59,000 feet). The larger-scale (1:55,200) set of color infrared high altitude NASA photography was thought to have been collected by the same Zeiss 5L camera on the same mission because both sets of photography were collected on the same date (8 February 1970) only 30 minutes apart (11:55 A.M. for the smaller-scale and 12:25 P.M. for the larger-scale). The same interpretation techniques applied to Landsat and Skylab imagery and photography were applied to the NASA high altitude color infrared photography.

Black and white, 1967, 1:20,000 scale, Soil Conservation Service photography was interpreted but provided little diagnostic information. This photography was of rather poor quality. As a result, vegetational characteristics were not well defined, although indications of fissure configurations were suggested by vegetational patterns.

Of major interest regarding the possible identification of degradational processes were the low altitude color and color infrared photography collected by the researcher. This photography seemed more appropriate for identifying areas in the beginning stages of the desertification process.

The procedures for collecting these data involved renting a small, high-winged aircraft. The aircraft facilitated the collection of oblique to near vertical photography at selected altitudes of approximately 183 meters (600 feet) and 366 meters (1200 feet) above the terrain. One 35 mm, single-lens reflex camera was utilized with color and color infrared film for data collection. The information was collected first at Site 1, then at Sites 2 and 3 because of their proximity to each other. The lower altitude flight, 183 meters (600 feet), was conducted first, followed immediately by the higher altitude flight, 366 meters (1200 feet), in the same sequence. These procedures assured essentially an equal (winter) sun angle which was important for obtaining more effective photographs of the fissures. This allowed shadow in the deeper parts of fissures and a bright, solar illuminated, south fissure side for easy identification of fissures.

This photography was collected in slide form and thus proved easier than the smaller-scale photography to analyze. Each slide was projected thus enlarging each particular scene. This facilitated interpretation by making patterns of interest more apparent. These patterns included vegetational stress, pockets of more healthy vegetation that correspond with the occurrence of one or more fissures, surficial erosion characteristics, and changes in surficial drainage characteristics.

Slides of each site were visually analyzed for patterns or characteristics indicative of degradation of the natural environment resulting from the occurrence of fissures. Important characteristics observed from slide interpretations included vegetation enhanced by the occurrence of fissures, erosion centered on fissures, no apparent patterns of vegetational stress, and no apparent changes in drainage characteristics.

Since headward erosion was observed as being quite obvious along segments of various fissures, a test was devised to calculate the ratio of headward erosion to fissure length utilizing the low altitude photography. A section of Fissure C at Site 1 was selected for the test. Measurements on the projected slide were made using known distances from the corresponding 1:24,000 U.S.G.S. topographic quadrangle. The length of the selected fissure segment was caluclated to be approximately (allowing for measurement error along the curvilinear fissure segment) 277 meters (908.7 feet). In that distance, sixteen incidences of headward erosion were noted and measured. The total measured length of these sixteen occurrences of headward erosion is approximately 55.16 meters (180.97 feet). The ratio, dividing fissure length (277 meters) into erosion length (55.16 meters), is 0.199. This means that for every 1.5 meters (5 feet) of fissure length, there is approximately 0.3 meters (1 foot) of headward erosion. Incidences of these sixteen erosional gullies ranged from 1.46 meters (4.8 feet) to 5.12 meters (16.8 feet).

The above ratio (0.199) of headward erosion to fissure length seems moderately high because the fissures and erosion along them are geologically very recent. Because the direct impact from variables such as climate, man, and continued groundwater withdrawal/subsidence are unknown, it is difficult to predict if such erosion rates will continue at the same rate.

Degradation patterns characterized by vegetation stress

An attempt was made to quantify and categorize all vegetational stands along each fissure according to whether or not they were dead or alive. The low altitude color and color infrared slides collected by the researcher were used for data analysis. Viewing the slides allowed the various plants to be categorized as either dead or alive. Where a true diagnosis could not be made when using color photographic information, color infrared information was employed to show the more apparent infrared reflectance from live leaves. It was hoped that the end product would be a map showing the boundary between degraded and non-degraded areas along the various fissures.

The results of analysis at Site 1 show that 33 percent of the plants along fissures A, B, and C are dead. In addition, a distinct stress difference, as indicated by infrared reflectance, was noted following the general trend of fissures A, B, and C at Site 1. On the southeastern (up-slope) side of the fissures the infrared reflectance was brighter red than on the northwestern (down-slope) side, which was more pink in infrared reflectance intensity. Noted on the "healthy" side were seven large palo verde trees; also noted were twenty healthy (primarily creosote) plants either growing in a fissure or on the up-slope side but still near the fissure. In the same area are thirty-three obviously stressed (dying) plants on the down-slope side.

Because of the locations noted above of the dead plants, a map showing degradational boundaries cannot be effectively produced. Almost all categorized plants occur either in a fissure or on a fissure bank. Thus, any map attempting to show this would not effectively show spatial relationships.

Sites 2 and 3 provided little information about live versus dead vegetation as indicators of degradational boundaries. For example, fifty-six healthy plants were counted along the fissures at Site 2 and only four obviously dead plants. The dead plants were bunched together and not sufficiently spaced to be effectively mapped. Site 3 has no larger stands of vegetation (i.e., creosote), so no degradational patterns relating to vegetation exist.

Chapter 4

RESULTS

The data leading to the results of this study were collected, analyzed, and interpreted from two different viewpoints. A ground level survey provided micro-scale information, and remote sensing techniques provided a macro-scale survey from a synoptic viewpoint.

Ground Level Analysis of Fissures

Results of the ground survey will be discussed in terms of degradation of the vegetation, natural drainage characteristics, and surficial morphological tendencies of each individual site.

Site 1

At Site 1 erosion is the key to degradation. Erosion was not a problem in this area until fissures first appeared at the surface in the late 1960's. This site has three well-developed fissures because of erosion, and it is quite apparent that continued erosion is much more aggressive on the up-slope side of fissures.

Vegetation

The degradation of vegetation was not found to be occurring on a broad scale; but isolated incidences of plants under various degrees of stress were identified and examined. No one plant type was found to be more affected by stress and degradation than any other plant type.

Contrarily, there were occurrences noted where vegetational vigor has actually increased because of fissures. For example, seedlings have become trapped in the fissures and are nourished by water channeled into fissures. Palo verde trees and some creosote bushes do particularly well once growth in fissures begins (figure 9). Plants in fissures actually receive more water than do plants not located in fissures. As a result, many of the plants in these older fissures at Site 1 are larger and healthier. These fissure-induced plants often are sufficiently abundant to allow for rather precise delineation of fissures from high altitudes since the plants, as opposed to the fissures, are actually observed (figure 10).

Erosion, changes in drainage channels, and prolonged drought conditions during the year of field investigations all contributed to the noted vegetational conditions and patterns. Erosion has detrimental effects on vegetation at Site 1 primarily through the removal of soil from around plant roots. Within the Site 1 area this occurs in three ways: one is the removal of soil from around plant roots within the fissure zone, another is the removal of soil from around up-slope plant roots by up-slope erosion; and the third is the increasing cavity-like underminings of plants (mostly annual grasses) which occur as up-slope erosion continues. The first leaves roots openly exposed extending from the sides of the fissure gorge, the second tends to totally wash away plants; and the third leaves plants intact within the surface soil, but the roots are exposed within a subterranean cavity, often partially open to the outside (figures 11 and 12). Vegetation is also lost as fissure gorges expand when erosion (primarily water) widens the gorges. Plants located immediately next to

Fig. 9. Palo verde and creosote growth in fissures

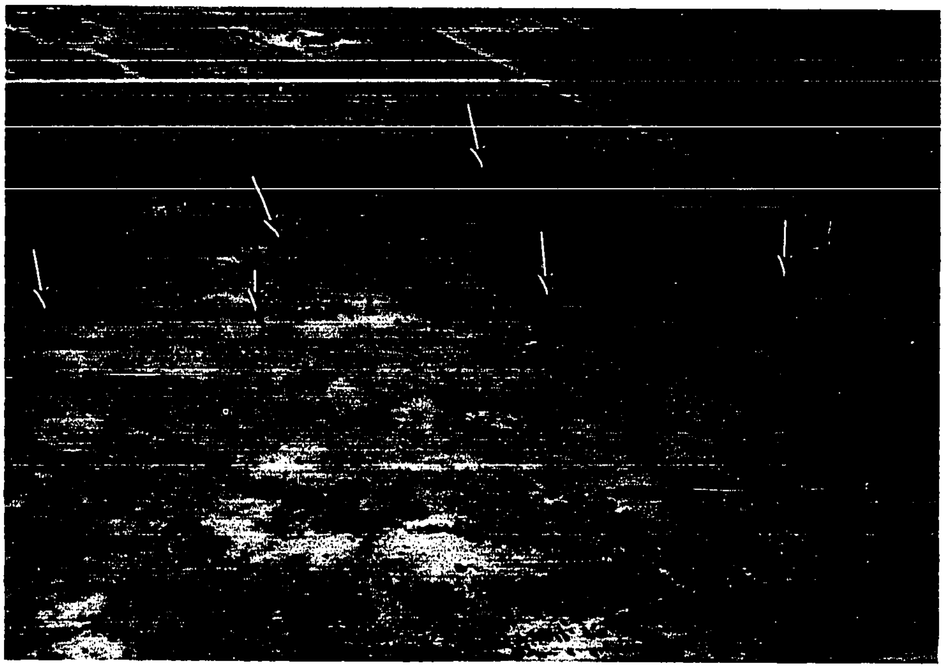

Fig. 10. Delineation of fissures at Site 1 by vegetational growth.

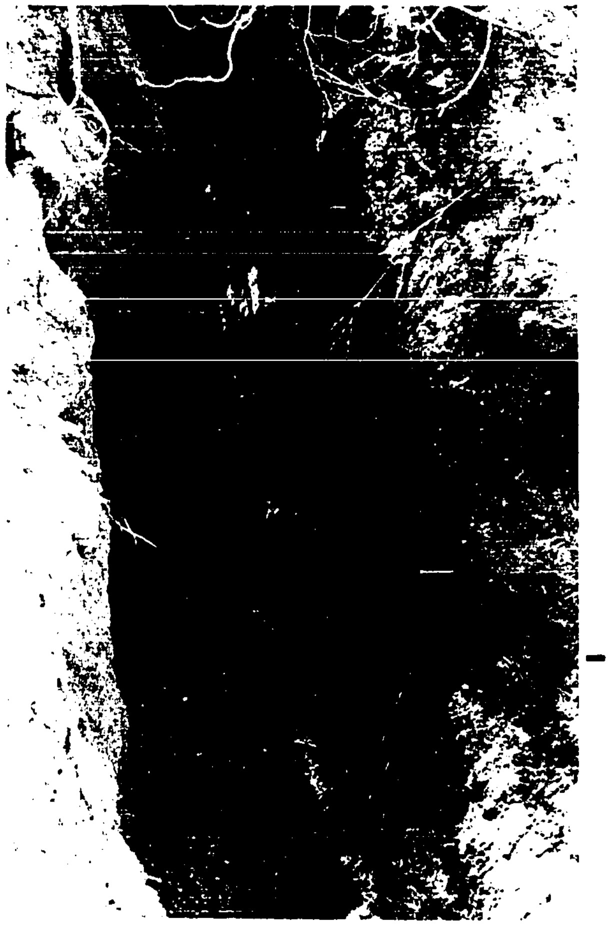

Fig. 11. Openly exposed roots extending from fissure walls caused by erosion.

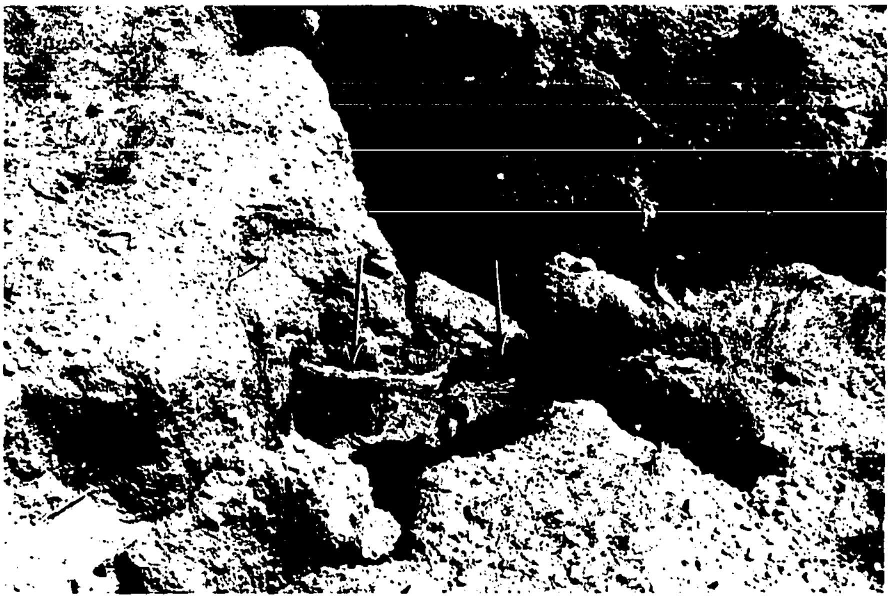

Fig. 12. Exposed roots within a cavity caused by erosion.

the fissures experience the loss of soil from around the plant as erosion widens the various gorges (figure 13). Because of the relative abundance of creosote bushes, most of the exposed roots were creosote. Their diameters were measured and found to be generally between 0.63 centimeters (0.25 inches) and 2.5 centimeters (1 inch).

While damage to larger and smaller plant root systems was prominent, the annual grasses characteristically appeared to be surviving much better where associated with fissures. Although not lush, these grasses were found to be more dense and usually about 2.5 centimeters (1 to 2 inches) taller in the fissure depressions (figure 14).

No stress patterns, from high stress to low stress, away from fissures were identified. Areas of stress were noted only for those plants in the fissures or situated close enough for roots to reach the nearest fissure. Few plants were identified as being under stress that were not already dead. These plants were situated near fissures such that their roots were losing the surrounding soil either through erosion within the fissure or through side erosion.

Another factor noted as having an effect on the vegetation vigor is the climatic history from approximately May of 1980 to May of 1981. During this period drought conditions were experienced. Records from the nearest weather station located at Phoenix's Sky Harbor International Airport indicated that only trace amounts of precipitation were received within the general area at various intervals during that twelve month period. The equivalent precipitation amounts must be assumed for the study area; thus, it is easily understood that plant growth is more dependent on falling precipitation than on surface flow. In most instances there is insufficient precipitation to cause surface flow.

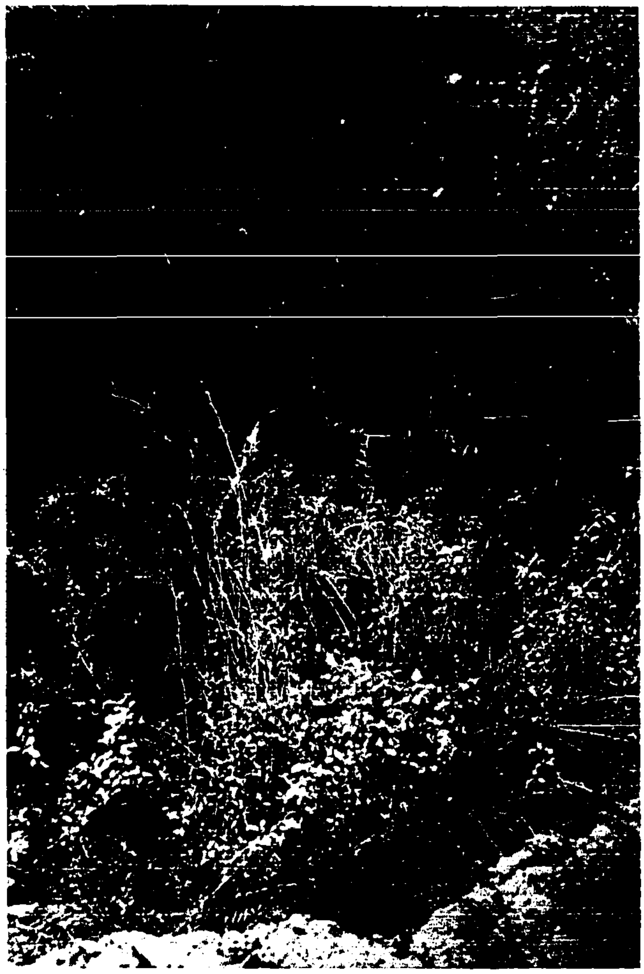

Fig. 13. Erosion of soil around plants causing widening of the gorge and death to some plants.

Fig. 14. Taller grasses growing in fissure depression.

Natural drainage

As more and more information was gathered relating changes in drainage to earth fissure development, it became obvious that the most apparent and intensive changes involved erosion. Almost every instance of noted erosion was preceding up-slope, as well as in the fissure opening itself. Erosion occurs every time precipitation is received because of a high erodability factor and because of low vegetation density. More importantly, a new base level is established each time a fissure opens at the surface.

Fissures cause the lowering of the base level in two ways, surficial folding and the opening of fissures. Surficial folding (figure 15) creates a down-warp allowing the speed of runoff to increase, thus intensifying the erosional process. These down-warps tend to be located on the up-slope side of fissures and cause an additional lowering of the base level which works in tandem with the lowered base level caused by the fissure opening. No proof, however, was found that more erosion occurs where folding and fissuring occur together than where fissuring alone occurs.

Erosion first occurred along fissure shear zones creating erosional gorges. In addition, the appearance of a fissure at the surface acts like a nick point along a stream. As water flows over the fissure edge, erosion occurs and continues to occur as surface flow is maintained.

The soil (Antho sandy loam), which is relatively soft and has good tilth, further facilitates up-slope erosion (figure 16). It is difficult to estimate the rate of erosion because it depends upon sufficient precipitation to cause surface flow. Weather disturbances of

Fig. 15. Surficial folding

Fig. 16. Example of up-slope erosion

this magnitude are infrequent, but those that do occur tend to be quite intense; consequently, erosion really only occurs during severe storms.

The greatest up-slope erosion noted during the field surveys at Site 1 was approximately 5.5 meters (18 feet). Drainage from this erosional tributary drops immediately into a 114 centimeter (45 inch) hole. Another up-slope erosional tributary measured approximately 3 meters (10 feet). This tributary was off Fissure A and came to within 0.6 meters (2 feet) of a branch of Fissure B. This type of surficial degradation has already removed much soil from around plant roots increasing chances of more vegetation loss leading to desertification.

Although expanding erosion is a chief cause of plant degradation, drainage characteristics themselves were noted as causing a few instances of plant stress. Changes in drainage patterns resulting from a renewed base level and/or from stream capture occasionally prevent plants from receiving sufficient moisture thus causing stress and eventual death. This result is minor because Site 1 experiences a near 0 degree slope and, therefore, almost all of the drainage channels are considered micro-channels. Over a period of time, however, much of the water that would have originally nourished these stressed plants is diverted to, and captured in, fissures.

Surface morphology

The types of surficial morphological changes suggestive of subsidence activity are slight folding at the surface, very similar to a micro-monocline, and offsetting of fissure banks. The monocline effect occurs only along the up-slope side of Fissure C at Site 1 approximately 4.9 meters (16 feet) away from the fissure opening. Offsetting of fissure banks at Site 1 is minimal. Maximum offsetting is 5 centimeters (2 inches), but normal offsetting is negligible.

Site 2

This site is less affected by erosion than is Site 1. The steeper slope, approaching 3 percent, at this site would suggest that erosion occurs much faster here than at Site 1. Comparing the erosional intensity at the two sites indicates this is not the case since the aerial photography shows that fissuring at Site 2 began occurring (in the late 1960s) approximately five years after fissuring at Site 1.

Vegetational effects resulting from the occurrence of earth fissures were found to be minor. Isolated spots of both plant stress and plant death were located, but more importantly, areas of enhanced, rather than degraded, vegetational growth were identified. Figure 17 shows a more lush area of vegetation. Although this pattern can be clearly identified, no degradational characteristics can be delineated.

No surficial evidence was uncovered to show that fissure alterations of surficial drainage have contributed to the degradation of the area. Subsurface water movement, however, has caused undermining of surface materials in areas of more consolidated soils. Plant roots have been exposed, but not yet to the extent that surficial degradation is apparent either from the ground or from the use of remote sensing techniques. Analysis at ground level has revealed subsurface erosion is a major threat and will result in severe degradation if allowed to continue.

Offsetting of fissure banks and slight surficial folding have not yet combined for surficial erosion to become apparent. Insufficient

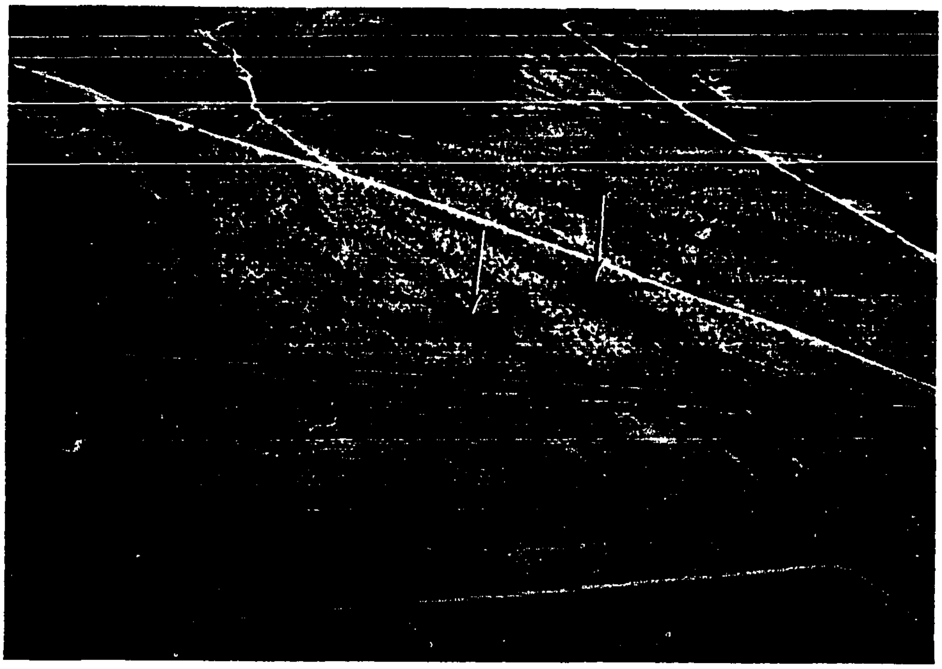

Fig. 17. Pocket of more lush vegetation at Site 2

time has passed since the occurrence of fissuring to allow morphological changes (offsetting) to be modified by infrequent and little precipitation. Determining a time frame for erosion is difficult because the amount, frequency, and intensity of precipitation are virtually unpredictable.

Vegetation

Of the fifty-eight cross sections taken along Fissures A and B, fourteen showed evidence of damage or death to plants. For example, within a 3.7 x 3.7 meter (12 x 12 foot) area where one cross section intersects the fissure, six dead creosote bushes (three on the up-slope side and three on the down-slope side) were noted. At another location, remnants of seven dead plants were observed within 1.5 meters (5 feet) of the fissure. Other damage included eight cases of exposed roots, primarily creosote and saguaro, and two cases of severed roots, one a creosote and the other a saguaro. The damage of exposed roots was quite obviously caused by the erosion of soil by water from around the various root systems. This damage was not exclusive to any one plant type; saguaro (the largest exposed roots), creosote, and grass (the smallest exposed roots) were all affected equally. The cases of two severed roots were not caused by erosion, but resulted from tension of movement along the fissure shear zone as subsidence occurred. Both of these roots were approximately 3 centimeters (1.2 inches) in diameter.

There was no identifiable pattern of vegetation stress away from fissures that could be connected more to the occurrence of fissures than to the hot, arid climate. The site gave the impression that degradation was occurring, but that more time is required before vegetation stress can be clearly identified and mapped.

<u>Natural drainage</u>

Of the fifty-eight cross sections taken along Fissures A and B, eighteen crossed at points where the natural drainage was altered. At the same time, three locations were identified where surficial drainage was not altered because there was no surficial expression of the fissure.

Most of the noted changes in drainage involved the termination of channels by fissures. Water now flows into fissure cavities. Consequently, side (up-slope) erosion was noted as being in the early stages as was the undermining of surface soil layers. These undermined areas have a cemented layer of unconsolidated materials about 2.5 to 5 centimeters (1 to 2 inches) below the surface. This hard under-layer inhibits erosion and is one reason why side erosion is much less extensive at Site 2 than at Site 1.

Another effect on the natural drainage by the fissures is the creation of micro-channels less than 15 centimeters (6 inches long). This is a result of a new, lower base level caused by the appearance of the fissures. Many of these new channels either have captured, or are about to capture, other small channels. The result is a restructuring of some of the smaller drainage channels within about 5 meters (16 feet) of the fissure.

The two longer channels in this area did not appear to have flow interrupted by the fissures. Even though the fissure could be seen crossing these streams at right-angles, sand in the channel bottom was undisturbed and seems to facilitate continued flow. Unfortunately, this cannot be verified because sufficient precipitation to cause water flow in the channels rarely occurs.

Surface morphology

Morphologically, several features came under study as resulting from subsidence at Site 2. These included surficial folding, offsetting of fissure sides, graben-like features, and undermining of surfaces.

The surficial folding (figure 15) is slight but is related to the fissure in two ways. First, folding occurs at the point on the surface where surficial fissure expression appears. This is related to subsurface offsetting along the fissure shear zone, the effects of which have not fully reached the surface. Second, folding can occur in the area of 1.5 to 3 meters (5 to 10 feet) up-slope from the surficial fissure expression. The reason for the occurrence of folding in this region is unclear and has not been found in any appropriate publication.

The offsetting is very similar to faulting. The up-slope side remains essentially stationary because of underlying bedrock while the down-slope side subsides along the fissure shear zone because of ground-water depletion. The primary effect caused by offsetting is the creation of a new, lower base level which increases the rate of water flow causing increased erosion, as previously described. As erosion continues, soil is washed from around plants, eventually preventing sufficient amounts of nutrients and water from reaching plants (figure 13). The consequence is increased vegetation stress over an increasingly wide area.

Along both Fissures A and B, only one small graben-like feature was observed. This feature was located near the western end of Fissure A, the longer of the two fissures. This small graben-like feature was characterized by a lineation of small holes between 1.3 and 2.5 centi-meters (0.5 and 1 inch) in diameter on the south side and a lineation of larger holes of approximately 7.6 to 10.2 centimeters (3 to 4 inches) in diameter on the northern side. The area in between, approaching 3 meters (10 feet) across, has subsided as much as 10.2 centimeters (4 inches). The reason for the appearance of this graben-like feature, as indicated by the holes on each side, is undermining of the surface alluvium.

Undermining is the fourth morphological feature as noted by the occurrence of fissures at Site 2. As water runs into the fissures from the terminus of drainage channels, it often flows along down-slope trending portions of fissures before seeping deeper into the fissure shear zone. During this process, material is eroded out from under the cemented layer and into deeper subterranean fissure holes. When sufficient material is lost, thus reducing the effective support of overlying materials, subsidence occurs. Because support for these small subsidence zones is maintained on each side of the undermining, rather sharp break points occur resulting in two high sides and a down-dropped middle sector, hence, a graben-like feature.

Site 3

Dynamic activities occur very slowly at Site 3. A 0 degree slope and a man-made embankment have essentially eliminated surface flow. As a result, erosion is negligible and degradation is not apparent.

Vegetation

The vegetative types found at Site 3 are essentially the same as at Site 2. Annual grasses, creosote bushes, and a few palo verde trees are the major types that tend to gather primarily around the drainage channel. No degradational effect on the various plants at Site 3 were observed. No cases of exposed or severed roots and no indications of dead or dying plants resulting from the fissure were observed. The vegetation density at Site 3 is much less than at Site 2. Site 3 was previously denuded of vegetation, like the eastern portion of Site 1, probably for agricultural purposes.

Natural drainage

The slope at this site is essentially zero. As a result, few problems or changes in the drainage characteristics were observed. The only major drainage channel transgressing this site measured approximately 0.65 meters (2 feet) deep. Soil is banked along the sides of this channel making it artificially deeper. This appeared to be the primary reason why this channel is unaltered by fissuring. Precipitation tends to pond at this site rather than drain off.

Surface morphology

This site is not characterized by holes or gorges as were the other sites; rather, one large graben-like feature occupied much of the length of the fissure.

This graben-like feature was not formed by undermining, as described earlier under Site 2. Instead, these surface fissures connect with the same fissure shear zone at an unknown distance below the surface. The distance between surface fractures, which are characterized by offsetting, varies between 13.7 and 22.9 meters (45 and 75 feet). The offsetting on the north side varies between 15.2 and 30.5 centimeters (6 to 12 inches), and the offsetting on the south side was as much as 45.7 centimeters (18 inches). The subsided area between the sides remained virtually level, causing no apparent minor slope or drainage changes.

Of the three sites, the fissuring at Site 3 is the only one that has no degradational effect on the surrounding environment. A large man-made embankment 7.6 meters (25 feet) to the south separates the field from the highway. These two man-made features have completely changed the slope and drainage previously experienced here and, therefore, minimized any effect this fissure might have had on the surrounding natural environment.

Summary of Degradation from Ground Level

Table 6 summarizes cross sectional incidences of degradation for all three sites. Table 7 summarizes cross sectional incidences of non-degradation factors.

Site 1 has the greatest number of degradational occurrences with 70, and the greatest number of non-degradational related factors at 32. This is related directly to the greater number of cross sections made at Site 1; however, it does not necessarily mean that degradational processes are greater at Site 1.

To help emphasize this, a ratio between the total number of degradational occurrences (70) and the total number of cross sections (71) was calculated and found to be .986 at Site 1. Performing similar calculations for Site 2, a ratio between the total number of degradatioanl occurrences (56) and the total number of cross sections (58), gives a value of .966. This means that in over 95 percent of the transects, some form of degradation was encountered.

TABLE 6

CROSS-SECTIONAL INCIDENCES OF DEGRADATION

Observation	Site 1	Site 2	Site 3
Rechanneling	3	3	0
Caving/slumping	2	0	0
Up-slope erosion	33	2	0
Gullying	1	0	0
Holes	4	2	0
Channel termination	0	6	0
Stream capture	0	1	0
Undermining of soil	0	4	0
Exposed roots	10	6	0
Dead plants	6	4	0
Stress difference	3	1	0
Undermining of plants	0	2	0
Plants fallen into holes	0	4	0
Severed roots	0	2	0
Dead grass	4	0	0
Dying plants	1	0	0
Subsidence	1	3	0
Folding	2	6	0
Offsetting	0	8	22
Graben	0	1	0
Cemented soils	0	1	0
Total	70	56	22

TABLE 7

CROSS-SECTIONAL INCIDENCES OF
NON-DEGRADATIONAL FACTORS

Observation	Site 1	Site 2	Site 3
Deposition	8	0	0
New channels	0	5	0
Healthy plants in fissures	15	0	0
Vague surficial expression	5	2	0
No effect	4	9	3
Total	32	16	3

Similarly, ratios can be calculated for subclasses such as up-slope erosion. For example, a ratio between total cross sections and incidences of up-slope erosion was encountered. This is the highest percentage for the various observations at the three sites.

The key factor noticed from studying tables 6 and 7 for Site 1 is that up-slope erosion is the dominant degradational process with 33 occurrences. Also significant is the rather high number of healthy plants and trees growing in fissures as noticed during field analysis; the largest and most numerous of these are the palo verde trees. It is clear that fissuring is not always detrimental; erosion may be occurring, but at the same time major plants are securing a solid position in the localized ecosystem because of the fissuring.

The next highest occurrences related to degradation are the ten cross sections which revealed eight exposed roots. It is interesting to note this erosion while eight cases of deposition were observed at the same site.

No one degradational type at Site 2 is dominant. Table 6 shows that several types of degradation are occurring with similarity. It should be noted, too, that nine cross sections showed no degradational effect at this site.

Site 3 has only one degradational category listed; this is offsetting. Because of the graben-like surficial structure, twenty-two cases of offsetting were observed as being the only degradational category. Three cross sections were classified as no effect.

Clearly numerous degradational consequences of fissuring are in the process of occurring. Most important is up-slope erosion, which is currently the most prevalent degradational type and which will have the longest term and greatest overall effect. Factors which are considered non-degredational (i.e., plant growth in fissures) do not outweigh the detrimental effects of fissuring.

Remotely-Sensed Data

Analysis of the various forms of remotely-sensed data revealed much less information concerning degradation of major elements of the surrounding natural environment than did the field survey. In fact, only the low altitude aerial photographs collected by the researcher allowed fissure gorges and eroded areas to be identified. All other forms of remotely-sensed data showed only linear stretches of vegetation delineating fissure patterns (discussed in chapter 3).

Interpretation of Landsat imagery and Skylab photography for surficial degradation leading to the identification of desertification was unsuccessful. Skylab photography did, however, provide evidence for the identification of the vegetation in and along Fissure C, as did Landsat, at Site 1.

Similar interpretation results of the Landsat imagery and Skylab photography suggest that differing resolutions and differing spectral bands between the two systems prevented optimum information extraction. The Skylab system has better resolution, but the Landsat system recorded reflected infrared energy, thus enhancing detection of vegetation having mesophyll layers (i.e., green plants).

Analysis of the 1970, 1:113,500 scale color infrared photography revealed two important factors. First, no patterns of vegetation stress were revealed which might possibly be related to the occurrence of fissures. This was true for all three sites. The second important fact revealed was that not all fissures existed in 1970.

Fissure C at Site 1 (figure 6) could not be identified on the 1970 photography. This suggests that subsidence would appear to be a continuing process since this major fissure has appeared within the last eleven years.

The analysis of the 1971, 1:113,500 scale photography also did not show the existence of Fissure C at Site 1. In addition, density analysis over the light table with the Model LT630 lens system revealed no surficial anomalies which might be tied to the existence of fissures. Thus, this fissure has appeared within the last ten years.

When analyzing the 1:113,500 scale photography for surficial degradational effects within the study area, features which appeared to actually be enhanced by the occurrence of fissures were also noted. For example, the photographs showed an accumulation of various vegetational stands on a portion of the southern (up-slope) side of Fissure A at Site 2 (figure 17). This was not obvious during the field survey. Theoretically, when drainage channels are terminated by a fissure, it is likely that more water would then be available for vegetation on the up-slope side, while vegetation on the down-slope side would continually be water deficient and react accordingly. This was not the case at this site. Photographic analysis did not indicate that the down-slope vegetation was under more stress than vegetation in other areas of Site 2; rather, vegetation growth simply seemed to be more dense on the up-slope side. This aspect was verified when the same analysis was applied to the 1970, 1:55,200 scale, color infrared photography.

As was previously discussed, analysis of the low altitude photography showed erosion to be the most apparent degradational process. This was more prominent at Site 1 than at the other sites as shown by the ground survey.

Prior to analysis, it was thought that vegetational stress patterns might be apparent using low altitude photography. They were not, but this may well change as erosion continues. Besides vegetational stress patterns, changes in surface drainage also were not apparent on the low altitude photography, although the ground survey proved that drainage alterations were in progress.

Summary of Remote Sensing Techniques

Remote sensing techniques were incorporated into this study to provide synoptic information regarding degradation of the major elements of the selected natural environment. Several forms of imagery and photography were utilized, from low altitude photography to Landsat spacecraft imagery.

Results show that the information gained from remote sensing techniques was of little value in delineating degradational patterns. Instead, vegetational patterns were highlighted suggesting that no real degradational process exists. The low altitude photography did, however, show that gullying and erosion were (and still are) significant problems. Insufficient reflectance of infrared energy by the various xerophytic plants because of the small leaf size prevents the recording of any meaningful information regarding plant stress. This type of study could not effectively be undertaken using remote sensing techniques alone.

Chapter 5

CONCLUSIONS

Factors contributing to degradation and eventual desertification of this study site are similar yet, at the same time, drastically different from factors which have caused degradation of major elements of the natural environment in Africa. At both locations degradation is clearly related to the misuse of resources. In Africa misuse of grazing lands by intense overgrazing and the destruction of woodlands for fuel are well-known and are contributing heavily to desertification. In general, cultural, political, and religious activities account for the misuse of natural resources in Africa.

In the southwestern United States, and more specifically this study area, the factors contributing to degradation are related to groundwater resources. The effects of groundwater mining are numerous and consequential, as figure 18 illustrates. One effect of groundwater mining is the development of earth fissures. Although little is known about the dynamics of earth fissures, they are becoming increasingly more apparent in arid environments where intense groundwater mining is commonplace.

This study is a basic investigation of the effects earth fissures have on major elements of a selected natural arid environment. Research was conducted to collect and analyze data which would either support or reject the hypothesis that earth fissures are causing degradation of

Groundwater Mining

Compaction of Sediments

Shear Zones Develop between Subsidence/Non-Subsidence Areas

Surficial Fissuring Develops

Lowered Base Level

Increased Erosion

Degradation

Coalescing of Degraded Spots into Areas of Desertification

Fig. 18. Sequence of activities and consequences leading to desertification.

major elements of the surrounding environment. Because no other studies have been concerned with understanding the effect on the natural physical environment when earth fissures develop, this investigation should serve as a foundation for future study.

The major conclusion of this research is that the hypothesis can be accepted. Isolated spots of degradation (a significant amount of up-slope erosion and many dead or dying plants) within the study area have been shown to be caused by earth fissures. The researcher is led to conclude, however, that insufficient time has occurred since the initial appearance of the various fissures and the clear-cut appearance of coalescing degradational patterns signifying desertification. The natural dynamics of the area have not had time to sufficiently degrade the natural desert environment to the point that desertification can be clearly identified.

Another important conclusion is that the occurrence of desertification within the study area seems inevitable. The key to degradation and eventual desertification of this area is erosion. The researcher believes that desertification, following the current state of degradation, will occur because this research project has proven that erosion is progressing steadily up-slope, and it does not appear that it can be circumvented. Erosion will continue to wash soil from around vegetational stands causing them to die as has been the case with some isolated plants. The natural surface environment will become less and less stable, resulting eventually in desertification.

Halting the degradational process described above seems impossible. As the mining of groundwater continues, subsidence and fissuring can only worsen. Although the problem of groundwater overdraft is recognized by scientists and state officials, the degrading and eventual desertification of the natural environment is not recognized even though there was no erosion in the area of the three selected sites prior to the appearance of fissures.

Correctional measures have not yet been undertaken or even seriously considered. More emphasis seems to be placed on obtaining additional water supplies than on conserving existing supplies. Serious conservation measures which might be explored are groundwater recharge, altering irrigation techniques (perhaps drip irrigation), and the phasing-out of agriculture in central Arizona. The latter course of action would be most unfortunate, but if serious planning and conservational measures are not imposed in the near future, the only alternative is to completely eliminate agriculture to preserve, maintain, and expand the urban environment.

Significance of This Study

The major significance of this study lies in spatially identifying areas of degradation in relation to the occurrence of earth fissures. Perhaps more importantly, this researcher believes, is the unclear end to this unnatural hazard currently in progress. That is to say, degradation in the areas of fissures may not be the end product of groundwater mining; rather, as figure 18 indicates, the likely result is the coalescing of these degraded areas over time into a region of desertification.

Although the occurrence of desertification within the study area has not been proven here, it is believed by this researcher that desertification will be a reality within time. The time frame for this event is not yet predictable, but those legislators and scientists in decision and policy-making roles need to be aware of the real and inevitable hazard of desertification occurring adjacent to a major city in the southwestern United States so that the necessary adjustments in water resource management and use can be implemented.

Future Research

This study was designed as a preliminary investigation of degradational aspects associated with earth fissures. Consequently, many detailed studies are warranted to further understand the processes of degradation and desertification associated with the occurrence of earth fissures.

For example, specific data about vegetation stress are not clearly understood. Also not well understood is the apparent healthy vigor of those plants (i.e., palo verde) growing in fissures while close by other plants are dead or dying. In addition, more research seems warranted to understand the true cause of earth fissures since no one theory has been proven, although the land subsidence theory seems the most credible. Other suggested detailed studies are investigations of surficial morphological characteristics (i.e., what does morphological folding at the surface mean in relation to the substrata and to the presence of earth fissures?) and influences on drainage characteristics.

Perhaps once the cause of earth fissures (in Arizona) is understood then sound predictive models can be established for determining future fissure locations. This is important because fissures are now beginning to appear in the suburban area of greater Phoenix, Arizona.

It seems that a variety of studies are warranted: biological, geological, hydrological, and geographical. Opportunities for positive investigation seem good since earth fissures are still developing and because the real danger, erosion, is just beginning to make an impact on the natural arid environment.

Summary

Researched in this study were the degradational characteristics associated with earth fissures in a selected arid environment. Specifically, changes in vegetation patterns, surface water flow, and the surface morphology were investigated for evidence of degradation due to the presence of earth fissures. The study area selected (a known fissure field in the area of Chandler Heights, Arizona) proved the best site for testing the hypothesis that earth fissures cause sufficient changes in the natural vegetation, drainage, and morphology for degradation, if not desertification, to occur.

Testing the hypothesis involved collecting data from the ground and from aerial platforms. A series of cross sections, or transects, was taken across each fissure at each of the three sites in the study area. Remote sensing techniques were employed to collect and analyze vertical data.

Results indicate that desertification is not yet a reality in the study area, but that degradation is occurring. The principal form of degradation recorded is up-slope erosion. The current growth patterns and characteristics of erosion suggest that degradation will continue to spread, eventually enlarging into a region of desertification.

If, as expected, desertification does become a reality within a matter of years, then the area researched in this study can prove to be a very important area for additional investigations. This is because of the possibility for observing degradation as it spreads into a desertified region.

The failure thus far of legislators and scientists to plan and implement groundwater resource conservation practices may well mean the appearance of more earth fissures, thus increasing the rate of degradation. In addition, the current rate of up-slope erosion needs to be considered, but it appears unlikely that erosion can be stopped, only slowed. The end result will be a harsher desert environment (desertification) than currently exists, and one that will require the importation and strict management of water as well as reforestation techniques.

It is hoped that intense desertification will be avoided, but the decision-making individuals need to be apprised of the current situation and possible consequences. When one considers the proximity of this area to metropolitan Phoenix and the large population there, the consequences of groundwater overdraft become a scary proposition indeed.

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