THE UNIVERSITY OF ARIZONA

ARID LANDS COLLOQUIA

1958–1959

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FOREWORD

A. Richard Kassander, Jr.
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Chairman, Executive Committee, Arid Lands Project

Two years ago, the Rockefeller Foundation made a grant of $201,800 to The University of Arizona, for a three-year period, to support an interdisciplinary pilot-study of the fundamental biological and physical mechanisms at work in the arid regions of the world. Arizona was to be thought of as a laboratory in which techniques could be developed and studied to illuminate the basic problem of how man can make better use of the arid areas of the earth which constitute approximately one-fourth of the land area.

This program, familiarly known as the "Arid Lands Project," is still a relatively small portion of the total arid land research being done at the University. However, it is a most important part since it formally organizes five University groups to work together on overlapping problems. The "interdisciplinary approach" has been emphasized in at least four different ways:

1. The mere business of preparing the original proposal required that the participating groups obtain a much deeper knowledge and respect for the strengths, weaknesses, problems, and capacities of each of the other groups.

2. Management of the program was placed in the hands of an Executive Committee composed of the Project Leaders of each of the groups. In this way, through frequent meetings, each group has been kept aware of the problems of each other group and the ability to modify, strengthen, and expand is maintained.

3. Personal contact between researchers in different departments was guaranteed. Because of the formal interdisciplinary organization, no researcher had to feel hesitant to ask a colleague to take time out to discuss a problem. Each scientist felt he had a stake in the activities of each other group.

4. A monthly Arid Lands Colloquium was organized. The papers were to serve the purposes of reviewing research in each field so as to bring the participants up to date; describing current research at the University so as to get maximum contributions from workers on other projects; discussing particular problems for future research plans; and advising the interested faculty members and the general public of the activities of the program.

Dr. Raymond M. Turner was appointed Colloquium Leader. He planned the colloquia so that they would have a logical sequence and cover all of the activities as well as possible. The speakers were asked to prepare an extended abstract of their papers. These papers are here assembled as the first in a series of reports of the Arid Lands Colloquia.

PREFACE

Raymond M. Turner
Colloquium Leader

The rapid increase in population in the arid southwestern United States is indicative of man's willingness to invade an area previously rejected as so harsh that few people remained year-round by choice. As each new arrival settles in the desert he contributes to the growing problem of how to increase man's use of these previously rejected areas, and, in a sense, he becomes a partner in a world-wide program aimed at enlarging man's use of these regions. Man's need to embrace and understand these areas is not always in response to a current immigration, such as that in southwestern United States or in Israel, but this need is induced, nonetheless, through existing or predicted population pressures on one of the few remaining sparsely populated climatic regions of the world.

The better utilization of arid lands for man's benefit must be preceded by a forceful program aimed at solving the many fundamental biological and physical problems which will ultimately contribute to man's more efficient use of a land where potable water is inadequate, but heat is not. The University of Arizona Arid Lands Project is possibly the first attempt to solve problems of arid lands by combining the forces of so many disciplines, for in the initial stages of this program there are already specialists working in the fields of anthropology, history, geochronology, geology, climatology and biology. Obviously, all possible forces have not been enlisted but as the program advances it is hoped that other important fields can be included to contribute a full degree of interdisciplinary effort to the solution of this great contemporary problem.

In a program of this scope, one of the major problems arises, and, at the same time, one of the greatest benefits lies, in keeping each member of the team as informed as possible about the work of his colleagues; to have advice and criticism converging from many directions on the work in the various fields insures steady progress toward a common aim. With this in mind a series of colloquia was early established. Those held during the first year of this program will be followed by others in which the emphasis will be placed more upon work accomplished and less upon a review of problems. But whatever the topic, it is hoped that it will be actively reviewed and discussed by workers in the many fields.

The following pages include the proceedings of the eight colloquia held during the first year of the Arid Lands Project. The first talks in the series dealt with such physical features of the desert as its climate and geology, after which, attention was focused upon the occupants of this habitat, with final emphasis given to man's past tenancy of the land. The theme of water or its scarcity pervaded each colloquium and there is little doubt that this same topic will provide continuity from this first report of The University of Arizona Arid Lands Colloquia to all future offerings in this series.

CLIMATOLOGY OF ARID LANDS

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Introduction

Viewed broadly, all of the research objectives of The University of Arizona Arid Lands Program can be regarded as ecologic in nature. Hence it is pertinent to draw attention in this first of our colloquium series to a very fundamental, and indeed almost self-evident, principle of ecology--the law of limits. The law of limits asserts that the physical environment sets limits to the areas within which any living organism can live and reproduce, the limits being either limits of excess or limits of deficiency. Thus, considering man himself, and his agricultural activities in particular, we find that of the 56 million square miles of the world's total land area, about 13 million square miles lie in regions too cold to permit significant agricultural activity, and another 16 million square miles are too dry for conventional agriculture. Thus we find the law of limits operating in a simple and straightforward manner to reduce, to somewhat under one half, the land area within which man can live in a locally self-sustaining economy. In these colloquia, our interest will center around the arid limit; and in the present discussion, in particular, our concern will be with those physical and climatological factors that impose this arid limit.

Aridity and the Hydrologic Cycle

Residents of arid lands looking out upon the more humid parts of the world are prone to complain that their own lands are not getting their proper share of world rainfall, as if there were some self-evident reason for believing that precipitation is a process to be taken for granted. As a meteorologist, I am forced to the opposite view; to me it seems rather more remarkable that our world is not entirely arid.

As a first point in defense of this thesis we may note that neither of our neighbor planets, Venus nor Mars, possesses spectroscopically observable traces of water in its atmosphere--hence, the very presence of this substance is not guaranteed even within the confines of the solar system. Furthermore, it has been made clear through geochemical studies that, early in its history, the earth lost all but perhaps one part in 10^{10} of its initial stock of substances with molecular weight as low as that of water, so our present hydrologic cycle now operates on the relatively small amounts of water derived either from breakdown of hydrates in the earth's crust or from volcanically released juvenile water. Astronomical factors also enter the argument through the fact that the earth would have to be moved only about 25 per cent farther from the sun to lower the global mean temperature from the present value of 15°C to a value of about -15°C, thereby locking up as relatively nonvolatile ice nearly all of the world's surface waters and hence powerfully suppressing the intensity of the hydrologic cycle.

But even given the earth's present abundance of ocean waters and its present mean temperature, it is not immediately obvious why the steady-state solution to the disposition of the available water substance did not turn out to be merely an evaporation--condensation equilibrium maintained across the air-ocean interface without any continental precipitation at all. Indeed, when one considers low-latitude west-coast deserts such as the Namib of South Africa or the Vizcaino of Baja California with their near rainlessness in spite of prevailing humidities near 100 per cent, this suggestion does not seem at all unreasonable. Certainly such an equilibrium is a physically possible state of affairs, and were such an evaporation-condensation equilibrium the actual nature of the terrestrial hydrologic cycle, continental areas would receive only such meager amounts of water as they could extract by dew deposition at night. Under such circumstances general aridity would prevail over all land areas.

The factor which enters to change radically the picture just outlined is the adiabatic ascent of moist air, which can result from forced lifting at mountain barriers, from buoyant ascent in areas of strong surface heating, or from forced ascent due to large-scale convergence of air in cyclonic storms. When air ascends adiabatically, it cools and this process, if carried far enough, finally brings the vapor to its point of condensation. But before taking this very important process for granted, it must be noted that most vapors must be compressed to cause them to condense. Were water one of these substances, our clouds would be found not at the tops of updrafts, but at the bottoms of downdrafts! The latter case would yield a greatly altered hydrologic cycle, since then the air feeding into clouds would originate in higher, drier strata; but still worse, the released latent heat of condensation would inhibit further growth (descent) of the cloud rather than enhance growth as is true under actual conditions. This major difference is produced simply by the circumstance that water has an anomalously large latent heat of condensation (though the thermodynamics of the point cannot be examined here).

But even if we take for granted the occurrence of adiabatic ascent and take for granted the consequences of the odd thermodynamic properties of water vapor, we still face an obstacle to cloud formation that ought not be put aside lightly. This is the nucleation barrier standing in the way of the phase transition from vapor to liquid that must precede the appearance of visible cloud material. Were it not for the fact that our atmosphere always contains tiny hygroscopic particles ("condensation nuclei") having diameters of the order of microns down to tenths of microns, clouds could form only on the ubiquitous ions created continually by cosmic ray bombardment of our atmosphere. Ionic condensation, however, is known to require about four-fold supersaturations (400 per cent relative humidity), from which requirement one can show that summer "cloud bases" over Arizona, for example, would lie at about 25,000 feet altitude were there no hygroscopic debris in our atmosphere. It seems quite unlikely that dynamical processes would frequently produce updrafts of such depth as to reach so high a condensation level; but even if they did there remains the fact that the large numbers of cosmic ray ions would almost certainly give rise to a cloud composed of such tiny droplets that these could not quickly aggregate into raindrop-sized particles, so precipitation would be inhibited.

Finally, even if we take for granted the observed abundance of hygroscopic condensation nuclei, and hence assume existence of clouds of familiar kind, there remains an intricate series of improbable steps by which these clouds of tiny droplets (order of 10 micron diameter) are converted into much larger raindrops (order of 1 millimeter diameter). Since knowledge of precipitation physics is still in a rudimentary state, it is not possible to point to the most crucial requirements Nature must meet to complete the precipitation process. Nevertheless, from the easily observed fact that only a small percentage of all clouds (a reasonable guess would be 1 to 5 per cent) succeed in reaching the precipitation stage, we know that much more often than not the last requirements are not fulfilled and the cloud simply evaporates back into invisible vapor.

All of the above considerations are offered in support of the contention made earlier here: It is actually quite remarkable that our world is not <u>entirely</u> arid. Thus, when we note that 25-30 per cent of the continental areas are too arid to support agriculture we must not be surprised; rather we must be grateful that the percentage is actually that low!

What Is A Desert?

Speaking etymologically, the term "desert" implies simply a deserted place; hence it is not improper to speak of the "desert wastes of Antarctica." Speaking climatologically, however, the term invariably connotes precipitation deficiency. A rather commonly used rule-of-thumb holds that deserts are areas with less than 10 inches of precipitation per year. This rule serves surprisingly well as a first approximation, especially in the thermally rather homogeneous lower latitudes (e.g. Africa, Australia). The rule overlooks, however, the basic ecologic fact that the determinant of plant growth and hence of the overall carrying power of a given region is not simply the amount of precipitation, but rather the fraction of the precipitation that survives immediate evaporation from the soil. The latter fraction is strongly influenced by temperature. Hence one is forced to define desert climatic boundaries in terms of some function of both precipitation and temperature. This is done, for instance, in the familiar definition of a desert as an area where potential evapotranspiration exceeds precipitation. Similarly, dependence of desert climatic boundaries upon both precipitation and temperature is built into the well-known Koeppen system of climatic classification. In the present discussion, the Koeppen definitions will be understood to dictate locations of deserts and their surrounding semiarid steppes. Neither the algebraic nor the graphical form of these definitions will be given here, however, since they are readily found in many sources in the literature.

Factors Governing the Geographic Location of Deserts

Desert geography is controlled ultimately by precipitation physics. Of all of the factors governing the series of steps culminating in precipitation, the two that exhibit most marked geographic variability are: (1) frequency of occurrence of adiabatic ascent of large bodies of air, and (2) availability of an oceanic moisture source in the prevailingly upwind direction. The principal deserts of the world will be found where one or both of these factors operate negatively.

The great low-latitude deserts, such as the Sahara, the Arabian Desert, and the Australian Desert, are dry primarily because of chronic lack of lifting processes. This is revealed to us in one simple way by the fact that isolated mountain areas lying within such deserts usually tend to be "humid islands" by virtue of their ability to cause orographic lifting. Thus the Ahaggar Mountains and the Atlas of North Africa, the Macdonnell Range in the middle of the Australian Desert, and all of the many fault-block mountains of the Arizona desert areas have markedly more rainfall than their surrounding plains. Were the aridity of these surrounding plains due solely to low humidity, no amount of mountain lifting would create the humid montane islands that are so strikingly present. This generalization needs qualification in the sense that deep within the interiors of the larger low-latitude deserts, sheer remoteness from oceanic moisture sources can dominate over even orographic lifting. Thus in the Sahara, the dryness of the Tibesti Range (as contrasted with the more humid Ahaggar Range) is probably an instance of this, since the Tibesti mass lies further from the Atlantic moisture source. The generalization also requires the qualification that presence of a mountain range upwind of a given low-latitude desert may so effectively lower the humidity due to rain-out on the upwind slopes of the range that the desert is to some extent a "rain-shadow desert." Thus, even the relatively low Eastern Highlands of Australia so block the southeast trades impinging on the Queensland coast that interior Australia is denied much moisture now falling on this barrier's east slopes. The arid limit is thereby drawn much closer to the coast than would otherwise be true.

When we look for the reasons for the chronic shortage of dynamical lifting processes in these low-latitude west coast deserts, we find that they are: (a) too far equatorward to be strongly influenced by the extra-tropical wave cyclones that so enhance the precipitation of the lands lying poleward from these deserts, (b) too far poleward to be benefitted by the doldrum (intertropical convergence) belt in its poleward excursions during the summer half-year, and (c) too far westward to be influenced by typical hurricane activity of low-latitude east coast littorals.

If we turn from the low-latitude, west coast deserts to the high-latitude continental arid regions (most of these, incidentally, are steppes and not deserts), we find that the principal factor imposing aridity is the second of the two main factors cited above--remoteness from an oceanic moisture source. This remoteness may be simply geographic, as in the case of the Kirghiz Steppe and the Gobi of Asia, or it may be "hydrometeorological remoteness" created by mountain barriers blocking the inflow of moisture-bearing winds, as in the case of the steppes of North American (High Plains area) or as in the case of the peculiar Patagonia desert lying in the lee of the mid-latitude Andes. Mountain barriers not only reduce, by simple rain-out, the absolute moisture content of the air currents traversing them, but, still worse, they lead to increase in potential temperatures of the traversing air currents by virtue of addition of the latent heat of condensation of the vapor released as precipitation on the upwind slopes of the barrier. What makes these effects seem to us so striking in the case of so-called "rainshadow deserts" is the fact that the entire desiccation process often occurs in horizontal distances of the order of only 100 miles or less. The desertic southwestern portions of all of the mountainous Hawaiian Islands, when contrasted with the lush tropically vegetated northeast portions, offer a particularly impressive instance of this process. The moist trade winds strike the northeast flanks of these island ranges and yield annual rainfall totals that exceed 100 inches over most of the upwind slopes (and reach about

450 inches in the world's wettest spot, northeast Kauai, in the Hawaiian chain), whereas amounts below 20 inches per year are typical of the cactus- and algaroba-covered leeward coasts of the Hawaiian archipelago.

The above-outlined meteorological factors operate to hold precipitation amounts to below the Koeppen desert limits in a total area amounting to about 14 per cent of the entire land area of the earth. This figure has been determined here by measuring an equal-area map of the Koeppen climatic system, the accuracy of the planimetry process being of the order of a few per cent. The Koeppen steppes comprise an additional 14 per cent of the continents, so the combined desert-steppe areas account for 28 per cent of the global land area. Because the literature does not seem to contain any recently published figures on these areas, the complete list of the Koeppen deserts (BW*areas in the Koeppen system) derived from planimetry measurements is given below:

Desert Region	Area (Millions of square miles)
Sahara	3.32
Australian	1.31
Arabian	.93
Turkestan	.76
North American	.44
Patagonian	.26
Thar-Afghanistan	.23
Namib-Kalahari	.22
Taklamakan	.20
Iranian	.15
Atacama	.14
Total area of world deserts	7.96 million sq. mi.

Total land area of world is 56 million square miles. Hence Koeppen deserts comprise 8/56 or 14.3 per cent of all land area.

SOME CLIMATOLOGICAL HIGHLIGHTS OF THE PRINCIPAL DESERTS OF THE WORLD

The Sahara Desert

The 3.3 million square miles of Saharan desert area amount to over eight times the total desert area of the North American continent (Koeppen definitions assumed here and below), and, in fact, exceeds the entire United States area of 3.0 million square miles. Curiously, the Sahara does not, as far as records indicate, contain the driest spot on earth (a distinction reserved to the Atacama Desert of South America) but it holds the record for the world's highest temperature, 136.4°F, observed near Azizia in Libya. Nevertheless, most of the interior Sahara is believed to receive less than one inch average yearly rainfall (Kendrew, 1942). The Libyan desert is significantly drier than the Algerian Sahara, almost certainly a matter of remoteness from the Atlantic. This area must depend chiefly upon the occasional invasion of a cold front trailing from a cyclone traversing the Mediterranean; and such fronts, by the time they reach Libya, are no longer lifting air masses containing appreciable moisture. In

*In the Koeppen system of climatic classification, BW stands for desert; BS stands for steppe, and BWk stands for cold-high-latitude desert.

addition, it is Libya's misfortune that the deep indentation of the equatorial Atlantic coast does not extend far enough eastward to place a warm water surface directly south of Libya, while the Algerian Sahara, at least on its southern margins, enjoys occasional summer precipitation derived from vapor evaporated into the southwest monsoon of the Guinea coast area. The greater aridity of Libya as compared with the western Sahara has apparently characterized most of post-Pleistocene time, for the abundant evidence of neolithic occupancy in the western Sahara is not duplicated in Libya.

The Australian Desert

Surely the most outstanding feature of this desert area is the unusually large fraction of its parent continent that it occupies: 44 per cent of all Australia is a desert by Koeppen standards. This may be contrasted with the 31 per cent of all Africa which is desert (Sahara plus Namib), the 6 per cent of South America, and the 5 per cent of North America that is desert (all values derived from planimeter data presented above).

Why does Australia exhibit so unusually large a desert-fraction? Clearly, one part of the answer lies in the simple observation that Australia's latitudinal extent precludes its possessing either extensive tropical rainforests such as suppress the desert-fraction in both Africa and South America, or extensive high-latitude tree climates to dilute the desert influence. In addition, Australian winter synoptic patterns of weather are prevailingly dominated by anticyclones to such an extent that the steady succession of cyclones passing by in the "Roaring Forties" south of Australia exerts only weak winter influence on the precipitation of the interior and of the north. Furthermore, for synoptic climatologic reasons that are not clear to me, the subtropical anticyclone of the winter half-year over the Indian Ocean (upwind from Australia), produces low-level divergence (Mintz and Dean, 1952), unparalleled in extent and intensity elsewhere in the north or south subtropics, and such divergence enhances dryness due to subsidence. Finally, as has been noted before, the Eastern Highlands add a rainshadow influence that is surprisingly effective considering the low altitude of this barrier (mostly under 3000 feet).

The driest portions of the Australian Desert, in the Lake Eyre area, average about 5 inches rainfall per year. Thus we see that aridity is here not nearly as intense as in the central Sahara, on which only an inch falls annually. Even the annual average of about 3 inches on Yuma, Arizona is not matched for dryness in Australia, despite the latter's desert area being threefold greater than that surrounding Yuma. We can correctly say that desert climate is very extensively but not intensively developed in Australia.

Grazing activities are pushed much farther beyond the dry side of the 10-inch isohyet in Australia than, for example, in North America. Taylor (1949) states that the grazing density in the "sparse-lands" of western Australia is about one cow per 640 acres, whereas in Arizona there are few active ranges where the carrying power is not at least one cow per 75 acres. This difference is a difference in availability, outside the arid zone, in good grazing lands in these two geographic areas.

The Arabian Desert

It would be difficult to decide whether it is the vast Sahara with its Foreign Legion or the smaller Arabian Desert with its bedouin horsemen that the layman pictures when he thinks of "the desert." Since we can scarcely doubt that the harsh climatic stress of Arabia Deserta shaped the life-views of the horsemen who swept out of this wasteland during the Dark Ages and established a Moslem culture across all of North Africa and into Iberia, we must admit that here is a region whose climate has influenced history.

Covering almost a million square miles (0.93 million according to the table above), the Arabian Desert seems to enjoy the distinction of being the sandiest of all deserts in terms of total coverage. Nevertheless, even in Arabia, the sand-covered portion is estimated as covering only about one-third of the total desert area--illustrating the rule that most of the world's deserts are far less sandy than is popularly believed to be the case. (Only about 10 per cent of the Sahara is sand-covered, the rest being "reg" or "serir," a desert pavement, or else bare rock called "hammada." Of the Gobi Desert, which is actually a steppe under the Koeppen system, about 5 per cent is sandy.)

Arabia has as another interesting distinction the complete absence of permanent rivers originating within it, or flowing across it. The latter absence stems from the accidental disposition of highlands in the vicinity of Arabia. No well-watered mountain sources send across this desert any analogs of the Nile, the Colorado, or the Indus.

The Turkestan Desert

The truly desert areas of Turkestan cover about 0.76 million square miles, but these areas are small compared with the great steppes that border the true deserts of the region. The oasis towns of Turkestan bear names steeped in history--Tashkent, Samarkand, Bokhara--but viewed more prosaically they appear as communities wherein man has struggled with aridity for centuries. The melting snowfields of the Hindu Kush and the Pamirs send out annual succor to the oases along the Amu Darya and Sir Darya, but agriculture is most precariously balanced here. As much as 10 acre-feet of irrigation water per acre of tilled land are required annually in most of this region. The peculiar kanatz-type of subterranean irrigation channels, now employed throughout widely scattered parts of the Afro-Asian arid zone, are utilized in all of the Turkestan farm villages, though modern irrigation methods are slowly appearing under Soviet development of this area.

The Caspian Sea bounds the Turkestan desert region on the west. Evidences of repeated strandline fluctuations in this now undrained sea have long been studied by paleoclimatologists seeking clues to the rainfall variations of this region. During the Pleistocene period the Caspian overflowed into the Black Sea through a channel lying 150 feet above the present surface of the Caspian, and this present level is about 85 feet below the present Black Sea level. It is generally believed that the Caspian, like the basin lakes of western North America, was completely dried up during the Climatic Optimum some five to eight thousand years ago, and that it was reestablished as a modern sea when the Near East began to receive more rainfall in the millenium or two before the Christian era. Historical records place its A.D. 1300 stand at about 45 feet above the present level, yet even today one can look down through ten feet of water and see foundation-work revealing locations of a community built on its shores in even drier Dark Ages. The Caspian stands two feet higher today than it did in 1845--an upswing that is strikingly opposed to the concurrent sharp downswing in the Great Salt Lake of the western United States. The latter has lost almost fifty per cent of its total volume in the last century. Since these two quite different trends are not understood in meteorological (or hydrologic) terms, they stand as danger-signs in the way of easy global-scale extrapolation of climatic inferences from one desert to another.

The North American Desert

In the southwestern United States and northwestern Mexico, 0.44 million square miles of land fit the Koeppen desert specification. Because those of us who live in or near this desert area naturally tend to regard it as "quite extensive," it is well to note here that it is only about an eighth as large as the Sahara Desert and only about a third as large as the Australian Desert.

It is interesting to speculate on what changes we might have asked of the geologic processes that shaped North America in order to yield much greater areas of desert than we actually find on our continent. Surely the chief requirement would be obliteration of the deep embayment of the Gulf of Mexico. Were the Gulf all land area, desertic conditions would quite certainly extend eastward from the present Sonoran and Chihuahuan deserts across all of Texas; and Louisiana would probably be in the steppe fringe. The now well-watered Mississippi Valley and marginally-watered Great Plains would suffer heavily from such an imaginary change of land-sea distribution. In addition, very much greater area of Koeppen BWk climates (high-latitude cool deserts) would exist if the Gulf were filled, at least as long as we did not also permit, in our speculations, the removal of the Cordilleran barrier to influx of Pacific moisture.

The southwestern deserts illustrate quite well the climatic dictum, cited earlier here, that low-latitude deserts are dry due to three main causes, which for the North American case run as follows: a) Our southwestern desert region is too far equatorward to be appreciably influenced by cyclonic storms coming in off the Pacific, except in winter when fringe effects give, say, southern Arizona its very modest winter rainfall. b) On the other hand, the region is too far poleward to be sensibly influenced by any precipitation that can be correctly attributed to the summer-migrating intertropical convergence belt. c) Finally, the region is too far westward from the east coast to receive any direct rainfall contributions from trade winds or hurricanes.

The last point requires some qualification. The peculiar summer rainy season of the Sonoran Desert is influenced by the trade circulation in the sense that the injection of moisture into the deep easterly currents that swirl in around the high-level anticyclone over the North American continent in midsummer occurs within the trade wind belt. Also, there appear to be weak but unmistakable indications that dissipating easterly waves originating in the Gulf or Caribbean area drift into the Sonoran desert occasionally and cause temporary increase in the convective activity of the July-August rainy spell. Finally, hurricane influences of a different sort than envisaged in the climatic dictum cited above do appear in the Sonoran Desert. Hurricanes forming not in the Caribbean but off the west coast of Mexico occasionally drift up into our desert area, and though they no longer have the surface circulations characteristic of true hurricanes, they do provide deep moist air masses that have given the Southwest and northern Mexico some of the heaviest rainfalls on record in the late summer period. (This situation is only parallelled climatologically, I believe, by the southward drifting hurricanes, locally called "willie-willies," that move down into the northern fringes of the Australian desert from the Timor Sea.)

I should like to stress that investigators dealing with any ecologic aspect of the arid Southwest need to bear constantly in mind the danger of loose extrapolation of climatological arguments (above all paleo-climatological arguments) from the western to the eastern limits of this desert region. The danger stems from the fact that the western portions (Pacific coastal areas) receive almost all of their precipitation in winter, but are almost rainless in summer due to the inhibiting influence of subsidence in the Pacific anticyclone, while the eastern portions (Texas high plains, Coahuila, etc.) receive almost all of their precipitation in summer. World-wide circulation changes which favor increased precipitation in one of these two subregions will tend to leave the other drier; so one must be constantly on guard against overlooking this opposition in seasonal phase of the rainfall of the east and west extrema. Tucson lies near the half-way point, with just about half its precipitation coming from each season. This two-season feature of the precipitation of southeastern Arizona is quite important to the sustenance of grazing plants and to the existence of the oddly arboreal character of the natural desert vegetation of the area. In this respect, I believe that the part of the world most likely to resemble southeastern Arizona with respect to its seasonal precipitation pattern is the Thar Desert of Pakistan. There the winter rains come as scanty leftovers in the cyclonic storms that move in from the Mediterranean basin, while the summer rains are due, broadly speaking, to convectional release from the western margin of the monsoonal current of moist air sweeping in from the south.

The monsoonal nature of the summer rainfall of Arizona and New Mexico is a final climatological feature of this arid region worth noting here. In southern Arizona, July typically receives about six or seven times as much rainfall as June. The rather sudden arrival of the rainy season is associated with a midtropospheric wind shift from southwesterly flow out of the dry-subsiding source regions of the Pacific to southeasterly flow from the deeply-moist Gulf of Mexico region. The shift results ultimately from continental heating over the central United States, but details are not yet well understood. It is paradoxical that this monsoonal current of moist air flows into the western United States in July and August across the country's most arid region on its way to supplying the vapor for the precipitation over the comparatively humid Rockies area of Utah and Colorado.

The Patagonian Desert

In the narrow southern tip of South America, some 0.26 million square miles of desert area lie in a region where mere land-sea geography ought to preclude any but a very cool moist climate. The Patagonia area is dry for one reason--it is the world's outstanding example of a "rainshadow" desert.

The Andes barrier immediately to the west effectively shut off the moist westerlies blowing in from the South Pacific. Perhaps half or more of this desert lies within only 200 miles of either the Atlantic or the Pacific oceans. One is tempted to term Patagonia a "maritime desert."

The Thar Desert

This desert lies along both sides of the Indus near the latter's mouth, a seemingly odd location when one thinks of the general pattern of India's Southwest Monsoon. That the Thar is dry is due to the rather sharp northwestward boundary to the moist current of the monsoon. The analogy between, say, Karachi in the Thar and, say, Yuma in the Sonoran Desert is very close. Both lie just a bit too far west of the main monsoonal upper-air flow to receive much monsoonal rainfall, save in exceptional years.

The Indus Valley, like the Nile and the Mesopotamian Valleys, was the site of very early civilizations. The cities of Mohenjo-Daro and Harappa were large communities four thousand years ago. Whether their decline was due to climatological changes is controversial. Archaeological evidence such as oversized street-drains, baths in most houses, and various pictorial representations of humid-zone fauna have been adduced by Piggott (1950) to support the view that the Southwest Monsoon must have lain farther west four thousand years ago than it does today and that the decline of these cities was dictated by an eastward shift to the modern pattern. Here, as in all other paleoclimatic arguments, caution is indicated.

The Kalahari Desert

Although the Kalahari bears the name of "desert," most of the Kalahari is only a Koeppen steppe (BS area). The portion truly constituting a Koeppen BW area covers 0.22 million square miles, exactly half the area of the BW region of North America. The Kalahari is to be regarded as chiefly a rainshadow arid region. The southeast trades of the Indian Ocean strike the east coast of Africa and lose so much moisture in crossing the Drakensberg Range that they descend as a warm, dry current into the Kalahari. The Kalahari extends out to the coastal desert known as the Namib, a close analog of the Atacama-Peruvian Desert.

The Taklamakan Desert

This desert occupies about 0.20 million square miles in the middle of the Tarim Basin of Sinkiang. Like Turkestan, its history is intimately entwined with that of the caravan routes from China to the Near East. It is difficult to decide whether to assert that the Taklamakan is a rainshadow desert or just a land-locked region too far from any moisture source to receive much rainfall. The area is agriculturally unimportant, but has some fascinating regional hydrologic problems that have been most confusing to students of climatic fluctuation.

The Iranian Desert

This is a very small desert--only 0.15 million square miles in area. The presence of many Neolithic occupation sites plus the ruins of capitols of powerful empires in or near this desert area raise questions of climatic change. The bleak landscape surrounding Persepolis today is probably enough to encourage such speculation on the part of anyone viewing it, but the evidence for marked desiccation in this area is not conclusive.

The sand dunes of the southeastern parts of the Iranian Desert are reportedly the largest (highest) of any desert in the world, rivalled only by those of the Taklamakan, according to desert explorers.

The Atacama-Peruvian Desert

The smallest desert area of all these here considered (0.14 million square miles), the Atacama enjoys the reputation of being the driest area on earth. The town of Arica averaged only 0.02 inches per year over a 17-year period of record, and all of this came in just three measurable showers. Iquique, another town in the area, has a long-term average annual precipitation of only 0.05 inches. This may be compared, for example, with the rough estimate of one inch per year in the heart of the Sahara, about three inches per year near Yuma, Arizona, and about five inches per year in interior Australia. The great dryness of the Atacama Desert is chiefly attributable to the persistent subsidence of air in the South Pacific anti-cyclone, but upwelling of cold bottom water along the coast is a secondary factor. As in the Namib, or as in the Vizcaino of Baja California, the coastal strip (perhaps ten miles deep) of this desert is extremely foggy despite its rainlessness. The cold offshore water is responsible for this feature of the climates of such low-latitude west coast littoral deserts. It is, perhaps, one of the most ironical aspects of the entire disposition of climatic liabilities to the world's arid region, that in the Atacama coastal region the native suffers under the joint climatic handicaps of frequent, heavy fogs and of almost utter lack of precipitation!

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GEOHYDROLOGY OF ARID LANDS
(Arizona - A Case Study)

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Introduction

In recent years one of the great questions of occupation of arid lands by man is: Can the established and proposed economy caused by large population increase be sustained in the arid zones? This question is particularly applicable in the Southwest; and Arizona, because it is typical of the Southwest, serves as an excellent laboratory in which to analyze the effects of such occupation.

Arid lands are characterized by two dominant factors: (1) an abundance of sunshine, and (2) a shortage of water. Part of the water shortage is due to scant precipitation; in addition, the abundance of sunshine causes an evaporation potential about ten times the amount of the annual rainfall. However, man's success in arid zones is dependent upon the availability of ample water supply. He needs large amounts for agriculture, moderate amounts for industrial enterprises, and an increasing amount per capita for municipal and domestic needs. In addition, man has more leisure time than in past years and is demanding more places with water for recreation.

The basic problem confronted by modern man in the arid zone is what happens when he exceeds the natural, readily available supply of the resources of the region--the one of most importance is water. The amount of water that is available perennially for easy capture by man is the water in surface streams and springs. In Arizona the demand for water has exceeded the amount available in streams and the demand has been met by the development of ground water resources. Indeed, the annual use of water in Arizona is more than three times that available from the surface streams. The use of water from the ground water reservoirs has caused a depletion of water reserves, and such mining of water may eventually cause exhaustion. How, then, can man continue to occupy arid zones unless he takes steps to conserve water?

The major problem today is not one of locating new ground water, but, rather, one of determining the ultimate amount of water that can be withdrawn and managed according to scientific principles and to conditions that prevail in the arid zone. Although the hydrologic systems in the arid zone are controlled by the same physical laws as those in nonarid zones, there are particular conditions and phenomena which are unique in arid lands. It is necessary that man understand these conditions and manipulate them to his best advantage for continued occupation. The problem can be solved by regional scientific investigations that obtain geologic facts as related to surface water, ground water, quality of water, and by understanding their interrelationships. The ultimate critical water problem in Arizona is in the ground water supplies, which have met the demand in excess of the available perennial water supply and undoubtedly will meet even greater demand in the future. Only when the quantitative facts are determined will it be possible for man to appraise the water resources and to manage them properly.

During the past fifty years water supplies have been developed intensively in Arizona. This development has yielded a wealth of hydrologic data which is invaluable for analyzing and understanding man's activities in arid-zone environment. The pattern of water management and achievements in Arizona may well establish the way of life and economic development in other arid zones throughout the world. In order to appraise the effects of Arizona's water development it is necessary to know something about its "water provinces"--such as their physical setting, environment, occurrence of ground and surface water, and related geologic conditions.

Water Provinces and Their Geologic Framework

The State of Arizona has been divided into three major water provinces (Figure 1): (1) Plateau Uplands, embracing the northern part of the state; (2) Central Highlands, a mountainous area that stretches diagonally across the state; and (3) Basin and Range Lowlands, occupying the southwestern part of the state. These provinces have been determined by topography, geology, climate, and the occurrence of surface water and ground water. The Plateau Uplands, although sometimes called a "cool desert," are nevertheless an arid zone; the Basin and Range Lowlands are, for the most part, hot and arid.

Plateau Uplands

The Plateau Uplands include high tablelands and several gently sloping mountains. The altitude ranges from 4,000 to 10,000 feet above sea level. A wide variety of land-forms occur in this area, commonly as buttes, mesas, and deep, narrow canyons. The Plateau Uplands are a country of vast expanse and magnificent scenery. It is the country of the Little Colorado River, the land of the Navajo, and a region of inadequate water supply.

The arid nature of these uplands is accentuated by the flat desert plains in most of the area. The meager rainfall has every possibility of returning to the atmosphere by the process of capillary recirculation. This is particularly evident, as there is a paucity of vegetation to protect the moisture from evaporation. The major point of natural discharge of water from the ground water system is near the junction of the Colorado and Little Colorado Rivers. Here Blue Springs (Figure 2) discharges 160,000 acre-feet annually.

Occurrence of Water

In the northeastern part of the state the ground water reservoirs occur in rock sequences of Permian age and younger. Owing to the lithologic character of the rocks, a series of water tables are perched throughout the stratigraphic sequence (Figure 3). For the most part, ground water occurs in sandstone and limestone that are separated by relatively impermeable beds of siltstone and claystone. The occurrence of water in these rock units in specific areas is related not only to their lithologic character but to the geologic structural conditions which constitute definite controls. Ground water does not saturate the rock units uniformly because of wavy uplifts and downwarps.

Some rocks older than Permian contain ground water, and several large springs discharge from the Redwall limestone of Mississippian age in the Grand Canyon area and along the Mogollon Rim escarpment. This formation is

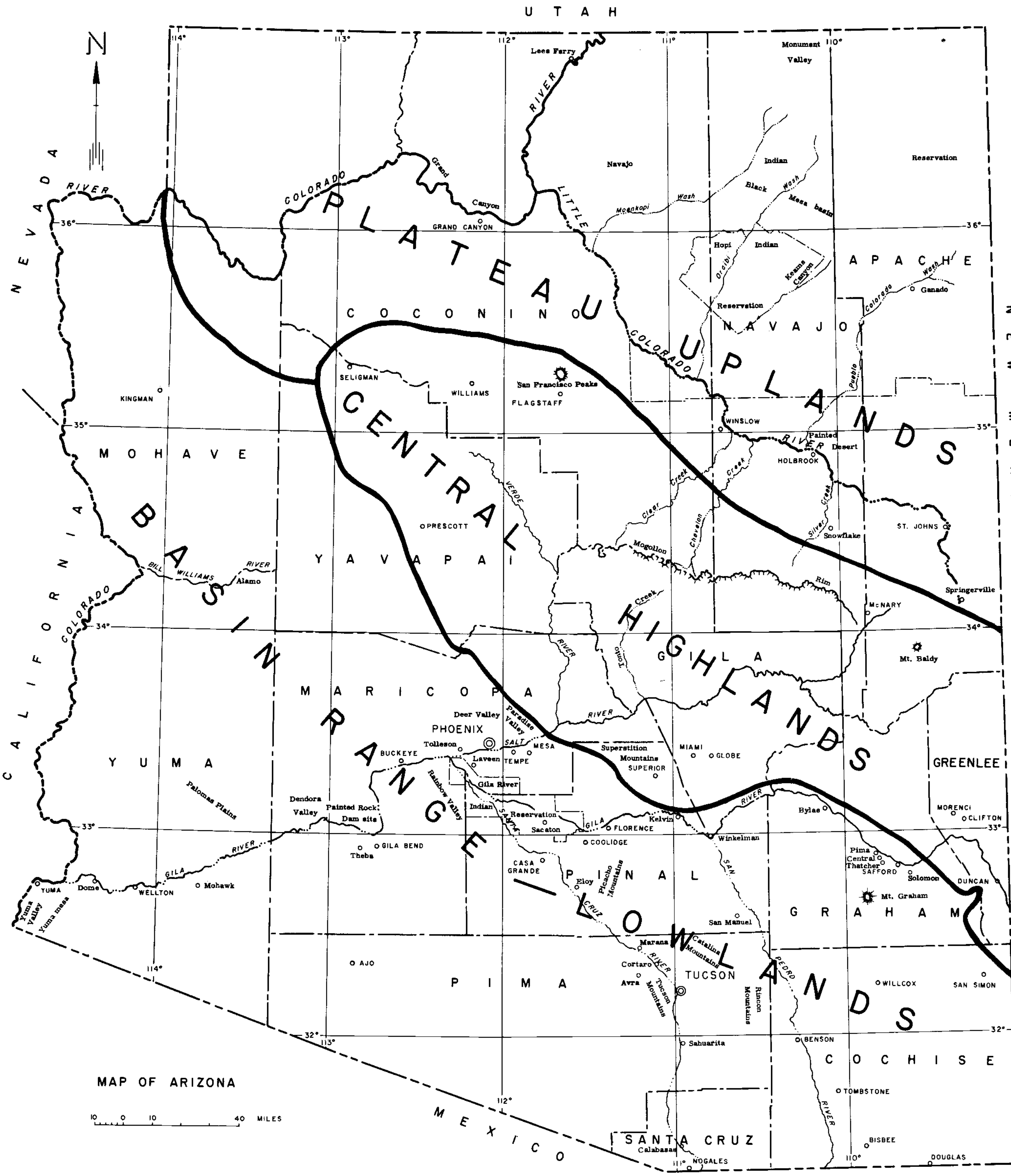

FIGURE I.-- WATER PROVINCES IN ARIZONA

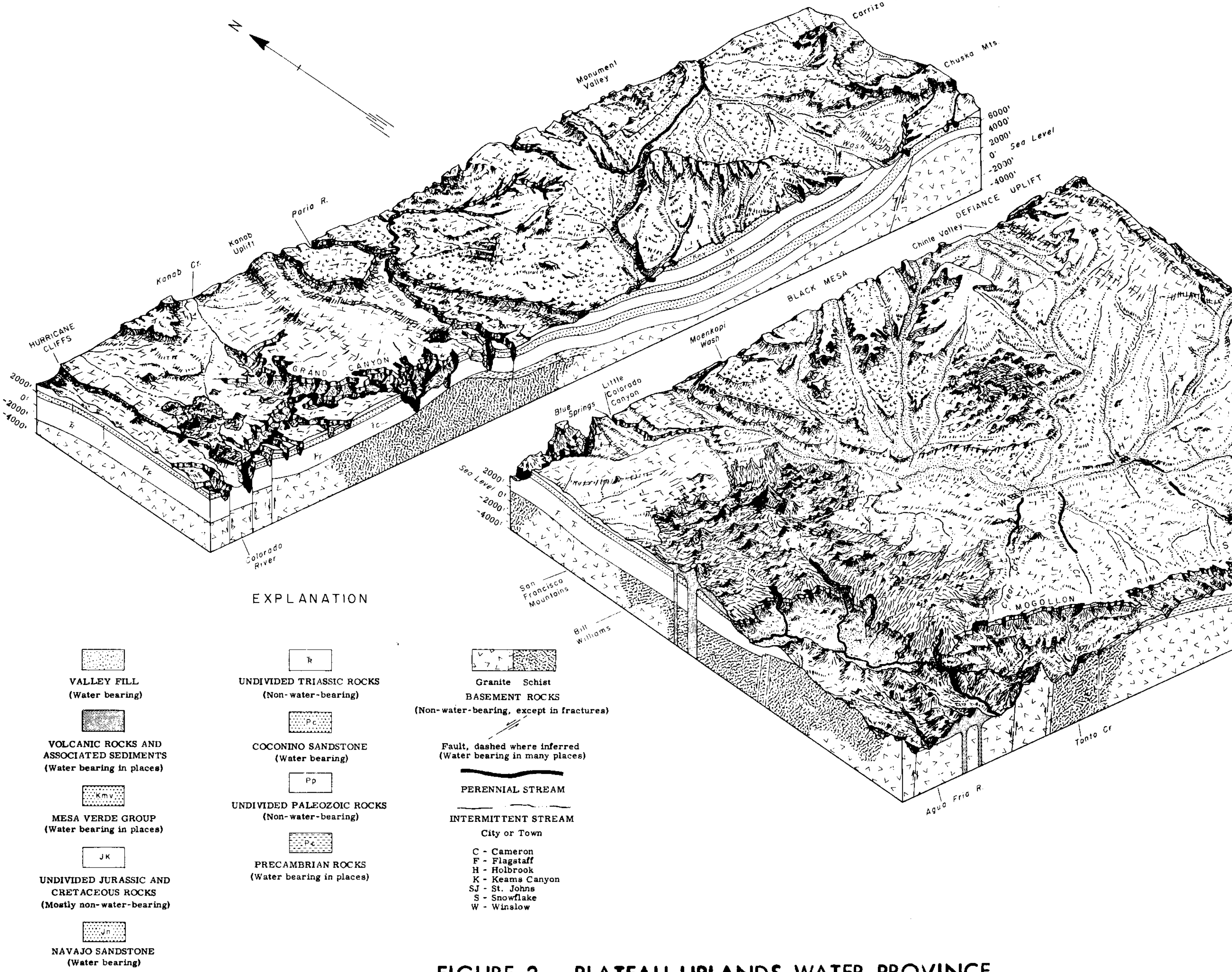

FIGURE 2.--PLATEAU UPLANDS WATER PROVINCE

so far beneath the land surface that it is not within practical reach of the drill or within economic limit for pumping water. Perhaps in the future these sources might constitute potential supplies, depending upon the need for ground water.

The Coconino sandstone of Permian age is one of the major water-bearing formations in the northern part of the state (Figure 2). It is a fine-grained sandstone, and it attains a maximum thickness of about 900 feet. Thus, where fully saturated, it constitutes a large reservoir. Unfortunately, however, the sandstone is relatively impermeable and does not yield large quantities of water to wells except in areas where it is highly fractured.

In Apache and Navajo Counties the Coconino sandstone yields moderate amounts of water to irrigation wells, and some wells topping this aquifer in the St. Johns-Springerville area yield from several hundred to 2,000 gallons per minute. Further studies may indicate that similar yields may be available in a larger area. The short growing season and the absence of a nearby market may account for the lack of development, but future demands may accelerate additional exploration.

Several aquifers of Triassic and Jurassic age are capable of yielding small supplies of ground water to wells (Figure 3). The most important of these is the Navajo sandstone which crops out in the Navajo and Hopi Indian Reservations. The Navajo yields only moderate quantities of water to wells because the sandstone if fine-grained.

The beds of sandstone in the Mesaverde group of Cretaceous age comprise aquifers that yield small amounts of water for institutional and domestic supplies. There is little likelihood that sufficient water could be developed from these sands for irrigation purposes. Several small industries have been supplied by ground water from these formations; per gallon of water produced, however, construction and well development in this area are more costly than they are in the southern part of the state.

Generally, wells yield only small amounts of water and use is limited mostly to domestic and municipal supplies. There are exceptions where geologic factors have rendered local areas favorable for large production. Although the aquifers are widespread, are several hundreds of feet thick, and contain large amounts of water in storage, they are not capable of yielding large quantities of water except locally. The natural character of the rocks makes it impossible to withdraw large quantities, and the movement of water within the rocks is extremely slow--perhaps a few inches a day.

Central Highlands

The Central Highlands form a topographic high across the central part of the state. One of the distinctive features of grandeur is the Mogollon Rim escarpment (Figure 4). It extends more than 200 miles and ranges in height from several hundred to more than 2,000 feet. As the escarpment breaches one of the main aquifers at its base, springs discharge into the Gila, Salt, and Verde Rivers.

Precipitation ranges from about 10 to 35 inches annually, accounting for the perennial streams in the central part of the state. Water from the

Central Highlands drains into Tonto Creek, Salt, Black, White, Verde, and Gila Rivers, and a lesser amount into the Little Colorado River. The Salt River and Tonto Creek join in the highlands area and discharge into the Basin and Range Lowlands through a single outlet (Figure 4). In this gorge are impounded surface waters that provide the perennial replenishment for agriculture, industry, and municipalities in the Salt River Valley and the Phoenix metropolitan area.

The Central Highlands consist for the most part, of hard, dense rocks which have been faulted and fractured. Water occurs in the fractures, and accounts for some of the large springs in the area. These springs, and those at the base of the Mogollon Rim escarpment, discharge annually about 130,000 acre-feet of water, which drains toward the lowlands province. Several small alluvial-basin deposits containing small amounts of water occur in the Verde Valley area and to a lesser extent in the Tonto Basin area. Surface water is much more plentiful than ground water in this province. The average run-off for the Salt River above Roosevelt Lake is more than 600,000 acre-feet per year. The average flow at the mouth of the Verde River is about 500,000 acre-feet per year. Thus a little more than 1,000,000 acre-feet of water is available perennially to supply the agricultural, industrial, and municipal needs in the Phoenix area. Without this perennial supply of water it is doubtful that man could have attained the foothold he has today in the arid lands of Arizona. How demands in excess of this perennial supply will be met remains a problem.

Basin and Range Lowlands

The fact that more than 80 per cent of the state's population is located in the Basin and Range Province attests to the desirability of this area as a place to live, since the climate is perennially favorable to outdoor work and recreation. The explosive population increase provides an adequate labor supply and the lowlands provide an ideal setting for agriculture, industry, mining, and living.

In the lowlands there are still large areas of fertile land that remain desert. These probably will someday provide additional space for occupation when adequate water supplies are developed. Man's activities in Arizona are limited because there is a deficiency of available water. Without this natural resource he cannot progress in agriculture and industry, or enjoy life; thus, it becomes paramount that he learn all there is about the water supply in this province, or he may find that it will revert to desert wasteland.

Occurrence of Water

The southern part of Arizona consists of large alluvial basins separated by mountain ranges (Figure 5). The mountain ranges, for the most part, trend northwestward. The mountains and basins are about equal in areal extent and the alluvial slopes are rather steep in the southeastern part of the state. The basins are larger and their slopes are gentler in the central part. The basins have been filled with alluvium and lake deposits, the upper part of the fill consists mainly of unconsolidated gravel, sand, silt, and clay. The material of late Tertiary and Quaternary age, that constitutes the younger or upper part of the fill in the basins, probably was eroded from the adjacent mountain blocks. At the time of their deposition,

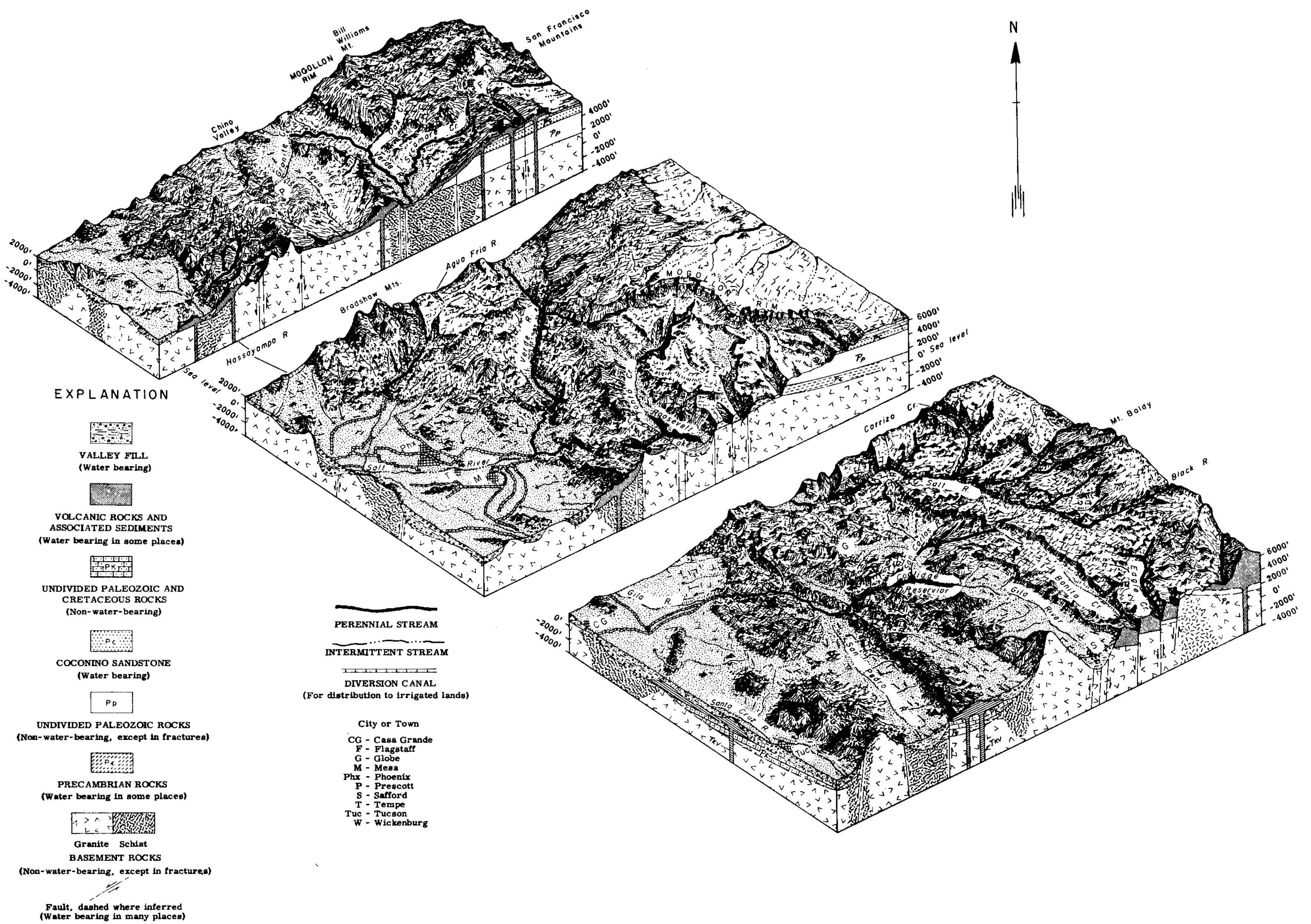

FIGURE 4.--CENTRAL HIGHLANDS WATER PROVINCE

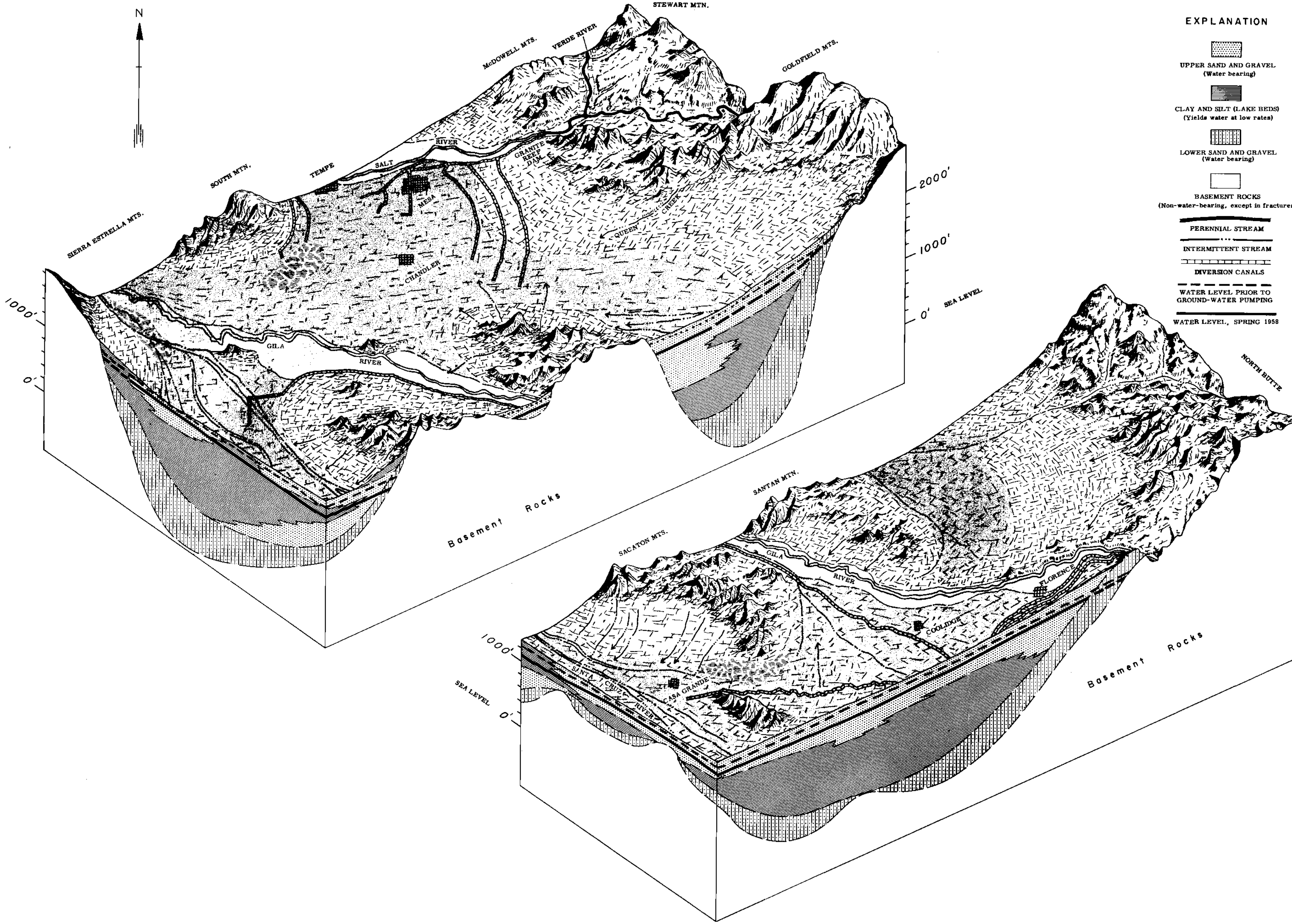

FIGURE 5--ALLUVIAL BASINS IN CENTRAL ARIZONA

the climate was wetter, allowing the basins to be filled with ground water. The deeper deposits of the basin undoubtedly are upper Tertiary rocks, and commonly are called "lake beds." Although the total thickness of lake beds and alluvial sediments in the major basins is unknown, it is believed that it ranges from less than 3,000 to more than 5,000 feet.

The water level in the alluvial fill of the basins ranges in depth from a few feet to several hundred feet below land surface. Ground water occurs in two ways: (1) under artesian pressure in aquifers overlain by relatively impervious beds of silt and clay, and (2) unconfined in water table or nonartesian aquifers.

Generally the water table has a greater permeability than the artesian aquifers and yields larger quantities of water. The artesian aquifers commonly lie at depths ranging from about 700 to 1,500 feet below land surface.

The alluvium contains perched water where clay lenses retard movement downward to the main water table. Water supplies from this source, however, are meager and sufficient only for domestic or stock wells.

Movement

The movement of ground water in the various basins in the state is controlled by: (1) permeability of the aquifers, (2) the cross sectional area of saturated sediments, (3) the hydraulic gradient, and (4) the replenishment.

Water in saturated sediments moves down gradient under the force of gravity toward an area of lower hydraulic head. A water table contour map of an area indicates the gradient of the water table, and ground water moves at right angles to the contour lines. When a well is pumped the water table is lowered in the immediate vicinity of the well, and the local gradient that is created, allows the water to move toward the well. The rate at which it moves, however, will depend upon the permeability of the material through which it moves and the magnitude of the gradient created.

Permeability is a measure of the amount of water that passes through a unit cross section of saturated material in a unit time under a hydraulic gradient of 100 per cent. It is dependent upon the size, shape, and degree of compaction of the grains. The "coefficient of permeability" was defined by Meinzer (Stearns 1928) as the rate of flow of water in gallons per day through a cross sectional area of one square foot under a hydraulic gradient of one foot per foot at a temperature of 60°F. The field coefficient of permeability is the same, except that it is measured at the prevailing temperature of the water in the aquifer. The coefficient of permeability of a water-bearing material gives the hydrologist more information as to how much water the material will yield to the well than does the porosity of the material. Cementation is important in regard to permeability because it can retard the rate of movement in various areas throughout the formation, which may have high porosity in some places and low porosity in others, and yet have an overall low permeability.

In general, fine-grained materials have low permeabilities. Some shale, siltstone, and claystone have permeabilities of less than one gallon per day per square foot; permeabilities of fine-grained sandstones generally range from 10 to 100. Aquifers composed of the larger sizes of medium and coarse-grained materials have permeabilities in the magnitude of 1,000. Aquifers consisting of unconsolidated gravel with intermixtures of sand, may have permeabilities that range up to 5,000 or 10,000.

Currently, "coefficient of transmissibility" is more widely used than is the permeability coefficient. The coefficient of transmissibility is defined (Theis, 1935) as the rate of flow of water in gallons per day through a vertical strip of an aquifer one foot wide and extending throughout the saturated thickness, under a hydraulic gradient of 100 per cent at the prevailing temperature. The relation between the two coefficients is $T = P_f m$, where T is the coefficient of transmissibility, P_f is the field coefficient of permeability, and m is the total saturated thickness of the aquifer, in feet.

The determination of either the coefficient of permeability or the coefficient of transmissibility of an aquifer presents many problems owing to the lenticularity of the sediments. In the southern part of the state the basins are made up of irregular lenses of gravel, sand, silt, and clay; thus the coefficient of permeability ranges widely throughout any one basin. With sufficient data, however, an estimate of the average coefficient of permeability for an area can be ascertained. Thus, in the alluvial basins it is important to know the detailed lithologic character, both vertically and laterally, as it is related directly to the permeability of the aquifer and the movement of ground water.

The rate of ground water movement ranges greatly throughout the aquifers of the state. In some of the fine-grained aquifers in the northern part of the state, movement may be only a few inches or a few feet a year, and well yields are small. In a few of the alluvial basins in the southern part of the state, ground water moves as much as several hundred feet per year, and the yield of wells is many times as great.

Storage

Storage of ground water in the alluvial-filled basins of southern Arizona and in the consolidated rocks of the northern part of the state is related directly to the porosity of the materials. The porosity of a rock is defined as its property of containing interstices or void space. It is expressed quantitatively as the percentage of void space to the total volumetric content. A rock having a porosity of 40 per cent can store water up to 40 per cent of its own volume. The unconsolidated alluvial materials in the basins, have a greater porosity than rocks that are consolidated and cemented. The porosity of the alluvial material ranges from about 10 to 35 per cent and averages about 25 per cent.

Specific retention and specific yield must be considered in order to determine the effective storage. The specific retention of an aquifer or storage reservoir is a measure of its capacity to retain water against the force of gravity during pumping or other forms of discharge. It is expressed as the percentage of water retained to the total volume of material dewatered. Specific yield is the amount of water that can be drained by gravity from a unit volume.

The determination of the effective storage or the specific yield of a basin is difficult, because of the variables that control these factors. It is impossible to arrive at any reasonable estimate of storage without detailed knowledge of the geology, including the interrelationships of the various strata and their structural setting (Figure 5). The total storage capacity of a basin includes its entire volume, parts of which may be beyond the economic pumping lift. Adequate knowledge of geologic conditions would make it possible to determine the amount of water that could be withdrawn from the aquifer within certain depths. Current economic factors would be used to determine whether pumping the available water from such depths would be practical.

Water table declines indicate that the amount of water in storage is being decreased in some areas (Figure 6). This does not mean that the entire ground water basin will be depleted within a few years, but it indicates a reduction of storage in part of the basin.

Withdrawing ground water from the storage basins in Arizona is largely a mining process. This natural resource, which has been laid down during geologic time, is being removed in amounts in excess of replenishment. A complete knowledge of the geologic conditions that control the ground water movement, and of the differences in permeability throughout the basins is necessary in order to make sound decisions regarding the depletion or mining of this important resource.

Use of Water In Arizona

The major beneficial use of water in Arizona is for irrigation. During the period 1936-58, an average of 1,300,000 acre-feet was diverted each year from streams, mostly from the Central Highlands. During the period 1948-58, the annual gross diversion from the Colorado River ranged from 720,000 to 1,270,000 acre-feet. Return surface flows from the Yuma area averaged more than 300,000 acre-feet, so that the net diversion from the Colorado River has not exceeded 970,000 acre-feet annually. The total net diversions of surface water for irrigation in Arizona are about 2,300,000 acre-feet per year. The greatest use of surface water for municipal supply is diversion of 30,000 acre-feet per year from the Verde River for the Phoenix area. About 10,000 acre-feet are diverted from the Black and San Francisco Rivers to supply water for the Morenci mining enterprise.

More than 95 per cent of the precipitation falling on Arizona (about 80 million acre-feet per year) is consumed by evaporation and used by natural vegetation. Percolation in the soil from rains is not deep and after the storm the surface soil moisture is soon evaporated. Much of the run-off that does occur is used to saturate the porous materials in the stream bed. Evaporation from flowing streams is usually very large in arid lands; also much water is lost by evaporation from surface reservoirs. During 1957, 90 inches of water were evaporated from Lake Mead alone--a water loss of 800,000 acre-feet. The total loss of water by evaporation from all the reservoirs within the state is more than one million acre-feet each year.

For the past five years the annual ground water withdrawal for agriculture has been more than 4-1/2 million acre-feet. Eighty per cent of the ground water is pumped in Maricopa and Pinal Counties. In 1957, industry, including mining activities, used more than 175,000 acre-feet from the ground water reservoir, principally for cooling and sanitation purposes. This is less than five per cent of the total ground water pumped, but represents a

400 per cent increase over the amount used in 1949 for this purpose. Because of the increase in population in recent years, the amount of water used by municipalities has become a significant part of the water used in the state. Municipalities used 40,000 acre-feet in 1949; their use increased to about 130,000 acre-feet in 1958.

In summation, Arizona uses more than seven million acre-feet annually for agriculture and industry and for providing man with modern comforts. About five million come from the ground water reservoirs and the other two million come from surface water supplies. Half a million acre-feet are used for industry and municipalities, and 6-1/2 million are used for irrigation. Although surface water supplies were originally adequate, many communities, such as Flagstaff, Winslow, Safford, and Phoenix, now use ground water as a supplementary supply.

How Can Water Supplies Be Increased In Arid Lands?

The problem of increasing available water supplies to meet the future demands in arid lands is of utmost importance. How can this be done? Many possibilities have been suggested to increase available water, but an analysis of these indicates that three are realistic: (1) conversion of saline or brackish water, (2) capture of water that is otherwise lost to the atmosphere, and (3) scientific exploitation of the existing ground water reserves.

The desalting of sea water for fresh water use seems feasible, and recently it has been shown that the cost of conversion is comparable to some present municipal water costs. One large factor, however, is the cost of transporting the water. To transport to Tucson, which lies 100 miles from the nearest seacoast and 2,500 miles above sea level, would cost several hundred dollars per acre-foot. This contrasts to present-day municipal costs of $50 to $80 per acre-foot. Converting brackish or saline waters in our ground water basins, however, offers a real possibility, since the cost of transportation would probably be small and within the realm of the present-day economic situation.

One of the most practical measures for increasing the availability of water supplies--and one that has been suggested by many early workers--is capturing liquid water and storing it underground. The newly stored water would not be lost by evaporation and could be recovered when needed, since there is little possibility that the water would leave the basin by underflow. This suggested measure includes: (1) the capture of flood waters in the lowlands and base flow from the highlands, both of which for the most part are now lost by evaporation; (2) transportation of the water in lined canals or conduits to areas where there have been large ground water withdrawals or areas which have the greatest need and highest use; and (3) recharge of the water into dewatered sediments by wells (Figure 7). One advantage of recharging water into dewatered sediments instead of bone-dry material is that the specific retention is already satisfied, and it would be possible to recover about 100 per cent of the recharged water. There are many engineering, geologic, and economic problems, however, that need to be resolved before artificial recharge can be put into operation in Arizona.

Conclusions

The greatest challenge to man occupying arid lands is the development of adequate water supplies. To meet this challenge it is necessary to make

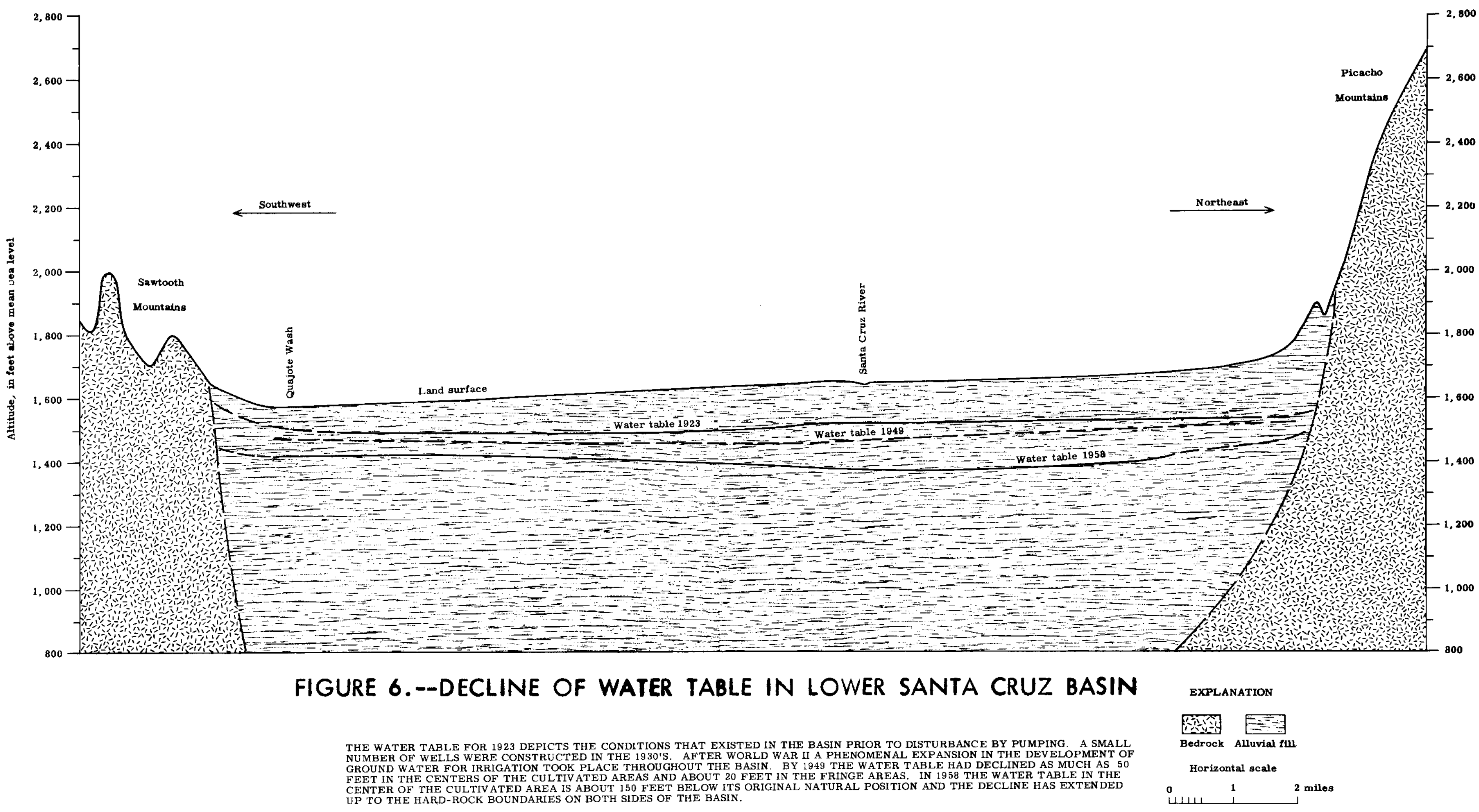

FIGURE 6.--DECLINE OF WATER TABLE IN LOWER SANTA CRUZ BASIN

THE WATER TABLE FOR 1923 DEPICTS THE CONDITIONS THAT EXISTED IN THE BASIN PRIOR TO DISTURBANCE BY PUMPING. A SMALL NUMBER OF WELLS WERE CONSTRUCTED IN THE 1930'S. AFTER WORLD WAR II A PHENOMENAL EXPANSION IN THE DEVELOPMENT OF GROUND WATER FOR IRRIGATION TOOK PLACE THROUGHOUT THE BASIN. BY 1949 THE WATER TABLE HAD DECLINED AS MUCH AS 50 FEET IN THE CENTERS OF THE CULTIVATED AREAS AND ABOUT 20 FEET IN THE FRINGE AREAS. IN 1958 THE WATER TABLE IN THE CENTER OF THE CULTIVATED AREA IS ABOUT 150 FEET BELOW ITS ORIGINAL NATURAL POSITION AND THE DECLINE HAS EXTENDED UP TO THE HARD-ROCK BOUNDARIES ON BOTH SIDES OF THE BASIN.

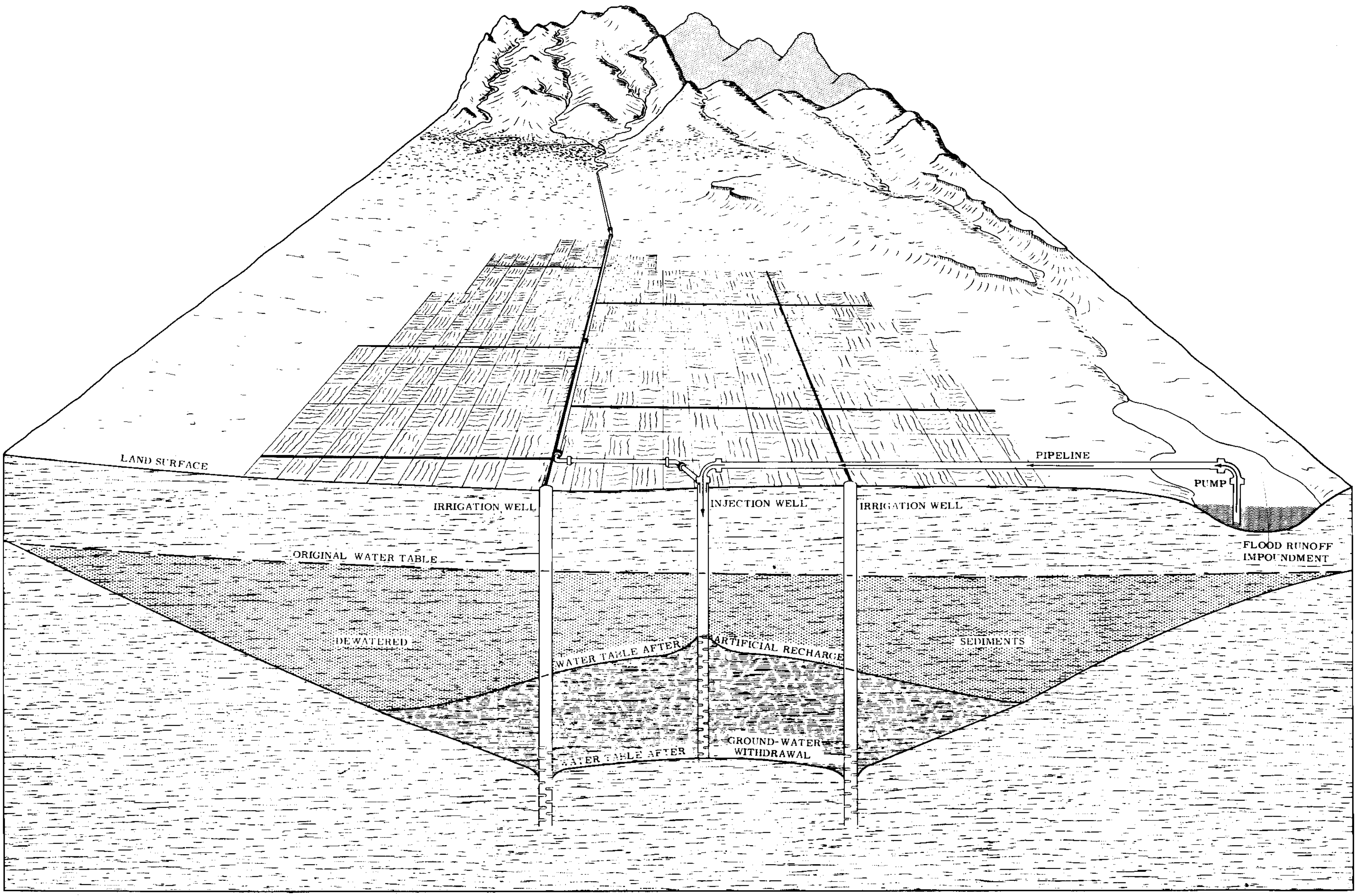

FIGURE 7.--ARTIFICIAL RECHARGE BY WELLS

quantitative determinations of all possible water sources and to manage them scientifically. When water demand exceeds supply or perennial replenishment, man has several choices to meet his needs: (1) transporting water into the area, (2) capturing additional water that escapes under natural conditions, and (3) moving into areas blessed with ample water.. Information is needed on our total water supply, the magnitude of our reserves, and the rates of depletion. A better understanding of the hydrologic system and the mechanics of ground water movement, particularly of the surface water and ground water interrelationships, is essential. All the disciplines in the water resources field need to be harmonized and merged to achieve a clear understanding of Arizona's hydrology, and to attain the most efficient manner of exploitation.

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VEGETATION CHANGE AND ARROYO CUTTING IN SOUTHEASTERN ARIZONA DURING THE PAST CENTURY: AN HISTORICAL REVIEW

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The University of Arizona

During the course of the last half-century a full-blown set of legends has grown up around changes that have supposedly occurred in the biological environment of southeastern Arizona. While too well-known to bear much repeating, its general tenor is that fields of grass "belly-high to a horse" used to wave across mesa lands that were free from brush and undissected by gullies.

In the lowlands, so the story goes, streams ran the year around, backed up into clear ponds behind beaver dams; the ponds in turn were filled with fish. Springs dotted the uplands. Cienegas were abundant.

In short, this area--defined as the region bounded on the north by the Gila, on the south by an imaginary line roughly parallel to and some fifteen miles south of the International Boundary, on the east by New Mexico, and on the west by the Sierritas, the Tumacacoris, and the other ranges lying to the west of the Santa Cruz River--was the Biblical "Land of Milk and Honey."

Two quotations may be appropriate: The first is from an account by James H. Tevis, who came to Arizona in the 1850's. In those days grass grew very tall--belly-high to a horse. He is however, talking about conditions fifty years earlier still as described to him by an Indian.

> In those days the grass grew very tall...in fact, so tall that one could see only the heads of antelopes. (Tevis, 1954: 81)

The second is from Colonel Green, Commandant of Camp Apache, Arizona Territory, writing in 1871:

> If you wish any further correspondence from me as to my views of Arizona, I can only tell you I have been over a great portion of it...and found it a rocky, mountainous desert, not fit even for the beasts of the field to live in. (<u>Arizona Citizen</u>, April 22, 1871)

These quotations are not intended to imply that changes have not taken place. Indeed they have; in general it is probably safe to say even that they have followed the lines of the legend.

What should be emphasized is that any reminiscences concerning early Arizona--in fact, any historically descriptive material at all bearing on the problem of change--has to be viewed in a context that recognizes two clear limitations.

One of them is the "good old days" fallacy. This longing after another time, another place, is implicit in much of human thinking; it operates particularly insidiously in the field of historical reminiscence; it is bound to color any conclusions derived from such sources unless the researcher uses extreme caution. To us the golden age of Arizona ecologically lay in Tevis' time. To Tevis, in turn, it lay fifty years still earlier, in the childhood of his friend, the Indian Esconolea. To Esconolea's grandfather--well, his reminiscences are not available, but we can make a reasonably accurate guess as to their tone.

The second limitation derives from the obvious fact that Colonel Green wrote in disparaging terms about conditions that seem to us to have been very good indeed. But we are taking the same spatial area and comparing it at two points in time. He, on the other hand, was making a comparison of two different areas in space at the same point in time.

To him the Arizona of a century ago seemed arid and undesirable because he tended to think of it in terms of Massachusetts or Virginia, or Ohio, or wherever. And compared to those well-watered regions of the same day, Arizona then was no "Land of Milk and Honey"; it was a howling, arid wilderness.

To this fact of its aridity we can trace many of what seem to be glaring contradictions in historical evidence. Because Arizona was arid--then as now--its plant life exhibited marked vulnerability to what would have been relatively minor fluctuations any place else, say two or three inches of rainfall in the annual total. At the same time that plants were unusually susceptible to variation--probably every speaker at these colloquia so far has made this point--much greater variation could be expected. An arid climate experiences greater variability than a humid one. Variation occurs from one area to another during the same season; variation occurs from one season to another; wide variation can occur from one season to the same season in a different year.

To illustrate the point, let me cite two descriptions of the junction of Sopori Creek with the Santa Cruz River.

One is written by Major Fergusson in 1862 and talks of the "good grass" there and the "permanent water" (Fergusson, 1863: 14).

The other, by J. Ross Browne in 1864 describes precisely the same spot this way:

> There was not so much as a pool left in the Santa Cruz River from which we could satisfy our own thirst, much less water our animals...The grass is crisped, the trees are withered, the bed of the river is dry, the sap of life seems to have deserted the place....(Browne, 1951: 258-9)

The same point in space, then, varies in time.

The same point in time varies in space. An 1849 emigrant, H. M. T. Powell, traveling across Arizona and northern Sonora on his way to the gold fields, says this about the upper Santa Cruz. The date is September 30:

> The soil is excellent, and fit for any kind of culture. I have no doubt that sugar, cotton and tobacco might be raised here with little trouble. The appearance of the country is beautiful. Gentle hills and dales. Trees scattered around singly and in clumps give it a park-like appearance. The grama and other grasses grow very luxuriantly....
> (Powell, 1931: 133)

One week later, however, further north along the Santa Cruz he writes waspishly:

> Everything is thorny, the grass even is pointed and, running up through your trousers, chafes and wounds you...Everything is armed, and all the insects are venomous...When we arrived at night camp we had to dip up the muddy water from the ruts and puddles in the road to make our coffee, and to drink... Hardly any feed for our cattle, and still they push on and on!...my cattle are failing...(Powell, 1931: 144)

One person reads in a journal that the Gila was dry below the Pima Villages in, say, 1846. He concludes that the Gila was much the same in the old days as now; it did not flow all the way to the Colorado.

But a second person reads in another journal that in, say, 1856--these dates are purely hypothetical--the clear waters of the Gila made a startling contrast with the muddy Colorado. The second person concludes that in the "good old days" the Gila, in marked contrast to conditions today, was perennial along its whole length.

Which page of the historical memoir do you read? Which historical memoir do you read? Which do you believe? If you happen to be a lawyer involved in the controversy between Arizona and California over water rights, presumably you believe the one that happens to support the contentions of the side retaining you. If you are a hydrologist, however, trying to accumulate some information on river-flow you read both, and you had better read a great many others besides.

This whole line of thought stemming from the twin notions of, first, the "good old days fallacy," and secondly, relative aridity, is of course, concerned with problems of historical evaluation. One must deal with the problems as an historian, not as an ecologist or a climatologist, even though the problems under discussion may lie perhaps more immediately in the latter two fields. The role of an historian in the Arid Lands Project is not that of attempting to answer the question of why changes have taken place in the Arizona landscape, or of which factors have interacted to produce the changes. These problems, after all, require the specialized attention of a variety of sciences.

The part of the historian is rather to piece together from an almost overwhelming number of historical sources--sources which otherwise might be neglected--a comprehensive, usable, and compact account that, first, will accurately describe what conditions were like prior to 1880; second, will describe the landscape-changing process as it began and advanced; third, will establish some sort of chronology for the changes; and fourth, will be useful to the specialist with whose field the subject properly deals, by providing him with background information he otherwise might not have.

This colloquium should be considered as a progress report only. The work is not finished; a great deal more remains to be done in assimilating and evaluating the information that has been gathered. The reader, of course, is interested primarily in hearing conclusions. The writer is equally interested in avoiding them this early in the study. Perhaps a middle ground lies in stating what seems to be indicated so far, with the mutual understanding that these inferences are tentative.

Some of the changes that have allegedly occurred will be noted in the following sections.

Thinning of Grasslands

First, there is the notion that formerly lush grasslands have thinned or disappeared; that grass cover now is notably less than it was before 1880.

Early travelers were concerned with grass conditions because of their animals; consequently their journals contain a great deal of pertinent information: so do early army records, emigrant itineraries and guides, ranchers' records, newspaper accounts of range conditions, and pioneer reminiscences.

All of these sources--in spite of the tricky and highly subjective problem of evaluating what a person means by "good grass" or "poor grass"--seem to support the generalization that the grasslands have deteriorated. The change, however, is probably not so pronounced as legend has it, and to any notion of deterioration one has to attach two firm qualifications.

In the first place the "lush grasslands" of the middle nineteenth century were not homogeneous. Conditions varied seasonally, so that, as mentioned earlier, travelers noted entirely different conditions for a given area, depending on when they saw it. Conditions varied from year to year. As an example of this, in the 1870's and 80's, hay for the cavalry animals at Fort Grant used to be cut in the Arivaipa Valley near the Fort, with mowing machines. ("Report on Hygiene," 1875: 535. Arizona Daily Star, September 28, 1890)

Here ostensibly is the ideal bit of historical evidence to verify the legend in every respect. But looking a little closer, we find that machine mowing occurred only during the wet years. Here is a quote from one of the hay contractors:

> During poor grass years we cut it with heavy hoes as it was too spotty to use mowers...The hoers would cut it at its crown level with the soil. (Franklin, n.d.: 4)

Perhaps one more observation is in order. This part of the Arivaipa Valley is still a long way from being impoverished rangeland. In exceptional years today, it might still be possible to use a mowing machine to advantage. The difference between 1880 and today may well lie in the decreased frequency with which these optimum conditions occur, not in any uniform deterioration in the quantity of grass.

Very well; seasonally and yearly, grass conditions were not uniformly good, nor were they good spatially. The Gila from the Pima Villages west was a source of apprehension to travelers, wet year or dry, because of the lack of grass for the animals. (Audubon, 1906: 162; Bartlett, 1854; II, 187; HED 108, 1859: 99)

The second qualification that has to be attached to any notion of changed grass conditions is that change is apparent for some areas only and not for all.

In the wetter parts of the region grass was excellent then; it is excellent still. In the mesa lands of the upper San Pedro Basin in northern Sonora, for example, grass used to be "belly-high to a horse." (Bell, 1932: 306; Powell, 1931: 130-3.) It still is. (See Figure I)

Conversely, along the International Boundary in the western reaches of Papagueria, travelers used to talk about there being "not a blade of grass." It is still scant.

One might take as a working hypothesis, then, that in the parts of southeastern Arizona where there are relative extremes in rainfall, either toward aridity or toward humidity, no change is evident from the conditions prevailing in 1880; or at any rate the change is less than for areas lying in the middle reaches of the rainfall spectrum.

Drying of Marshes and Springs

Leaving the grasslands and taking up another part of the legend, that pertaining to the prevalence of marshes and springs, we are on less subjective ground.

From various sources, including army medical records, we know that malaria was a serious problem in parts of southeastern Arizona. It was prevalent at Tucson (Report on Barracks, 1870: 462-3); around Calabazas, and on Sonoita Creek (Rothrock, 1875: 128); the San Pedro Valley seems particularly to have been afflicted. (Bourke, 1891: 8)

In 1868, for example, near Camp Grant, located at the junction of Aravaipa Creek and the San Pedro, a convalescence camp had to be established away from the marshy bottoms. Of some 2,100 hospitalizations in that year, about 1700 were for malaria. Some 215 men were located at the camp; that means each man was hospitalized an average of ten times during the year, nine of the times being for malaria. ("Report on Barracks," 1870: 465)

To point up the prevalence of the disease a little more: as late as 1879, with the coming of the railroad through southern Arizona, feelings in Tucson ran high against a rival city that Southern Pacific allegedly was going to build on the San Pedro. The Arizona Daily Star remarked:

> That imaginary city situated somewhere on the San Pedro is altogether a matter of fancy, the most convincing argument against a rival town to our city...being built there is the fact that the people would die off faster than the railroad or any other road could get them there. At the point where the railroad surely crosses the river and for miles above and below, the valley might well be called 'the valley of the shadow of death.' Malarial fevers of the most malignant type are prevalent eight months in the year. (<u>Star</u>, September 25, 1879)

The incidence of malaria corresponds with what is known about conditions along the river bottoms.

Marshes existed along a great part of the length of the San Pedro. From court records of an early trial over water rights, (Grijalba v. Dunbar, 1889), we can document the existence of one large cienega that began about where Benson is now and ran down the river as far as Tres Alamos. From the same trial, from trappers as early as Pattie in the 1820's (Pattie, 1905), from pioneer journals, from reminiscences (Ohnesorgen, 1929; Etz, 1939), from early correspondence (Tevis, 1954) and explorations, from newspaper accounts (Arizonian, June 9, 1959), we know also that beaver ponds dotted the course of the river, that beaver was trapped in considerable quantities along the stream, and that edible fish could be caught. Lieutenent Colonel Philip St. George Cooke says, for example:

> Fish are abundant in this pretty stream. Salmon trout are caught by the men in great numbers. I have seen them eighteen inches long. (Cooke, 1938: 142)

The Santa Cruz seems to have been less marshy than the San Pedro, and whether beaver existed on it as late as the nineteenth century is questionable. But there were some marshes. One existed to the south of "A" Mountain; it was a notable duck-hunting area. Another around Calabazas served as a nesting place for wild turkey. Others lay along Nogales Wash, on parts of Sonoita Creek, near Rillito Creek, on Cienega Creek, of course (Black, 1926: 3; Allison, n.d.: 12; Wheeler, n.d.: 1-3). As late as 1887, a nine-pound fish was caught out of the Santa Cruz near Tucson--or so the Arizona Daily Star of July 17 of that year says.

Along the upper reaches of San Simon Creek, San Simon cienega used to be a notable watering and camping place for travelers (Bell, 1869: II, 42; Box, 1869: 321). Its original condition apparently has not changed, in marked contrast to other marshy areas. Initially this looks like an anomaly. Actually, it supports the relationship of marsh-drying to channel trenching. A dam constructed below the cienega has checked the cutting of San Simon Creek, and has thus prevented the cienega from draining.

Two apparent anomalies do exist. One occurs just south of the International Boundary on the part of the Calderon Ranch that occupies the southern part of San Bernardino cienega. The cienega itself gives every appearance of being unchanged; yet only 100 yards away in some cases, running roughly parallel to it, San Bernardino Creek has trenched to a depth of ten or fifteen feet. No evident drainage of the marsh has occurred. (See Figures II and III)

A similar situation prevails along the San Pedro River and its tributaries in the basin south of the Huachucas. Early pioneer accounts emphasize the wetness of this area, usually in terms of how hard it was for the teams to cross. "Marshy" and "boggy" are the adjectives most frequently used (Evans, 1945: 146; Powell, 1931: 132; Bartlett, 1854: II, 324). They apply still, notwithstanding the fact that the San Pedro has channeled deeply the whole length of the basin, and its tributaries in turn have cut back short distances from the main stream. (See Figures IV and V)

Superficially related to marsh conditions in the bottom lands are conditions of springs in the uplands. A great deal remains to be done in making field checks of many of the springs for which good past descriptions are available. However, in at least three cases where present conditions have been checked, springs which once flowed regularly have either disappeared or have diminished strikingly in volume.

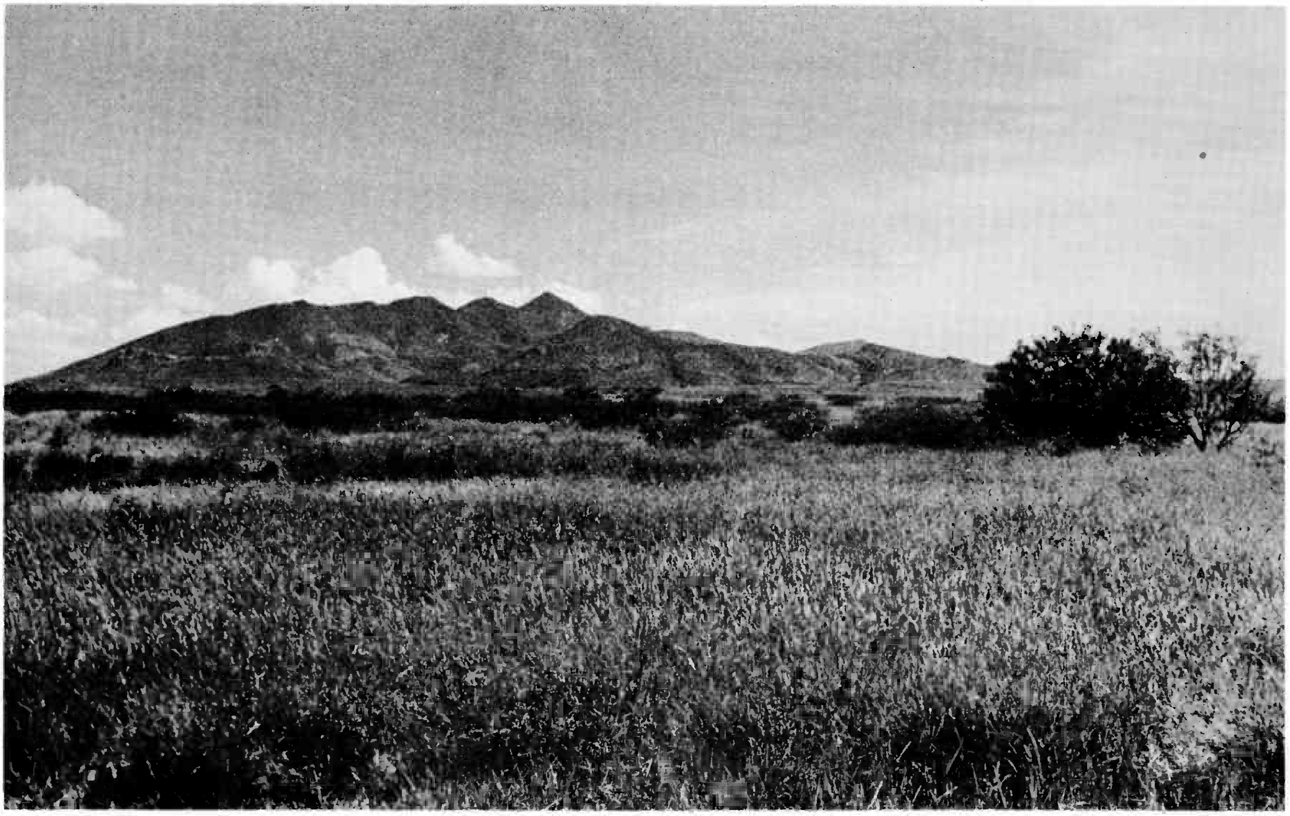

Figure I. Present-day grasslands in the upper San Pedro Valley, northern Sonora.

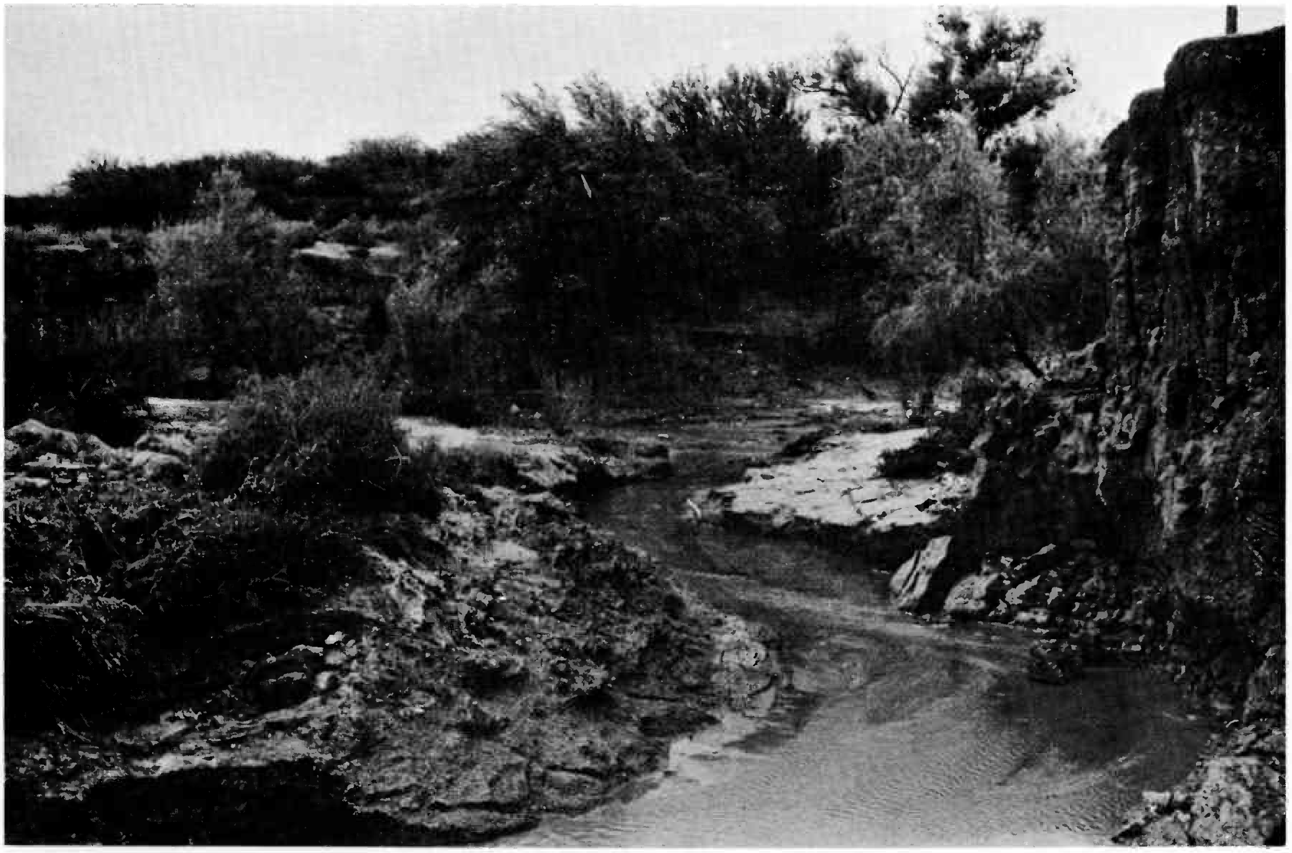

Figure II. Drainage from San Bernardino Cienega, northeastern Sonora, emptying into the channel trench of San Bernardino Creek.

Figure III. Upstream fifteen yards from the junction shown in Figure II. Nick-point beyond which the cienega maintains an undisturbed condition.

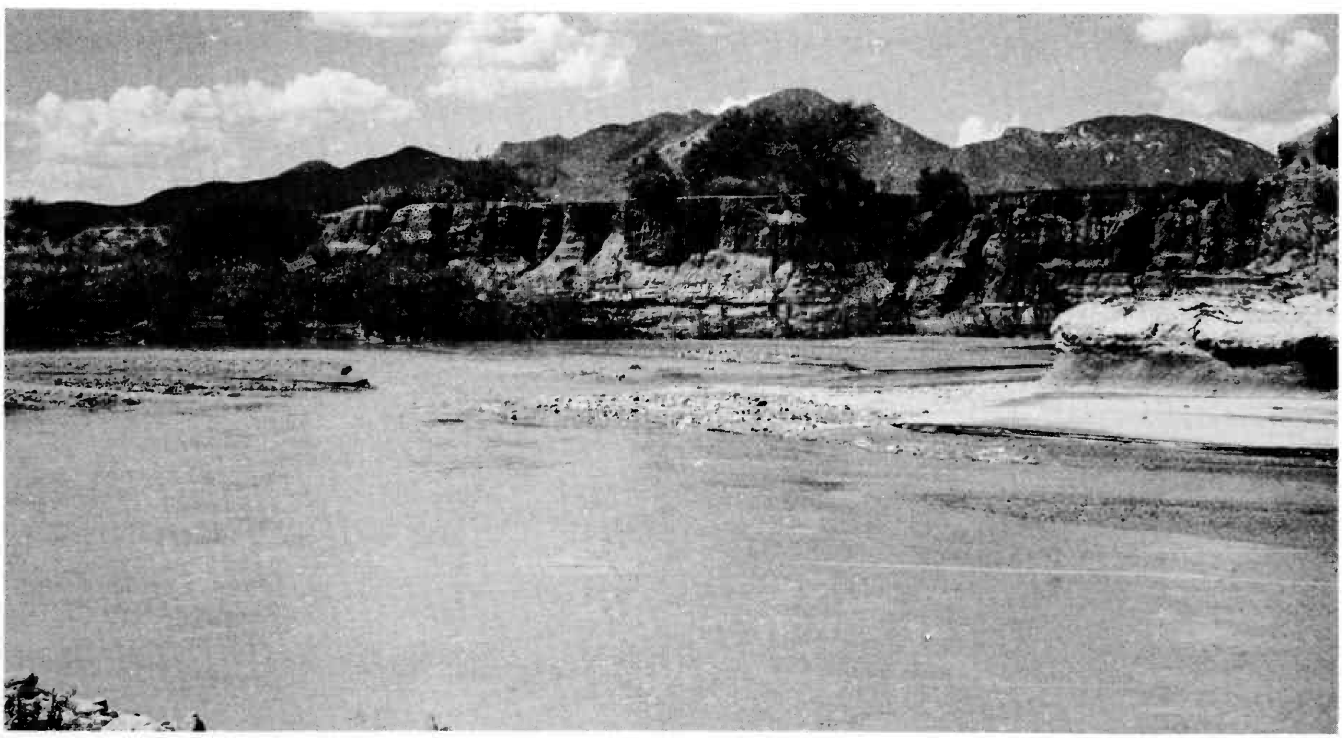

Figure IV. The channel trench of the San Pedro, northern Sonora.

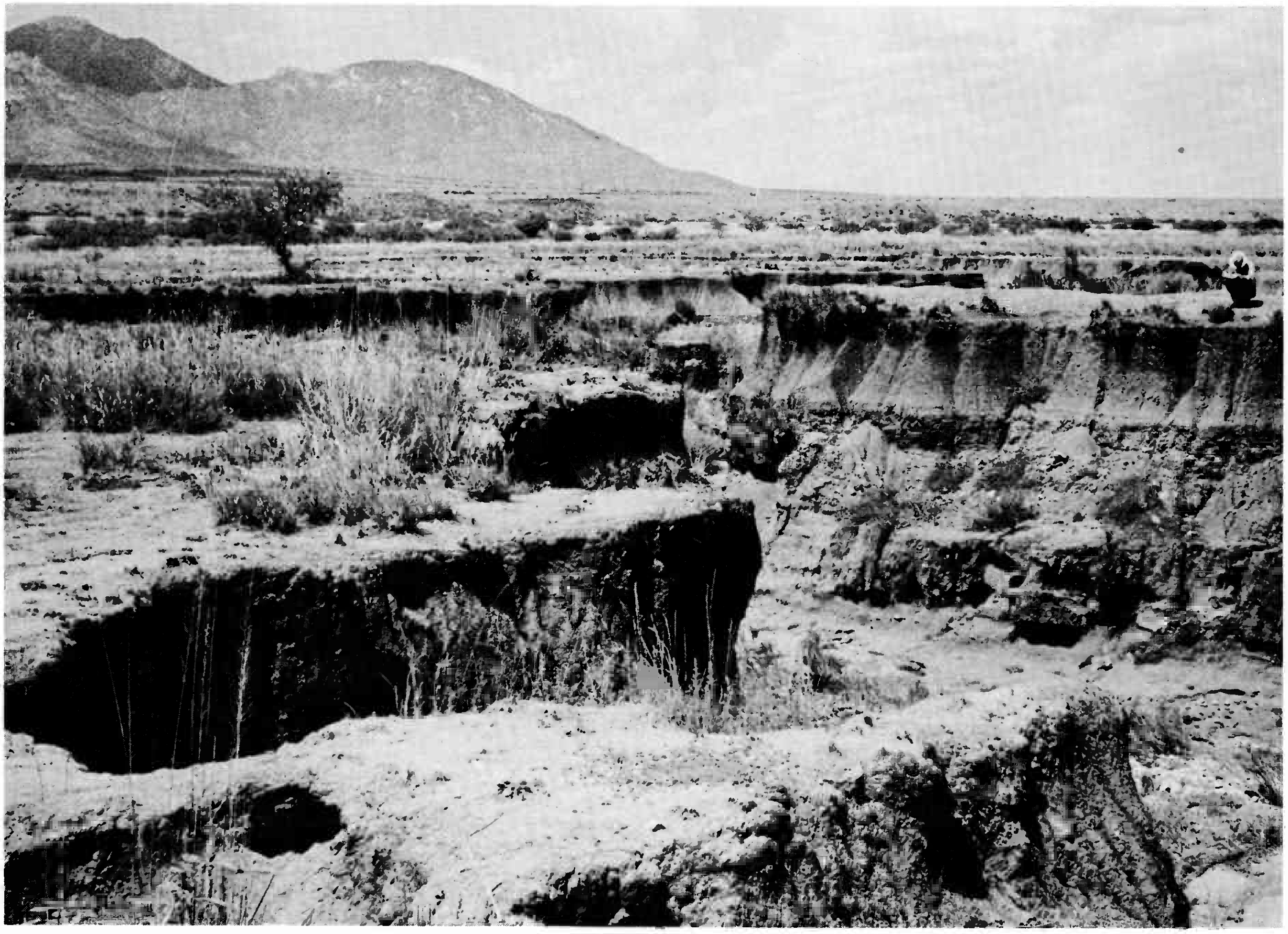

Figure V. Channeling along a tributary of the San Pedro. Photograph taken from nick-point five hundred yards east of river, looking west.

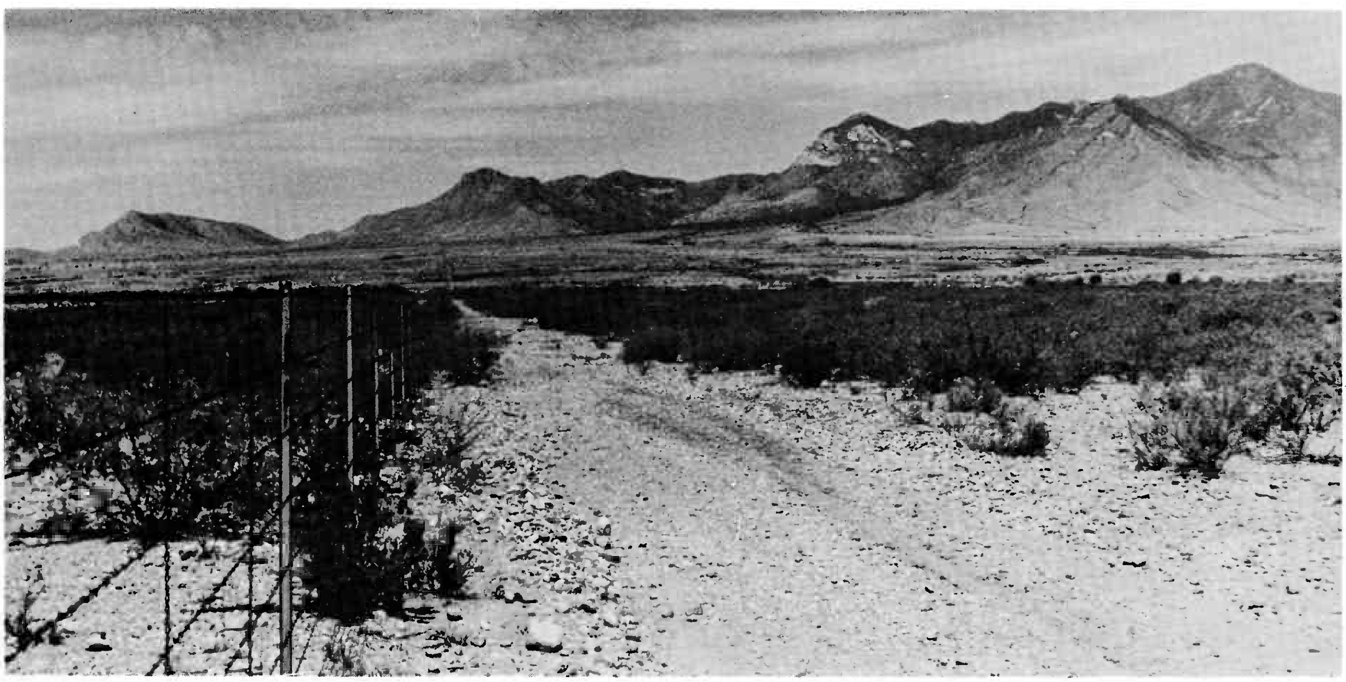

Figure VI. Bajada of the Sierra San José, looking west along International Boundary fence toward the San Pedro Valley.

Dragoon Springs, an old watering place along the Butterfield Stage Line, has apparently dried up completely (Conkling, 1947: II, 141). At Stein's Peak in the Peloncillo Mountains of New Mexico, the spring--never very reliable--used both by the Leach Wagon Road and the Butterfield Line, flows very rarely (Bell, 1869: II, 41; Bartlett, 1854: I, 366-8). At the north end of the Dos Cabezas Mountains, we have been unable to find any trace at all of Sycamore Springs, also on the Leach Road (Itinerary, n.d.: 23-9; HED 108, 1859: 54).

On the other hand, Croton Springs, southwest of Willcox, has an excellent flow still. Except for the probability that mesquite has encroached, no significant difference is apparent between conditions there in 1850 and in 1958.

With reservations then, we can postulate some changes in the general direction of drying out for the springs of southeastern Arizona, as well as for the river bottoms.

Does this imply that a climate change has occurred? Not at all; although, of course, this is one of the theories that has been repeatedly advanced.

It is equally possible to explain whatever tendency toward aridity exists in terms of arroyo-cutting, another part of the legend. If streams have cut deep channels where none existed before; if drainage courses near springs have similarly cut, then it is possible to account for changes in stream and spring conditions by assuming that the water tables in the areas have been lowered to the new level of the freshly cut trench. And if the water table has been lowered, that by definition implies a drying out of marshes and springs.

Has there, in fact, been arroyo-cutting or channel-trenching in the last 100 years? Here the evidence is overwhelming: yes.

Stream Channeling

The Santa Cruz around Tucson had no well-defined channel prior to 1890. A description by the "forty-niner" Powell again is typical of many:

> The road from San Xavier to Camp, 1 Mile short of Tucson, was very level, running through mesquite, etc. We encamped in a grassy bottom, much covered with saline efflorescence. The river has divided to a mere brook, the grassy banks of which are not more than 2 yards apart (Powell, 1931: 145).

The flow in the Santa Cruz near where Mission Road now crosses used to be diverted into acequias for irrigating the farm lands west of town. The present channel-trench, with steep banks and a sandy bottom, cuts across what used to be the farms of Dolores Gallo, Pasqual Ochoa, Jose Herreras, Deloris Rameriz, Solano Leon and Philipe Romero (Fergusson, 1862).

During floods the river formerly spread out in a shallow sheet across the fields and lowlands. While damage occasionally resulted, as in 1872, it was not usually extensive (*Citizen*, July 13, 1872, September 7, 1872).

The transition from past to present conditions began evidently about 1885. The summer of that year was unusually dry; rainfall records show that precipitation was only about one third of normal for the season (Climatic Summary: pp. 26-20). In spite of the deficient rainfall, rather severe floods occurred in August (*Star*, August 6, 1885, *et seq.*).

1886 was dry again--about half of normal rainfall. Floods washed out the railroad in several places, and inundated Calabazas and the Tucson bottoms (Star, August 3, 1886, et seq.).

1887 had the second wettest summer in history; floods were proportionately great (Star, July 15, 1887, et seq.).

1889 was abnormally wet again; again high floods. On August 5, 1890, the Santa Cruz began cutting its present channel--along a ditch dug by Sam Hughes, so far as we can tell, to irrigate some holdings of his lying north of Speedway across the present channel.

Let the Arizona Daily Star tell the story:

> August 5, 1890. The flood yesterday washed a deep cut across the hospital road, so that the road now is not only impassable but extremely dangerous for teams or travel as the embankment of the cut is perpendicular and the water below deep, and pedestrians might easily endanger their lives.
>
> August 6. Another flood...It is thought that the washout in the Santa Cruz, opposite this city, will reach Stevens Avenue this morning.
>
> August 7. The channel or cut being made by the overflow of the Santa Cruz River, is now one mile and a half long, by from one to two hundred yards wide--in other words--it extends from the smelter to about two hundred yards this side of Judge Satterwhite's place.
>
> August 8. More than fifty acres of land which has formerly been under cultivation in the Santa Cruz bottom, has been rendered worthless by being washed out so as to form an arroyo.
>
> August 9. The single channel which was being washed out through the fields of the Santa Cruz by the floods, resulted in considerable damage but this danger has been greatly increased from the fact that the wash or channel has forked at the head, and there are now several channels being cut by the flood, all of which run into the main channel. If the flood keeps up a few days longer there will be hundreds of acres of land lost to agriculture. As these new channels or washes are spreading out over the valley, they will cut through and greatly damage the irrigating canals.
>
> August 13. The raging Santa Cruz continues to wash out a channel and the head of it is now opposite town. It may reach Silver Lake before the rainy season is over.
>
> August 29. The head of the new channel of the Santa Cruz River is now opposite Judge Osborne's place, on the road to Silver Lake.

Inevitably, something had to be done about it. It was

> Several suits for large sums are threatened, on account of dangers resulting from the recent floods...(Star, August 14, 1890).

Channel-trenching along the San Pedro River is equally striking (see Figures IV and V), but presents a less tidy pattern. One modern writer--the late Kirk Bryan--states that:

> The trench on the San Pedro River was cut progressively headward between the years 1883, when the arroyo first formed at the mouth of the river, and 1892, when the head waterfall cut through the boundaries of the Boquillas Grant 125 miles upstream (Bryan, 1925: 342).

Our study indicates that the channeling process may not have been so clean-cut. The earliest for which we can document cutting near the mouth is 1890. During the same month that the Santa Cruz was carving its channel near Tucson, a new cut in the San Pedro was raising havoc with irrigation ditches in the vicinity of Dudleyville, a small farming town near the junction of the San Pedro and the Gila, and was threatening the Dudleyville general store (Star, August 15, 31, 1890). Dudleyville no longer exists. Much of it was subsequently washed away; the difficulty encountered in raising irrigation water out of the new channel presumably was a factor in the final abandonment.

Some evidence, not conclusive by any means, points to cutting upstream at Mammoth four years earlier, in 1886. Another piece of evidence indicates that the bed of the river was lowered twelve feet on the Tres Alamos region between 1885 and 1889 (Grijalba v. Dunbar, 1889).

The floods of 1885, 1886, 1887 and 1889, mentioned earlier as providing a sort of transition at Tucson between past and present conditions, did not, so far as we can tell, initiate cutting there. Apparently they did along the San Pedro. Why the different effect?

One factor was possibly the greater volume in the San Pedro. Other factors may have been different soil conditions, a different stream gradient, extensive lumbering in the Huachuca Mountains as a result of the demand for mine timbers at Tombstone and a greater concentration of cattle at an earlier date. There are a dozen possible factors. None of them can be pinpointed for the simple reason that they have not yet been sufficiently investigated.

As if the question of cutting along the San Pedro were not sufficiently complex, half a dozen sources confirm the fact that a channel trench existed at places along the river several decades before 1880. To cite a few:

John Russell Bartlett, writing about the river near the mouth of Dragoon Wash in 1851, says:

> The valley of the San Pedro River near our camp was anything but luxuriant. It consists of a loam, which if irrigated might be productive, but as the banks are not less than eight or ten feet high, irrigation is impracticable, except by digging a canal a very long distance. The grass of the vicinity is miserably thin and poor, growing merely in tufts beneath the mezquit (sic) bushes which constitute the only shrubbery...In order to cross the river, it was necessary to level the banks on both sides, and let the wagon down by hand (Bartlett, 1854: I, 379-81).

Lieutenant Colonel Graham, a member of the same expedition, confirms this:

> The San Pedro was pretty high when we arrived here. The San Pedro runs here through a soft, alluvial soil, and its rapid current has worn a deep bed for it, leaving steep banks on either side (SED 121, 1852: 35).

N. H. Hutton, Engineer for the Leach Wagon Road, says that in 1857 a few miles downstream from Tres Alamos Wash:

> The San Pedro...has a width of about twelve (12) feet, and a depth of twelve (12) inches, flowing between clay banks ten or twelve feet deep, but below it widens out, and from beaver dams and other obstructions overflows a large extent of bottom land, forming marshes, densely timbered with cottonwood and ash... (HED 108, 1859: 87).

There are enough other accounts to warrant the statement that the San Pedro has no continuous channel trench prior to 1890, but in the early part of that year, and as far back as the 1850's, did have a discontinuous one.

Does this imply, then, that the current cycle of arroyo-cutting began earlier than is generally supposed--even before the large-scale introduction of American cattle; that the San Pedro Valley reacted earlier than the other streams to whatever these changing conditions may have been, because of physical, or ecological, or climatic peculiarities of its own? Possibly, but a number of other explanations do not involve such sweeping assumptions and may be equally correct.

The two points to be made here about this early cutting have nothing to do with ultimate cause. The first--once again--is the wide variety of conditions that existed in the "good old days," and the dangers, therefore, of making sweeping generalizations of the nature that, prior to 1880 no streams had channel trenches.

The second--once again--is the biological insecurity of this area, even in the 1850's. We are dealing with an arid zone; even in the good old days it was an arid zone; present conditions were implicit in what seem superficially to have been very different conditions. The line between past and present is thin; in this case, as early as 1850, the line had evidently been crossed.

San Simon Creek, next most easterly of the principal drainages, seems to have been more intermittent than the Santa Cruz and the San Pedro. Like the others, however, it flowed through an unchanneled, almost imperceptible bed, in contrast to the present deep trench (Bell, 1869: 51). There is no evidence of a trenching process prior to 1880.

The story told by several modern commentators is that channeling began along a ditch dug near the mouth of the creek by settlers who wanted to divert its flood flow away from their fields. The date for this ditch is variously given as anywhere from 1883 to 1900 (Calvin, 1935: 11, 39; Olmstead, 1919: 79; Bryan, 1925: 342).

For us, the San Simon has been a peripheral area; research on it so far has been largely incidental. It is impossible to say yet how much there is to the ditch story, or what a likely date for channeling might be.

The same thing applies to Whitewater Draw, in the southern Sulphur Springs Valley.

Shrub Invasion

In the part of the legend that deals with brush invasion, is found a fairly controversial aspect of change. Ecologists and range management experts have studied this problem for a number of years. Some especially able work on it has been done at The University of Arizona, in recent years most notably perhaps, by Doctor Robert R. Humphrey.

The change legend states, more or less, that mesquite was virtually unknown in Arizona in the "good old days"; that it has invaded since. This is simply not so.

The view of most of the biologists who have worked with the problem seems to be that mesquite was widespread even before whatever change that occurred did occur, but in general was confined to river bottoms and drainage channels. The subsequent invasion has been characterized by a further spread to open country in the uplands and mesa lands. Most of the work of the biologists, of course, has been concerned with the reasons for and consequences of this invasion.

Historically--and here is one of those subjects about which we have so much information that it has not yet been possible to piece all of it together--we can say that a mesquite invasion certainly has occurred in some areas. The Santa Rita Experimental Range is one. It would be difficult to deny the evidence of those famous before and after pictures.

A second invasion point is the *bajada* on the northwest side of the Sierra San Jose in northern Sonora and southern Arizona--the slope stretching away from the mountains toward Greenbush Draw on the north and toward the San Pedro on the west.

The *bajada* is now covered with scrub mesquite and acacia. (See Figure VI.) Powell reports, however, that in 1849 his train had to go without eating because there was no wood in the area with which to build a fire. It is not likely today that anyone would go hungry for that reason.

A third point is around Croton Springs, southwest of Willcox. Mesquite now approaches within perhaps one hundred yards of the principal springs. Hutton's report on the Leach Wagon Road states that in 1857 wood was "distant" (HED 108, 1859: 99). An itinerary along the same route says that "Firewood must be dug from the ground, the roots of the Mesquite being the sole dependence." (Itinerary, n.d.: 28-9.)

A comparison of present conditions to those shown in a photograph taken around 1894 indicates that an invasion has also occurred around Pearce in the Sulphur Springs Valley. Similar evidence points to a thickening of mesquite south of Charleston along the San Pedro River. At Charleston, itself, dense thickets of white thorn now cover what formerly were grassy hills. (See Figures VIIA and VIIB.)

But there is another side to the story too. It seems pretty clear that mesquite prior to 1880 was not confined to river valleys and drainage courses.

Colonel Cooke with the Mormon Battalion, for example, complains about mesquite on the smooth plain around Naco, and again on the slope west of Agua Prieta Creek (Cooke, 1938: 135-6).

William A. Bell, with a railroad surveying party in 1876, notes similar mesquite conditions on the plains between San Simon Creek and Railroad Pass (Bell, 1869: II, 56). So does a mail rider, S. W. Grant (Grant, 1924: 11).

John Spring makes general statements about the prevalence of mesquite on mesa lands (Spring, 1902); so does Elliott's History (History, 1884: 306).

One of our current projects is the compiling of a map of southeastern Arizona that will show where mesquite was known to exist prior to 1880. When there is such a map, and when it can be examined by the appropriate specialists to see what the relation may be to present mesquite population, to altitude, to rainfall, and to soil, perhaps more of a pattern will emerge than seems evident now.

This much can be said safely--that mesquite distribution prior to 1880 was probably more general than has been usually supposed.

Theories of Change

So much, then, for a survey of a few of the aspects of Arizona's legend of change. In some cases the legend takes liberties with what we think must actually have happened. All in all, however, its general outline seems to be correct. Marked changes have indeed occurred in the Arizona landscape--not so many, perhaps, as alleged; still, however, enough to be impressive.

Many theories have been advanced to account for what has happened. In general, one can classify these theories under three headings. (1) They may explain the changes edaphically--that is, in terms of the biological balance involving the soil and the things that grow in it. The theory of paramount importance here attributes changes to the introduction of cattle, (2) or the changes may be attributed to geological processes. Diastrophism, here a tilting of the earth's surface so as to cause an increase in the gradient of local streams, has been advanced as a reason, (3) or climate changes are alleged to have occurred. There have been a variety of these suggested. Desiccation was the earliest: we simply get less rainfall than we used to. Various minor shifts in rainfall pattern, rather than quantity, have been postulated: a change in the number of small rains is one; a change in the time of the onset of the summer rainy season is a second. A change in the intensity of storms, so that we get more big storms with high run-off and fewer small storms with moderate run-off, is a third.

In general, geological and climatic reasons are presented by individuals who are dissatisfied with the cattle theory on one of two grounds:

First, an increasingly extensive body of evidence points to the possibility that not one, but several cycles of erosion have visited the Southwest. Kirk Bryan postulates no fewer than four, the one presently under discussion being the most recent. The next latest, Bryan says, occurred between 1200 and 1400, possibly on the heels of the great drought of the thirteenth century.

Figure VII-A.   Charleston, Arizona, about 1883, looking south toward Bronco Hill.

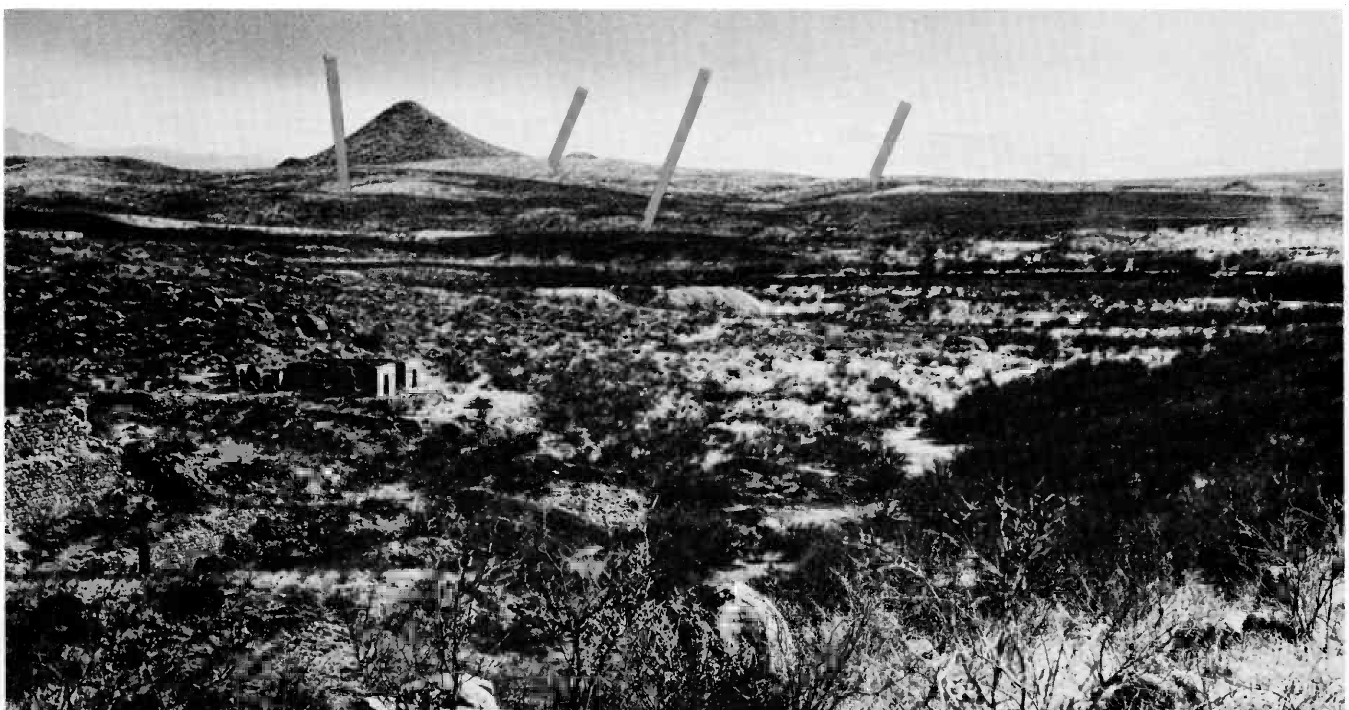

Figure VII-B.   Charleston, 1959, from the same spot. Arrows indicate hills on which white thorn acacia has replaced grassland.

If channel-trenching and arroyo-cutting have happened before, so the argument goes, and in pre-Columbian times at that, then pretty clearly, factors other than cattle must be involved.

Both Bryan, and more recently Leopold (1951) recognize the possible effects of overgrazing. They reconcile it with climatic factors by means of the so-called "trigger-pull" theory, which states essentially that the long-term trends producing erosion cycles had already begun in the Southwest by 1880, that conditions were approaching the critical point where erosion might have been initiated anyway, and that the coming of cattle merely served as the trigger-pull that set off an already loaded weapon.

The second ground on which there is unwillingness to accept the cattle theory is somewhat more emotional than logical, but it exists, nonetheless. A hydrologist who had recently been out in the field looking at the results of erosion put it this way: "There <u>has</u> to be more to it than an old cow walking around."

But the old cows have some powerful evidence behind them.

Even a superficial examination of the figures available on cattle population shows a close correlation to the facts of cutting. Parenthetically, these figures are from assessment rolls; while they may reflect trends, they are probably considerably under the actual numbers.

In 1883, before the trenching process began, there were only 68,000 cattle in the three principal Arizona counties comprising this area: Pima, Cochise, and Graham (Wagoner, 1952). In 1886, by which time apparently unwarranted floods had begun in the Santa Cruz and San Pedro, and possible channeling in the middle reaches of the San Pedro, the number increased by about two and one-half times--to 156,000.

By 1890, when channeling began on the Santa Cruz and at the mouth of the San Pedro, the number increased by another 100,000--to 253,000.

Mean precipitation is not necessarily a safe way of judging the effect of rainfall on vegetation. Too many other factors enter in: when the rain fell; how--in big storms or small, in slow, soaking rains or in hard, fast ones.

But these reservations notwithstanding, when one looks at the facts of cattle population in the 80's, when one then looks at the incidence of flooding and cutting; when one sees that in 1882, 7.08 mean inches of summer rainfall and 50,000 cattle produced no unusual flood conditions, whereas in 1886, 4.63 inches and 156,000 cattle did--when one looks at the damage 7.92 inches and 253,000 cattle did in 1890--there is certainly a very tempting conclusion, and it involves the coming of cattle, the effect of overgrazing on vegetation, and the effect that the depletion of vegetation, in turn, had on run-off and erosion.

Pursuing this point any further would be a little like flogging a dead horse. There probably is no one who entertains serious doubts that the coming of cattle did play a major part in initiating the great change.

Where most of the controversy seems to lie is in what subsidiary role, if any, climate played. We have done some work on old weather records, but not enough to isolate any one cyclic climatic factor and say, "yes, this probably contributed to the change." Enough work has been done, however, to make it clear that it is much too early categorically to reject the idea. A distinct possibility exists that secular trends in climate were operating; operating in such a way as to load the gun in preparation for the pulling of the trigger by overgrazing.

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BURIED VALLEYS AND THE CLIMATIC FACTOR

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How was the Southwestern landscape formed? What roles did climate and climatic change play in the construction of arid land topography? Do landforms around Tucson typify those found in desert areas of other continents, or are they unique to the Southwest? The purpose of this paper is to seek answers to these questions through a study of the factors involved: the construction of the landscape, the role of climate, and the character and occurrence of the landforms.

Scientific consideration of these factors dates back almost 100 years. While of prime importance to the geologist, study of the evolution of desert landscape falls also within the domain of the biologist, climatologist, archaeologist, and geographer. Stability of the surface of the desert is not entirely an academic matter and may be of some concern to the home owner living on a bajada.

In the Basin and Range Country of the Southwest we encounter a series of isolated mountains rising from gently sloping valleys. These, such as the Santa Ritas, Santa Catalinas, and the Dragoons, form the desert skyline. More important in terms of area are the gentle slopes extending several miles down from the mountains to an arroyo or a stream and its floodplain in the center of the valley.

The slopes, or parts of them, are endowed with a formidable terminology. In addition to pediment and bajada, Tator (1953) lists the following in order of precedence: hills of planation, mesa, conoplain, rock-floored piedmont slope, rock-floored desert plain, rock-cut plain, suballuvial bench, subaerial bench, mountain pediment, concealed pediment, piedmont pediment, rock fan, rock plane, partial pediment, pediplane, and peripediment. This is an incomplete list, but it should indicate the terminological labyrinth. What is being described?

In 1897 after one of the first studies of the Papago-Seri country, or what the biologists call the Sonoran Desert, McGee wrote as follows (p. 91): "During the first expedition of the Bureau of American Ethnology it was noted with surprise that the horseshoes beat on planed granite or schist or other hard rocks in traversing plains three to five miles from mountains rising sharply from the same plains without intervening foothills..." and then in a charming example of scientific reserve, "...this generalization seemed so far inconsistent with facts in other districts that it was stated only with caution even in conversation."

McGee evidently found it difficult to believe that the valley-plain area is not entirely sedimentary, but that it is rimmed by planed rock similar or identical with that constituting the mountains.

McGee is generally acknowledged as the first author to apply the term pediment to the bedrock plain around a mountain range. According to McGee, pediments occupy two-fifths of the Sonoran Desert area, alluvial slopes occupy another two fifths, and desert mountains the rest.

For present purposes I will follow McGee in applying the term pediment to the planed-rock surface, with or without a shallow alluvial cover, which one finds near the mountains. The surface above deep fill near the center of the valley is called the peripediment (Howard, 1941). The entire footslope, from mountain escarpment to the middle of the valley, including both pediment and peripediment, was originally designated the bajada (Hill, 1896, p. 297).

Unfortunately in current geological usage this term is often restricted to depositional slopes (for example Gilluly, Waters, and Woodford 1955, p. 269, 353). As depositional and erosive surfaces can not always be distinguished in the field, and as both may occur in the same valley, it seems desirable to retain Hill's proposal, that extensive arid land slopes be known as bajadas. When the slope-forming process is known the appropriate genetic term, either pediment or alluvial fan, can be applied.

Most biologists have found Hill's definition useful. The bajada reveals a characteristic vegetation gradient distinct from the plant communities of the mountain backslope or valley flood plain (see Benson and Darrow, 1954, p. 4). In distinguishing upper from lower bajada vegetation the ecologist may have encountered a floristic expression of the difference between rock pediment and peripediment (Figure 1). As an example around Tucson the saguaro cactus grows most luxuriantly on upper bajadas where bedrock lies at or near the surface. Saguaros are less numerous or absent over deep fill of the lower bajada which is dominated instead by creosotebush (Larrea tridentata). Differences in bajada vegetation are attributed to differences in soil type (Yang and Lowe, 1956).

Turning from the surface aspect we may consider the alluvial-colluvial and lacustrine material between the mountains. This valley fill constitutes clay, silt, sand, assorted gravel and boulders, the whole cemented to varying degrees by caliche. Superficially there is a certain resemblance to glacial drift. Not all fill is coarse and in certain basins much of it may be a lacustrine or fine alluvial clay. The fill extends downward to an unknown depth; estimates summarized by Heindl (1952) range from 1000 to 8000 feet. Within four miles of the Chiricahua Mountains in the San Simon Valley the Arizona Oil and Gas Corporation drilled a hole 7,568 feet deep, mainly through rhyolite gravel, without reaching bedrock (Sabins, 1957). A gravity profile across the Fairview Valley in central Nevada revealed a section of Cenozoic sedimentary (and volcanic?) fill 5,000 feet in depth (Thompson, 1959). Apparently the desert mountains rise like islands of bedrock from a sea of detritus, Pleistocene and older in age.

There seem to be two major views on the origin of valley fill. One idea, developed by Blackwelder (1931) is that it is the result of diastrophism. The rising mountain blocks and the downfaulting valleys created an inequilibrium; the valley fill of the bajada equalized it.

The other view, advanced in 1914 by Huntington, holds that the valley fill is the result of climatic change and that it represents the effect of a desert climate. Huntington claimed that in all parts of the world deep valley fill deposits preserve a full record of the climatic change to which they have been subjected"...The bajadas, playas, and half-buried mountains of the southwestern part of the United States reproduce exactly the topographic forms

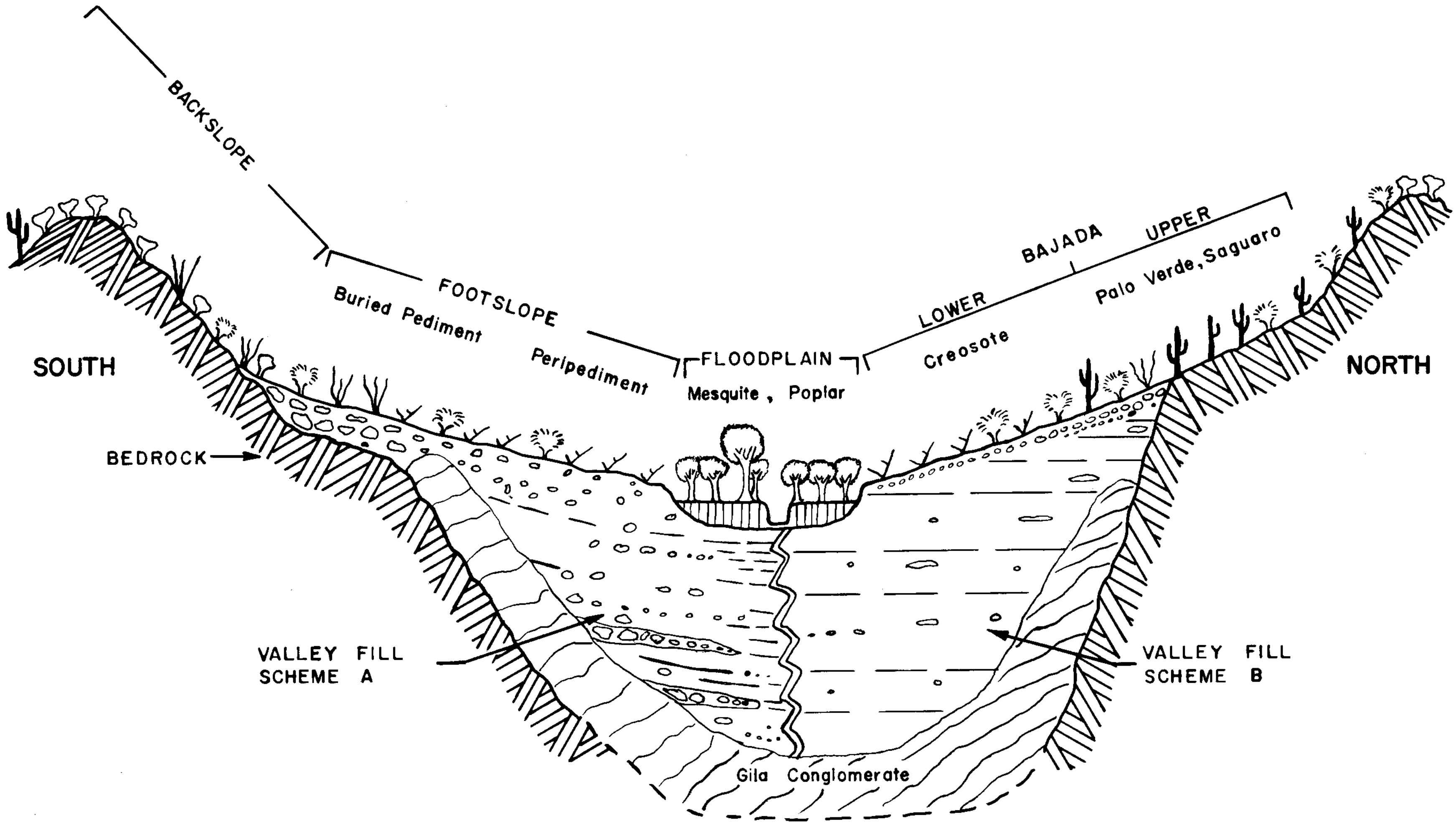

Figure 1. Diagrammatic profile of a valley in the Basin-Range province of the Sonoran Desert. Scheme A illustrates the conventional concept of valley fill with coarse material adjacent to the mountains grading into fine alluvium and lake sediments near the middle of the valley. Scheme B illustrates deep deposits of fine sediment contacting bedrock as seen in dissected basins (Lance 1959). A thin mantle of boulders is the main source of coarse fill.

The vegetation pattern across the bajada is influenced by both slope exposure, soil texture, and availability of ground water.

of other deserts in distant regions, such as Syria, Persia, and western China." "...evidently any comprehensive study of the climatic conditions of the geologic past demands a careful examination of complete sections from the bajada slopes not only of America, but of all parts of the world," (p. 19).

Concerning the effect of climate Huntington reasoned as follows: if the vegetation is rich, the climate is moist, and run-off of streams is clear and steady, the streams proceed toward the ocean and gradually erode their watershed, as one observes in more humid regions. If the cover of vegetation is poor, as in a dry climate, the streams are overloaded with sediments, run infrequently, don't reach the ocean, dam themselves, build fans, and gradually fill their valleys with sediment.

Huntington thus infers that the valley fill, to a depth of thousands of feet, was deposited during a dry climate when vegetation was poor and the soil surface was not stabilized by plant roots. Dissection of the bajada slopes near the center of the valley occurred during more moist times, presumably a glacial-pluvial period when there were permanent streams (thus he would explain the terraces near Tucson at the edge of the Catalina Foothills on River Road and along the bajada of the Tucson Mountains above Silverbell Road).

But <u>are</u> bajadas and deep valley fill typical of all arid lands? Much has been written about Africa. Mabbutt (1955) discussed pediment forms in Little Namaqualand, South Africa, a region with between two and five inches of rainfall. He illustrated rock pediments which invariably show a thin detrital horizon above a little-weathered rock surface. There is no mention of deep valley fill.

Dresch (1952) found no trace of a former sedimentary cover on the pediplaned surface of the granites forming the plateau of northern Cameroun, French Equatorial Africa.

In the central Libyan Desert, Peel (1941) reported driving a compass course for several hours at a constant speed of 60-70 km. per hour in a Ford V-8 car across solid rock covered with sand a few feet thick. Would anyone dare a similar experiment on one of our rock-strewn, dissected, Tucson bajadas? On this and other evidence Peel concluded that the Libyan Desert of North Africa had a geomorphological history different from that of arid North America.

King (1953) and Dixey (1955) have written extensively about the erosion surfaces of Africa. They recognize three types, of Mesozoic, Early Tertiary, and Late Tertiary age. They do not comment on subsurface deposition. In an article with the stately title, "Cannons of Landscape Evolution," King generalizes that the pediment landscape with planed bedrock and no valley fill is <u>the</u> typical landform of semiarid climates. A landscape with valley fill he considers typical of completely arid climates.

In northwest Queensland, Australia, Twidale (1956) recognized three major surfaces of subaerial erosion, and he claimed a broad correlation of these with African and Indian surfaces of Mesozoic and Cenozoic age. Thin extensive sheets of silts may contain vertebrate fossils, but they are too shallow to be considered valley fill.

According to these authors it would seem that arid parts of both Africa and Australia lack deep valley fill. Apparently Africa is an especially stable segment of the earth's crust and the lack of fill can be related to the absence of deep troughs. Huntington's hypothesis can not be tested in this region. Is it valid in those parts of the world where deep fill has been found?

In addition to Syria and Persia, mentioned by Huntington, there is rather deep alluvial fill in parts of Spain, Portugal and Greece. Such deposits are termed rañas in the Iberian Peninsula.

Hernandez-Pacheco (1950) described Upper Pliocene alluvium representing a phase of intense deposition that occurred during a climate of accentuated semidesert character with intense, accidental rains. Ribeiro and Feio (1950) claimed that the Mediterranean climate with its long dry season is sufficient to maintain or form rañas. Mistardis (1950a, 1950b, 1950c) noted similar deposits in Greece and classified pediment surfaces of the Mediterranean region in detail. There is some disagreement about age of the rañas and related alluvial features, whether Late Pliocene or Early Pleistocene, but the above authors would concur with Huntington that aggrading conditions required drought, while the dissection of detrital slopes occurred in more moist periods.

Another region that may be similar to the Southwest is the Tarim Basin of Turkestan. Su (1950) reported detrital fans, entrenched and their floors exposed. Unlike Huntington he felt that the pediments originated by glaciofluvial floods.

The Teheran Plain of Iran is underlain by thousands of feet of alluvial deposits (Rieven, 1955). Of these only the upper few hundred feet (Kahrizak formation) are considered Pleistocene. This heterogeneous material is thought to have been deposited in a relatively cool period immediately following orogenic activity.

In brief, Huntington's hypothesis can be criticized on two grounds: (1) deep valley fill is not universal to arid areas and (2) the climatic significance of valley fill is in dispute. More recently the field studies of Lance, Harshbarger, and the Arid Lands group in the Safford area have revealed that valley fill may not be structured as is generally assumed. In deeply dissected basins where one can study subsurface conditions it appears that much of the sediment is fine-grained; according to Lance (1959) it does not necessarily grade into gravel and boulders next to the mountains, but may be in direct contact with bedrock (see Valley Fill Scheme B on Figure 1).

To bring the subject back to home, what about the city of Tucson, built on an alluvial surface of unknown depth? A mobile surface such as the arctic tundra and subarctic taiga, with seasonal thaw and soil flow, challenges the construction engineer. Similar problems do not arise in the Southwest and the present surface seems relatively stable. Nevertheless, the residual boulders of eighteen inch diameter on top of the bajadas close to Tucson remind us of the past. If Huntington is correct, we should see such stones roll down these same bajadas.

That Huntington's valuable climatic hypothesis proved ephemeral is not my main point. In an interdisciplinary program it seems appropriate to note his interest in the relationship between paleoecology, climatology, and geomorphology. At present it would appear that the phenomenon of valley fill defies a simple climatic explanation.

Conclusions

1. Valley fill in the Southwest is remarkably deep (thousands of feet) and poorly known.

2. In its formation in southern Arizona, climate appears secondary to tectonic and hydrologic history.

3. Valley fill is not universal to arid areas; it appears best developed in southwestern United States and adjacent Mexico, in Iran, and in parts of the Mediterranean region.

4. In the evolution of desert landforms an individualistic concept seems to apply, as stressed by Wirthe (1958): "Each desert area is in many respects an individuality of its own with its own landforms and its own laws for their formation."

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EVOLUTION OF THE VEGETATION OF THE SOUTHWESTERN DESERT REGION

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Introduction

The bearing that evolution might have upon vegetation and the evolution of vegetation, as such, has been given relatively little attention. To study vegetation as a static phenomenon--or at best as something that will change when burned, grazed, or bulldozed but is otherwise of more or less permanent occurrence--is not fully rewarding. Admittedly, such an approach has an important place in land management since these present-day conditions need to be understood. But to ignore the evolution of vegetation is pedagogically and intellectually unrewarding, for evolution remains the basic precept underlying the field of biology. To be sure, the often-belabored dogmas of the climatic climax and succession have brought us tantalizingly close to a consideration of the fundamental topic of the evolution of vegetation. But contributions of such workers as Chaney, Berry, Axelrod, and Clements have been largely unheeded by authors of ecology textbooks, who are content to describe existing communities without any consideration of their evolution. The information is available, for those who will use it, to construct an incomplete but useful evolutionary saga which links together the many presently existing plant assemblages.

Space does not allow a full description of the evolution of the vegetation of the entire North American continent and only brief reference will be made to this complete picture as a means for showing the relationship of the desert to the remainder of this continent's plant cover. The desert is emphasized because it has a biological uniqueness that makes studies of its relation to other regions especially fruitful.

To set the stage for the discussion of the desert, reference will have to be made to times well before deserts appeared and to places far removed from regions that have ever supported deserts as we know them. The evolution of North American vegetation will be briefly summarized showing how North American deserts have segregated from previous, more generalized vegetation. This topic will be coupled with a discussion of evolution _in_ the desert, since this can hardly be divorced from a consideration of evolution _of_ the desert.

Pre-Cenozoic Angiosperm Evolution

Axelrod (1952) has recently presented a broad scheme describing the possible evolution of the Angiosperms. It is pertinent to consider some of his points, for it is the Angiosperms that dominate the vegetation of the world today; if we understand something of their time and place of origin, we shall have some basis for understanding the evolution of the vegetation of which they are a dominant part.

For many years the early evolution of the Angiosperms was considered an enigma. Darwin was led to write that the evolution of the Angiosperms was "an abominable mystery." The fossil record showed that they arose with surprising abruptness and the ancestors of the group were unknown. Axelrod's scheme solves the problem of their abrupt appearance in the fossil record and may ease somewhat the search for possible ancestors, although it is recognized that these progenitors are possibly irretrievably lost.

Angiosperms appear to have assumed dominance during mid-Cretaceous time for it is in deposits of this age that their fossils first predominate. However, there are a number of Angiosperm fossils from the Jurassic, and the oldest plant fossil that can conceivably represent an Angiosperm is late Triassic in age. Thus we see that it is not the complete absence of Angiosperm fossils in pre-Cretaceous beds that has led to the notion that they suddenly gained ascendancy in the Cretaceous; it is rather the vast increase of these fossils in Cretaceous times versus earlier times that has promoted this theory. However, the notion of their near-absence in pre-Cretaceous times is probably more apparent than real.

In an interesting application of negative information to substantiate a theory, several paleobotanists have pointed out that were the Angiosperms largely committed to upland sites during pre-Cretaceous times, we should not expect to find them well-represented in the fossil record, for their remains would be less likely to find lodgement in sites of deposition or, if these upland species did actually find their way into the fossil record, this record would likely be lost following later base levelling. An important feature of the uplands is the presence of relatively large habitat differences compared to the lowlands, and, since certain prime biological requirements for evolution will be satisfied in the uplands, we might expect rapid evolution here. Among the prime biological conditions necessary for rapid evolution of a population is proper population size. Small populations are more likely to undergo rapid change than large populations. The diversity of the upland habitat would have a tendency to dissect populations into the requisite small units. This small size would have the effect of hastening the diversification of existing types.

During Triassic times (200 million years ago), the lowlands were occupied by Gymnosperms but the uplands, also dominated by Gymnosperms, were being invaded by the newly appearing Angiosperms. The climate during this time was more extreme than in preceding or succeeding times. The great environmental diversity tended to promote new adaptive types, among which were the early Angiosperms. The tropical region was relatively narrowly defined during this interval, but there is some evidence to indicate that it was in the restricted tropical region, or its border areas, that the greatest number of early Angiosperms occurred.

During late Triassic-Jurassic times there was a world-wide moderation of climate to which the plants responded by migrating to higher latitudes, for tropical conditions had now expanded. The Angiosperms were still largely upland species at this time.

During the early Cretaceous, the Angiosperms are believed to have gradually displaced the Gymnosperm floras from the lowlands, and by the mid-Cretaceous they were in full control of their new found home. These lowland plants were broadly grouped into tropical floras, and in addition into temperate floras, for there had been considerable expansion of Angiosperms into cooler regions. This grouping appears to have persisted into the Tertiary and given rise ultimately to the Arcto-Tertiary, Antarcto-Tertiary, and Paleotropical- and Neotropical-Tertiary Floras. It is the Arcto-Tertiary and Neotropical-Tertiary Floras which occupied the North American continent at the beginning of the Tertiary.

Cenozoic Vegetation History

The following presentation of the history of North American desert vegetation through Cenozoic times places emphasis upon changes in composition of plant communities and shifts in the ranges of these communities. For this reason it should be particularly noted that most Angiosperm families, as well as many of the genera now recognized, seem to have been represented by the beginning of the Cenozoic Era. That these parallels are recognized is of the utmost importance, for the paleobotanical method relies upon the assumption that plants of the past which bear close morphologic similarity to present-day plants were similar to them also in their physiologies. Thus plants of the past are believed to have occupied regions with climatic regimes similar to those occupied by their present-day correlatives. This does not deny that evolution was still progressing, for, undoubtedly, Cretaceous forms in many instances have given rise to widely divergent present-day forms. If, however, we consider groups (communities) of plants rather than individual taxa, the assumption that like plants indicate like climates becomes more tenable, for it is unlikely that a group of plants, occurring together in the past, will simultaneously undergo parallel changes in their physiologies, allowing them to grow under a single completely new set of environmental conditions today.

Figure 1 is presented as an aid in comprehending the following description of desert evolution through Cenozoic Time. Although such a representation makes the scheme more easily followed, the reader should be aware of certain inadequacies of this diagram. First, such a diagram merely shows that certain communities occur somewhere on the continent and ideally a diagram should be constructed for each of many areas, for a particular community may first appear at one restricted place, then with a changing climate subsequently migrate to another area. As a corollary to this, such a two-dimensional presentation can hardly show the geographic location of the many present-day communities considered.

Secondly, the communities referred to in such a diagram should not be viewed as static through millions of years. Each community undergoes with time either intrinsic changes or receives a more or less great floristic "flavoring" from those communities upon which it abuts.

Figure 1 embodies more detail than will be specifically considered in the present discussion, but it is this same detail broadly considered that allows one to view desert vegetation in the proper perspective.

The construction of this diagram is based upon information from Axelrod (1939, 1948, 1950, 1958), Chaney (1947), Braun (1950), and others.

Early Tertiary (Paleocene to Eocene). The climate of the world appears to have been more equable than during any time since this period. The temperature extremes were not great, and rainfall appears to have been rather evenly distributed throughout the year. With the exception of the Appalachians, which were already old mountains, there were no prominent mountain masses in North America, so that there were no important rainshadows to the lee of mountains, as there are today. The continent was probably more restricted than today and arid conditions over broad areas had not yet developed.

Some members of the Tropical-Tertiary Forest extended to 55° North on the western margin of the continent, thus confining the Arcto-Tertiary Forest to higher latitudes (Figure 2A). These were the only two generalized plant communities at this time and there was a broad ecotonal band between them. The southern Tropical-Tertiary Forest was similar to tropical forests in Mexico and Central America today. The northern Arcto-Tertiary Forest was essentially an admixture of the extant eastern deciduous forest and western coniferous forest. These two forests swept from east to west across the North American continent. Highly localized arid habitats, possibly to the lee of minor mountains, were probably in existence at this time in the southwestern portion of the continent.

Eocene to early Oligocene. During this time period there appears to have set in a gradual cooling of the climate resulting in the slow displacement southward of the two broad belts of vegetation (Figure 2B). Accompanying this gradual cooling of climate there occurred in the southwestern portion of the North American continent an expansion of the localized aridity. This expansion in aridity, caused by forces still not understood, continued through succeeding epochs of the Tertiary. The plant life of this arid area has been called the Madro-Tertiary Flora (Figure 1) to denote the center of its presumed early development (Sierra Madre and adjacent plateau) and the time when it was developing into its present derived communities (Axelrod, 1958).

Later Oligocene. There was continued cooling of the climate with further southward displacement of the Arcto- and Tropical-Tertiary Floras. The Rocky Mountains began rising with a resulting weakly defined rainshadow to their lee. This is the first time that there is indication of grassland on the continent (Figure 2B) since the first fossil grazing mammals have been found from deposits laid down at this time. This grassland was likely preceded by the segregation from the Arcto-Tertiary Forest of a community similar to the Oak-Hickory Forest which today occurs to the east of the grassland and represents the most xeric component of the present eastern deciduous forest. This grassland undoubtedly contained an important element of plants from the adjacent tropical forest to the south. It may have been during this same time interval that the spruce- and fir-dominated Taiga first became segregated in the far north from the Arcto-Tertiary Forest.

Miocene. Further shift southward of the forest vegetation and continued uplift of the Rocky Mountains caused several noteworthy changes in western North America. The eastern and western deciduous forests were completely separated for the first time (Figure 2C). This separation was induced by the expanding broad area of grassland in the center of the continent, the southward-migrating coniferous Taiga to the north, and the Madro-Tertiary Flora to the south was dominating ever larger areas of the only remaining corridor for east-west migration. This splitting of the Arcto-Tertiary Forest is important, for later events purged the west of most deciduous tree members and left the western forests with a distinctive evergreen element which persists today.

Chaparral was an important plant community in southern California (Axelrod, 1950, 1958) and probably over other broad areas in the southwest during Miocene times. This was a generalized plant community which later became segregated into the chaparral that is now found in California, Arizona, and rain-shadow areas in northeastern Mexico. This community reached its maximum extent during the next epoch.

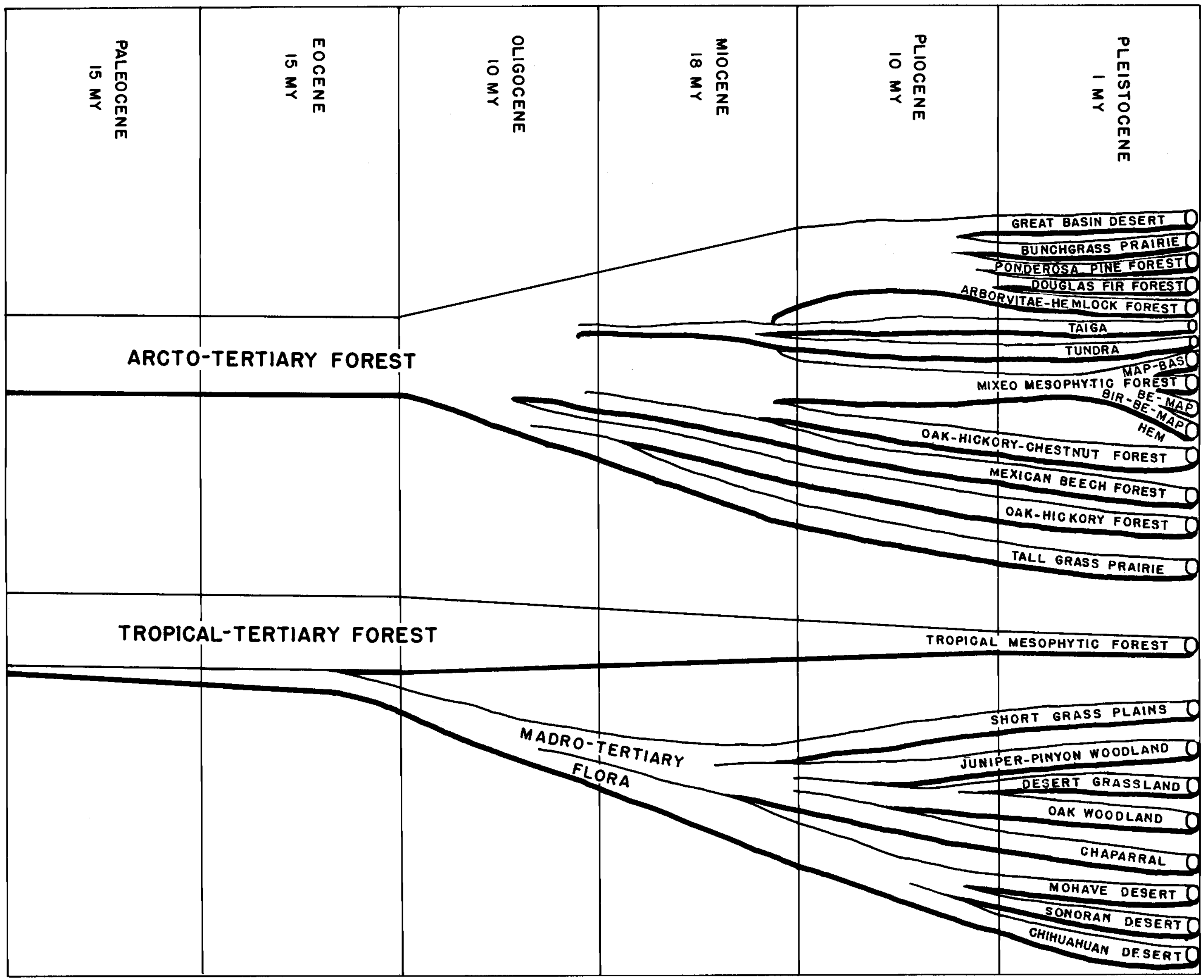

FIGURE 1. GENERALIZED SCHEMATIC REPRESENTATION OF THE EVOLUTION OF NORTH AMERICAN VEGETATION THROUGH THE CENOZOIC ERA.

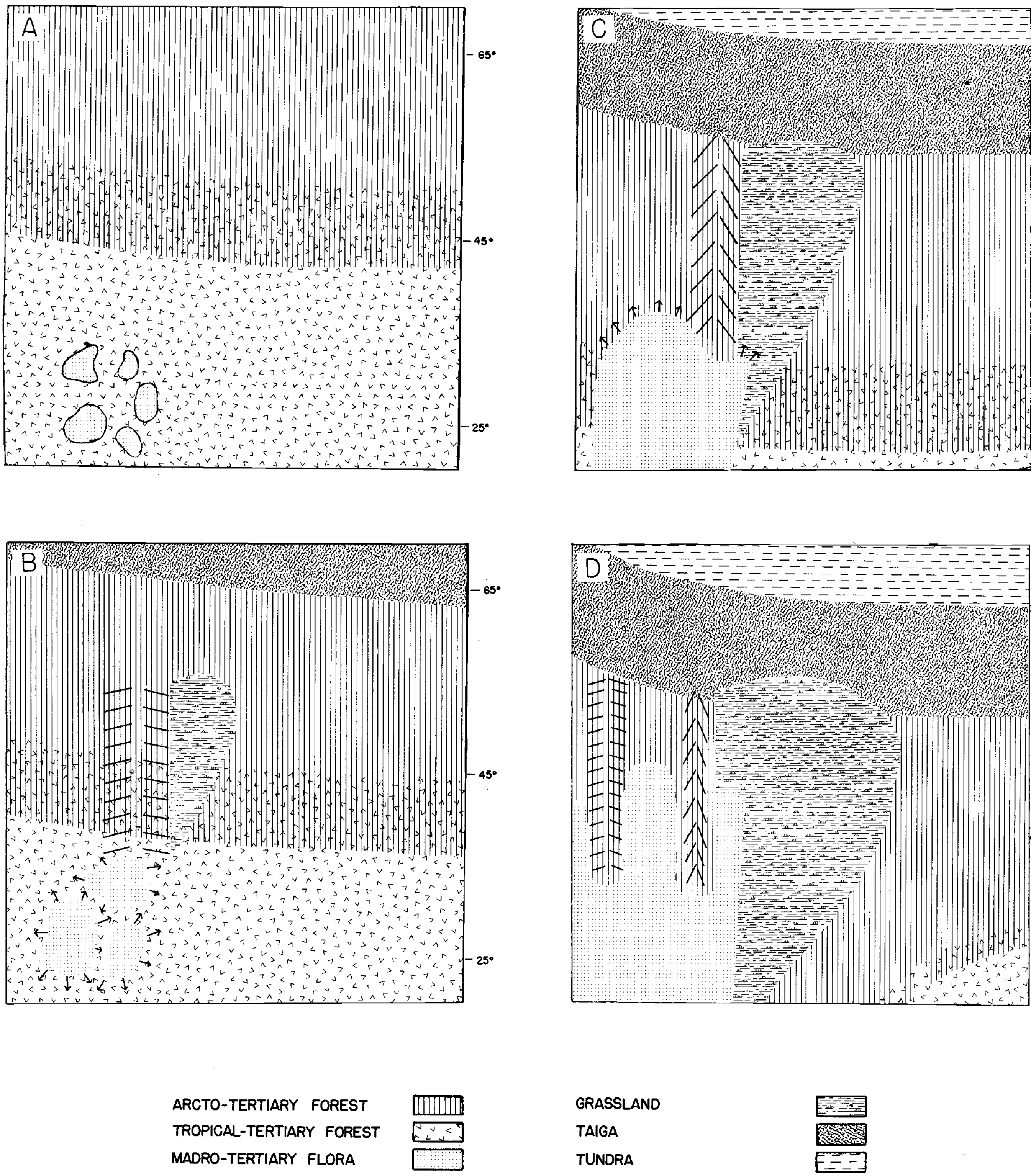

FIGURE 2. GENERALIZED DRAWINGS SHOWING CHANGES IN MAJOR PLANT GROUPS ON THE NORTH AMERICAN CONTINENT THROUGH THE CENOZOIC ERA. THE SEPARATE DRAWINGS INDICATE APPROXIMATE CONDITIONS DURING THE FOLLOWING TIME PERIODS: A. PALEOCENE-EOCENE; B. OLIGOCENE; C. MIOCENE; D. PLIOCENE. MOUNTAINS ARE INDICATED IN B, C, AND D BY SHORT OBLIQUE LINES.

The generalized woodland vegetation at this time contained plants that still persist today in the Oak Woodland of California, Arizona, New Mexico and Mexico, as well as members from the widely ranging Juniper-Pinyon Pine Woodland found to the north today.

As with the history of other grassland communities, the origin of the Short Grass Plains is largely conjectural and the conclusion shown in Figure 1 is based upon present-day ecologic relationships between grasslands and their adjacent plant communities. In making correlations between species of fossils and living grasses there are pitfalls that are even greater than for some of the other vegetation histories that have been reconstructed. According to some workers (e.g., Elias, 1942), there is strong evidence that grasses have undergone rapid evolution since the Pliocene. If this is the case, then only the most general comparisons can be made between present-day and past grasses. This rapid evolution was perhaps in response to the warm, dry climate which was characteristic of broad areas in western North America during middle Pliocene time, augmented later by an increased diversity in local habitats.

The ecologic position of the Short Grass Plains on the xeric side of the woodland today would make its origin from such a community seem likely. The origin of the Desert Grassland may have occurred at this time also (Axelrod, 1950).

During Miocene time, grassland probably was not important, as such, in southwestern North America but many grasses occurred intermingled with trees to form savanna. As aridity increased, the arboreal vegetation migrated to more mesic sites, and the grasses appear to have invaded the lowlands from the habitats of lesser extent that they had occupied earlier, and during mid-Pliocene times grasslands were largely characteristic of lowlands in the present desert region (Axelrod, 1950).

An important Miocene lowland community in southwestern North America was Arid Subtropical Scrub. This community is the direct forerunner of the present deserts. Today this vegetation is best developed in southern Baja California, Sinaloa and adjacent Sonora as well as in Tamaulipas and Nuevo Leon. Each of these areas is characterized today by summer precipitation and mild winters, conditions that can be attributed to the assumed Miocene homeland to the north, including southern California. The following genera representative of this scrub community today were found in the Mohave region and its border areas during the Miocene and Pliocene (Axelrod, 1950): *Acacia*, *Bursera*, *Caesalpinia*, *Dodonaea*, *Erythea*, *Ficus*, *Jatropha*, *Lysiloma*, *Pithecolobium*, *Randia*, *Sabal*, *Xanthoxylum*.

These plants are believed to have also occupied the Sonoran Desert region during Miocene and early Pliocene times. It is assumed that they existed in these areas at a time when the climate was essentially frost-free and precipitation occurred as summer showers and winter rain. This Arid Subtropical Scrub became restricted southward later as the result of lowered winter temperatures (because of greater insulation from oceanic influence) as well as the disappearance of summer rain and although the scrub community no longer remains, certain species of some of these genera remain today as prominent members of the Sonoran, Chihuahua and Mohave Deserts.

Pliocene. A review of many western fossil floras has led Axelrod (1948) to conclude that the general cooling tendencies common throughout much of the Tertiary were reversed during mid-Pliocene times when conditions became warmer and perhaps drier than at present. This picture must be modified for those desert and sub-desert regions that occur to the lee of the Sierra Nevada and Rocky Mountains. The Sierran orogeny during the Pliocene had a drastic influence upon the interior climate and vegetation, and the still-rising Rockies were extending their expanding influence eastward. "As a result, these interior regions now have a climate which is drier than that which existed at any time in the Tertiary, and they are colder" (Axelrod, 1948: 131). Thus aridity has become intensified, with many fluctuations, up to the present (see also Axelrod, 1958: 472).

Since mid-Pliocene times the increased continentality of climates with a reduction of summer rainfall in what is now the extreme southwestern United States led to considerable modification of vegetation (Figures 1 and 2D). The western forests, derived from the Arcto-Tertiary Forest, were purged of most of their deciduous forms and the remaining conifers became segregated into Coastal, Sierra-Cascade, and Rocky Mountain units, each with its own array of ecologically distinctive communities. The Great Basin or Sagebrush Desert, although under development since the Miocene, was probably not widespread in the northern Great Basin until late Pliocene times when it replaced the grasslands of the lowlands.

Upper Pliocene saw the initial steps in the segregation of the Sonoran and Mohave Deserts. It was during this time that the Mohave region became isolated from the Sonoran region by the formation of the San Gabriel, San Bernardino and smaller mountains to the south and east. There was also a general increase in elevation of the Mohave region which caused even more pronounced differences between these two deserts, for plants intolerant of the resulting lowered temperatures were purged from the Mohave. Following this segregation of the Sonoran and Mohave Deserts there appears to have occurred a mingling of the Arcto-Tertiary-derived Great Basin Desert and the Madro-Tertiary Mohave Desert. The Mohave Desert emerges, then, as a kind of ecotone between the Sonoran and Great Basin Deserts.

Pleistocene. The Pleistocene was a time of great changes in climate and there were undoubtedly corresponding changes in the vegetation. However, the major patterns of vegetation in North America were probably set by this time and what took place during the Pleistocene was a number of migrations, expansions and contractions of the then existing broad communities, as well as refinements of the major communities into the presently recognized subordinate communities of lesser extent. It may have been during this time that the Mohave and Great Basin Deserts exchanged components to make of the Mohave a desert transitional between those derived from the Arcto-Tertiary and those derived from the Madro-Tertiary Floras.

"Differentiation of the great desert floras into their present distinctive communities was accomplished chiefly during late Pliocene and Pleistocene times, largely in response to environmental selection as topographic and climatic diversity increased over the ever expanding dry regions into the latest state of geologic time" (Axelrod 1950: 296). It is also stated in the same paper that "the evolution of desert floras is continuing actively at the present time," a topic that is pursued in the following paragraphs.

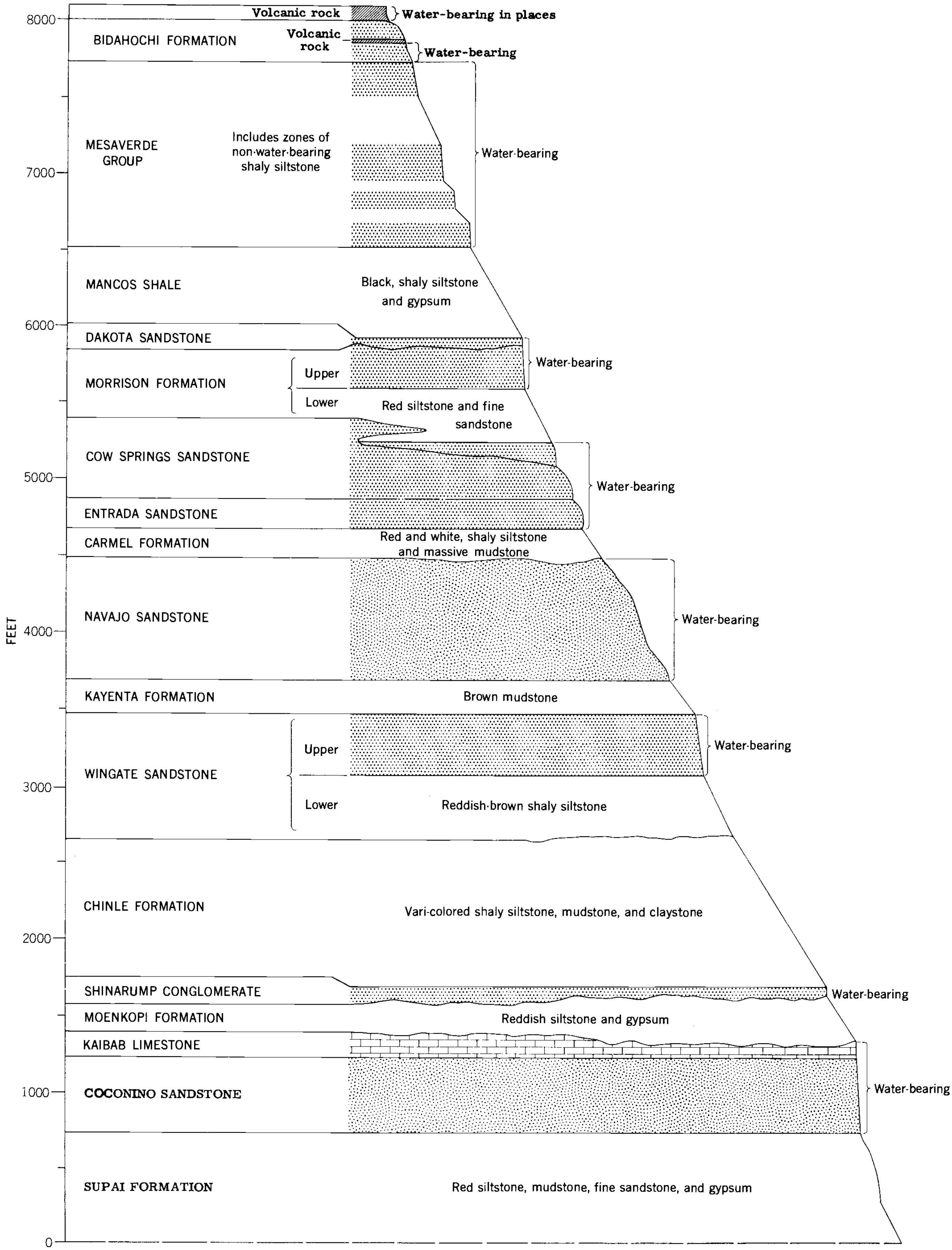

FIGURE 3.--ROCK FORMATIONS IN THE NAVAJO COUNTRY.

Evolution in the Desert

"Evolution is not a series of even, steady trends, directed from within the evolutionary line, or from without by some preconceived plan or supernatural force. Rather it is opportunistic, depending upon the interaction between the hereditary variations which happen to surround the population at that time," (Stebbins: 1952). In the same paper Stebbins goes on to say that in contrast to humid regions, arid regions appear to provide the hereditary and environmental diversity to promote rapid evolution. This concept is advanced despite the fact that the greatest number of species per unit area is found within the humid tropics. The greater number of species here could be the result of accumulation through long periods of time, while in the desert the apparent poverty of species could be the result of viewing conditions during one time interval. That is, the species turnover could be far greater in the desert climate than under the relatively stable conditions of the tropics when viewed over vast periods of time. Furthermore, the diversity of communities in arid regions is greater than in humid regions and, although there may be but few species represented in any one community, there are many communities, each responding to some habitat factor which compensates for moisture inadequacies in some slightly different manner. These habitat differences tend to be maintained in arid regions whereas in humid regions these initial differences tend to converge upon fewer habitat types.

An example of what is meant here can be sought in the response of different soil parent materials to the climate in desert versus humid regions. One reads in textbooks on soil development that in humid regions soil parent materials of diverse types, when found under one climate, tend to produce zonal soils that are relatively similar. Concerning desert soils one reads no such thing, and if more than a paragraph is devoted to desert soils it is an unusual book indeed. In one of the few discussions of desert soil formation, Nikiforoff (1937) mentions that over vast upland areas in the desert the upper layers of the soil have hardly been touched by soil-forming factors. Initial differences in the nature of parent materials are maintained over long periods of time. These soil differences have their expression in differences in kinds of plants they support, as was noted earlier by McGee and Johnson (1896: 130): "Partly by reason of the absence of humus, the superficial deposits are comminuted mechanically but imperfectly reduced chemically, so that they vary from place to place with variation in rocks and quantity of water, and thereby tend to produce local floras, or a provincial habit of the general flora." Here we see, then, just one of the reasons for the diversity of plant communities in the desert.

This environmental shattering into small fragments must have a profound influence upon speciation. Large populations are divided and small genetic differences are accumulated in these fragments. With further passage of time these small subpopulations become genetically isolated, and then, perhaps through a shift in the climate, long-isolated subpopulations become sympatric and the merging of their genetic material causes an increase in genetic diversity.

Without stressing the point further, emphasis should be placed upon the important observation that the warm desert areas have emerged as regions of great flux, and the complexity of communities found here is the result of (1) the diverse environment, (2) the action of that environment on a complex flora derived from the tropics in relatively recent times.

Summary

The evolution of North American deserts from their early tropical derivatives has followed a unique course toward greater complexity. Unlike most other communities, the desert has evolved in place in an environment of aridity, new since the rise of the Angiosperms. The desert prototype did not migrate from higher or lower latitudes, but gave rise to contemporary deserts under the compulsion of increasing and expanding aridity in southwestern North America.

It has been only in relatively recent times (late Pliocene to Pleistocene) that the major Madro-Tertiary-derived subdivisions of the North American Desert (Mohave, Sonoran, Chihuahua) have become differentiated. The individual communities of these deserts not only reached their present forms recently but are probably still undergoing rapid change because of the peculiar desert environment. This desert environment is characterized by great diversity of habitat types with the habitat differences being maintained over great spans of time.

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CONTEMPORARY BIOTA OF THE SONORAN DESERT: PROBLEMS

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Introduction

Several theoretical problems in ecology arise when the attempt is made to interpret data and design experiments for investigations of biological mechanisms operative in arid lands in general, and deserts in particular. It is my purpose here to treat three of these problems under the headings of limiting factors, the climax, and the community. Each problem arises from the circumstance that the ecologic facts for populations and communities of desert-adapted species are often inconsistent with classical theory developed over the past half-century as the peculiarly deductive American ecology.

For the intelligent investigation of desert ecology, an understanding of the evolution of desert vegetation is required. Equally necessary is a comprehension of the interrelationships of the forces of evolution, viz., those forces which affect the genetic equilibrium of the breeding population (mutation, selection, gene exchange, and population size). The forces of evolution, operative in both plant and animal populations, are not phenomena merely of the past, but are operating at the moment as well.

In the preceding paper, Dr. Turner has outlined the evolution of desert vegetation as revealed by the paleobotanical record and the method of floristic analysis for evaluating facies and age that has been developed by Chaney (1936, 1938, 1944a) and his students (primarily Axelrod, 1938-1959).[1] It is concluded by Axelrod (1950) that deserts are the youngest environments today characterizing wide subcontinental regions, and that the distinctive desert vegetation of modern aspect is not more than four to five million years old; its continuing differentiation was accomplished chiefly during late Pliocene and Pleistocene time.

Tropical Affinities of the Biota

Within and marginal to the geographic limits of the Sonoran Desert[2] there are today derivative communities of two major continental Tertiary Geofloras, viz., the Madro-Tertiary Flora and the Arcto-Tertiary Flora. One of these, the Madro-Tertiary Geoflora, is derived from earlier Tropical-Tertiary Forest.

[1] The method involves a reconstruction of Tertiary environment by a comparison of a fossil flora with the living vegetation which resembles it most closely.

[2] One of the objectives in the Arid Lands Program is to further clarify and map these limits as precisely as is possible on the basis of plant and animal distribution (see Lowe, 1955).

The vegetation of the desert is derived from the warm-adapted Madro-Tertiary Flora of southern origin. The adjacent high "desert mountains" support derivative communities of the cold-adapted Arcto-Tertiary Flora of northern origin (see Chaney, 1944a, 1944b; Axelrod, 1950, 1957).[3] For example, in the vicinity of Tucson, Summerhaven is situated at 7700 feet elevation in a modern derivative community of the Arcto-Tertiary Flora primarily dominated by western yellow pine (*Pinus ponderosa*), whereas Tucson itself is situated at 2400 feet elevation in a modern derivative community of the Madro-Tertiary Flora largely dominated by creosotebush (*Larrea tridentata*). Within these modern derivative communities are found characteristic animals which have had evolutionary histories in either Madro-Tertiary or Arcto-Tertiary environments (see Epling in Dobzhansky and Epling, 1944; Lowe, 1950; Axelrod, 1957).

For our purposes here of brief review, the boid family of snakes is especially illustrative of the fact that many desert animals as well as desert plants have been derived ultimately from warm-adapted tropical and subtropical stocks. This is particularly true for the Sonoran Desert.

Figure 1 is a map of the known distribution of the boa constrictor (*Constrictor constrictor imperator*) in Sonora, Mexico, where it occurs in the Sonoran Desert and in the adjacent Arid Subtropical Scrub.[4] This species occurs today in three of the seven principal regions of the Sonoran Desert, viz., the Central Gulf Coast, the Plains of Sonora and the Foothills of Sonora, as outlined in Shreve's (1951) provisional map. The boa constrictor remains in relictual distribution in a relatively humid and frost-free portion of the Sonoran Desert. Thus, while it is a tropical and subtropical species in South America, Central America, and in southern Mexico, it also still occurs today in what have become the southern mainland regions of the Sonoran Desert, and to within approximately 70 miles of the border of the United States.

Other species and subspecies of boas not only occur in arid lands but have evolved there. They have a Madro-Tertiary environmental history. Figure 2 is a map of the geographic distribution of the Mexican desert boa (*Lichanura trivirgata*) which occurs primarily in the Sonoran Desert in Mexico. Other desert boas occur in Arizona, California, and Baja California. *Lichanura* is a true boa with desert-adapted forms occuring today within Sonoran and Mohave Desert environments in which they have evolved.

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[3]Moreover, the vegetation of the Great Basin ("Cold") Desert is also derived from the Arcto-Tertiary Flora. It is distinctive from that of the Sonoran Desert in both its geologic history and in the general and physiological ecology of its contemporary biota.

[4]From earlier assumptions based in important part on vegetation studies during the past several years in Sonora, it has been possible to determine subsequently, by field collections, the northward relictual distributions of several primarily tropical and subtropical species of plants and animals still remaining today with disjunctive distributions within the Sonoran Desert. In addition to determining the extent of these northernmost extensions within the Sonoran Desert of such tropical plants and animals, we are attempting to determine the particular compensating factors which permit their continued successful existence within the relatively new desert environment.

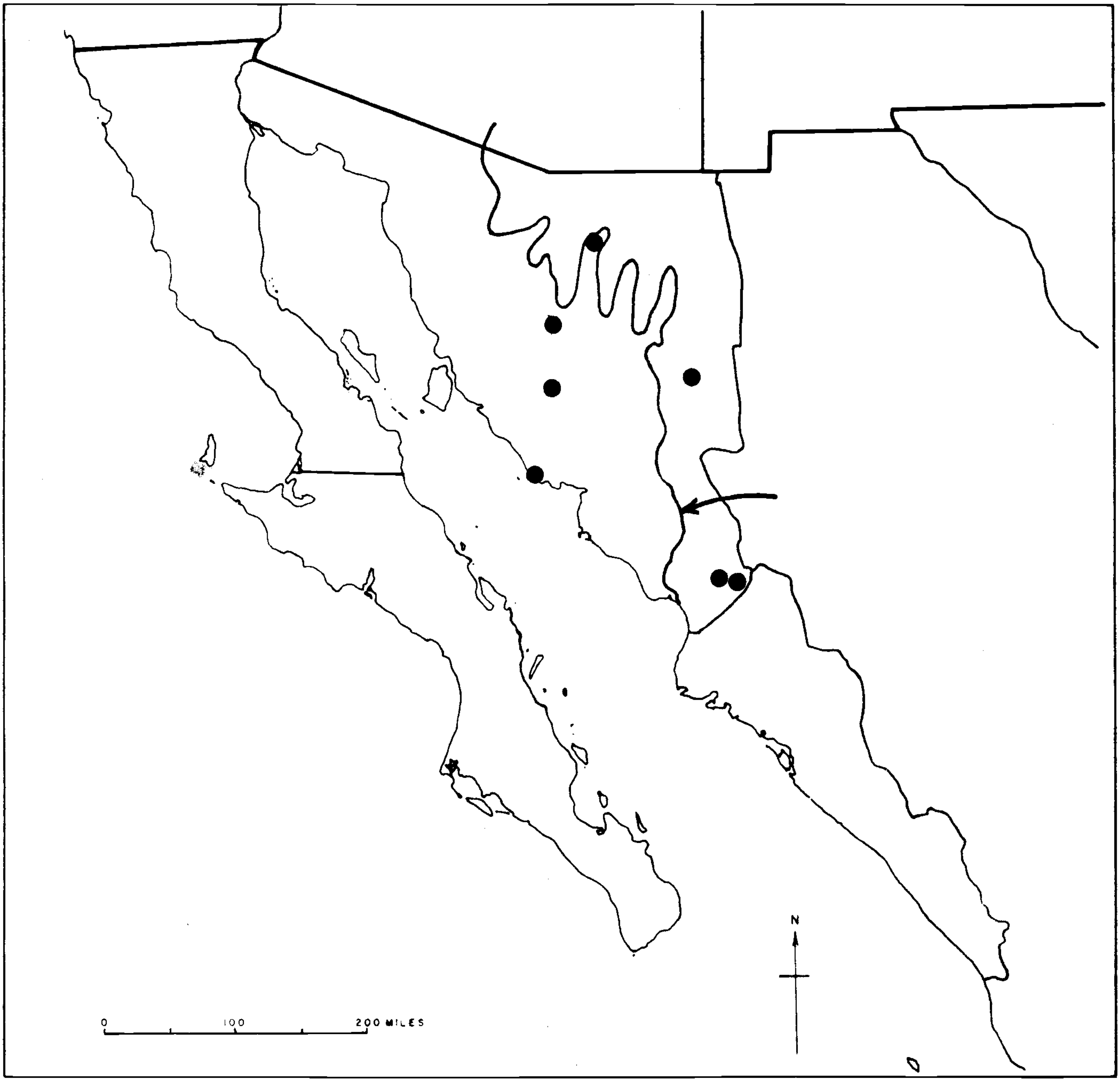

Figure 1. Distribution of the boa constrictor (Constrictor constrictor inperator) in Sonora, Mexico. The easternmost three localities are not in the Sonoran Desert. Arrow points to a line approximating the southeastern edge of the Sonoran Desert, in Sonora.

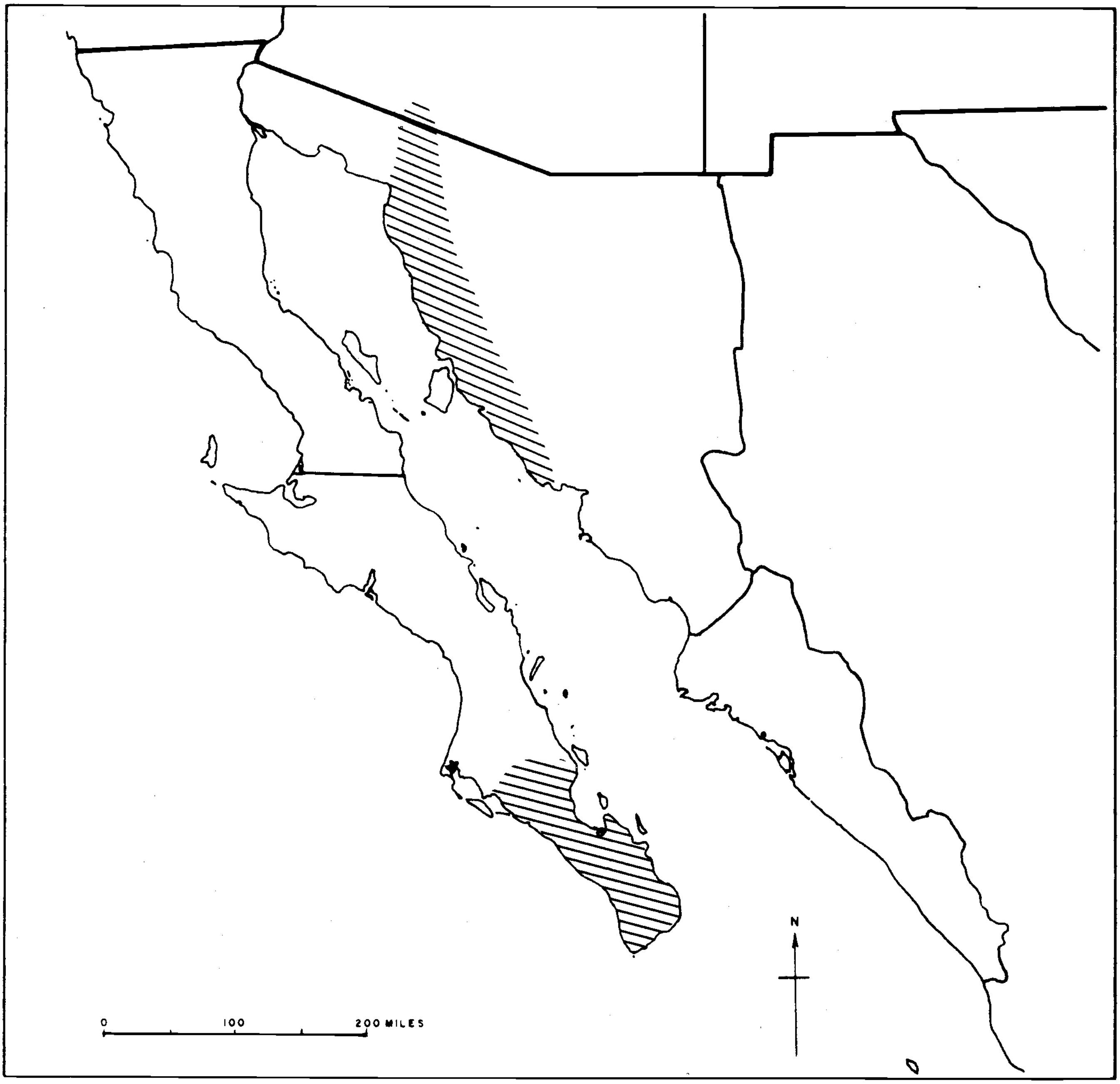

Figure 2. Distribution of the Mexican desert boa (Lichanura trivirgata). In Arizona this species occurs in the Ajo Mountains. The geographic and ecologic distributions of Lichanura and Constrictor overlap in the area of Guaymas, Sonora.

In the Old World, the sand boas (Eryx) of Eurasia and Africa also inhabit arid lands. The sand boas, while neither wholly desert forms nor as "tropical" as the boa constrictor, inhabit deserts and semiarid regions within their wide latitudinal range from northeastern India and northwestern China southward to northern Africa, including the Sahara Desert, and into central Africa east of the rain forests.

Desert and sand boas succumb to laboratory environmental conditions that are humid or cold, i.e., conditions involving damp soil and air, and/or temperatures below approximately 70°F. Their intolerance of high humidities and high substratum moisture content stands in marked contrast to these essential requirements for boas and pythons in general, animals which characteristically inhabit tropical and subtropical regions of the world. The moderate thermal requirements of the desert boas and sand boas are, however, similar to those of their pan-tropical, warmth-adapted family relatives.

In summary, it is clear that during the evolution of the North American Desert, species of plants and animals now characteristic of the harsh desert environment were evolving from organisms originally from contiguous milder environments. It is beyond reasonable doubt that characteristic species, if not the majority, of plants and animals today living within and marginal to the southern limits of the Sonoran Desert, and other deserts in both the Eastern and Western Hemispheres, have been ultimately evolved from warm-adapted, essentially tropical or subtropical stocks. This conclusion is important to the study of stress and its relationship to the environmental determinants operative as limiting factors for contemporary populations of desert plants and animals.

Limiting Factors: Averages vs. Extremes

Temperature

> "The line which marks the extreme southern limit of frost is the most important climatic boundary in restricting the northward extension of perennial tropical species, and it is the line along which the influence of winter cold is the simplest in its operation."--Forrest Shreve, "The Influence of Low Temperatures on the Distribution of the Giant Cactus," 1911:136.

The mechanisms by which climatic determinants limit the geographic and ecologic distributions of plants and animals are little understood. Cain (1944)[5] provided a well-balanced review of important aspects of the general problem in which he refrained from developing the thesis for either side of the argument of climatic control by average versus extreme environmental conditions. The Clementsian view of control by average climatic conditions was divorced from genetic response, and what is known today as the Hardy-Weinberg law, because, as an essentially complete environmentalist, Clements believed in the inheritance of acquired characters. While there is no longer any doubt that a particular physiologically controlled ecologic

[5]It should be noted, however, that, as with authors both before and after him, Cain (op. cit.) did not refer to several critical works bearing on this problem which have been published over several years by a few students of desert ecology.

amplitude is an expression of a particular genetic system subject to the forces of evolution, there remains the problem of control through natural selection by average vs. extreme climatic (and other) conditions.

The concept of control by climatic extremes and/or environmental minima has been emphasized by investigators of both desert-adapted and non-desert organisms (Liebig, 1840; Mitscherlich, 1909; Shreve, 1911; Thornber, 1911; Russell, 1932; Taylor, 1934; Mason, 1936; Turnage and Mallery, 1941; Turrill, 1939; Cottam, 1937; Fosberg, 1938; Detling, 1948; Gunter, 1950; Bogusch, 1951; Hepting, *et al.*, 1951; and others). Recently Daubenmire (1956) has criticized the concept that plants and animals are controlled by the distribution of extremes of climatic conditions and has stated disagreement with the conclusions of some of the authors cited immediately above. Unfortunately, he did not make reference to several of these papers, and, in particular, to those treating species of the Sonoran Desert.

Daubenmire's (*op. cit.*) method and the organisms to which he applied it may explain in part his criticisms of Mason's (1936) concept of tolerance (see below), and of Taylor's (1934) time extension of Liebig's Law of the Minimum (1840),[6] as well as his inconsistency with the results of Shreve (*op. cit.*) and of others with respect to desert species derived from the Madro-Tertiary Flora. Qualitatively used climatographs were constructed by Daubenmire (*op. cit.*) with mean temperature plotted on median precipitation, for data from a series of weather stations in eastern Washington and northern Idaho representative of derivative communities of the Arcto-Tertiary Flora dominated by conifers, grasses, and sagebrush.

It is of credit to Daubenmire (*op. cit.*, p. 151), nevertheless, that, at the end of his discussion, he recognizes that the "chief possible exceptions" to his general argument against extremes as important components of phytoclimate are (1) at "the borders of areas with frost-free climates," and (2) "in very dry or very cold regions." With regard to these situations as exceptions, however, the investigator of desert environments is impelled to mention (1) that it was shown nearly 50 years ago that both frost-line phenomena and the number of consecutive hours below freezing at localities north of the frost-line are critical to the existence of species in the Sonoran Desert (Shreve, 1911; Thornber, 1911), and (2) that the very dry regions of North America (=desert) and the very cold regions (=tundra and ice) taken together account for about one-fifth of the entire continental landscape.

Need for the experimental method is indicated. Important will be experiments directed along the lines of Shreve's (1911) original experiments of the temperature tolerance of the saguaro (*Carnegiea gigantea*), or giant cactus, of the Sonoran Desert. While Shreve's work on the saguaro was excellent as far as it was carried, several questions have remained unanswered. We have, therefore, designed experiments to extend the investigation of environmental stress on this species.

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[6]Taylor's (1934:378) rewording of the law, so as to bring it into line with the concept of critical time, is as follows: "The growth and functioning of an organism is dependent on the amount of the essential environmental factor presented to it in minimal quantity during the most critical season of the year, or during the most critical year or years of a climatic cycle."

The saguaro proves to be an especially useful desert organism for experimental work both in the laboratory and in the field. It is a member of a large tropical and subtropical group of arborescent columnar cacti all allied to the genus *Cereus*. Only three of the approximately 60 species in this group extend into the Sonoran Desert and north of the frost-line. These are the saguaro, organ pipe (*Lemaireocereus thurberi*) and senita (*Lophocereus schottii*). Of these, the saguaro alone extends to the northern limit of the Sonoran Desert, in Arizona, and no arborescent columnar cacti extend into the Mohave and Great Basin Deserts. Undoubtedly, temperature is a primary limiting factor at the northern and northeastern boundaries, and at the elevational limits (4400-4500 feet) of the saguaro.[7] Temperature also appears to be a limiting factor for many of its community associates, both plant and animal.

Table 1 provides a summary of the results of two experiments in which two-year-old saguaros were used. These experiments have been repeated with two-month-old seedlings and the same results have been obtained. We have verified Shreve's findings that environmental temperatures below freezing are lethal to the saguaro (Fig. 3). In addition, we have shown that prolonged temperatures slightly above freezing (1°C - 3°C) are harmless. Experiments are now being conducted at temperatures in the range -1°C to -15°C to determine the relationships of temperature, acclimation, surface-volume ratio, and genetic variation to the lethal freezing of tissue. Figure 3 is the freezing curve for a two-year-old saguaro at -15°C.

TABLE 1

Experimental Low Temperature Mortality

For Two-Year-Old Saguaros, *Carnegiea gigantea*

(Mean Stem Height, 21.1 ± 0.86 mm; Mean Stem Weight, 1.8 ± 0.17 gm)

Exposure Temperature, °C					
1 to 3			-15 to -17		
n	Days Exposure	Per Cent Killed	n	Hours Exposure	Per Cent Killed
25	1 - 32	0	27	.5 - 12.5	100

With the finding that prolonged exposure (up to 32 days) to environmental temperatures slightly above freezing (1°C - 3°C) has no lethal effect, it is clear that climatic records for the mean temperature of the coldest month of the year (January) indicate that this datum is not critical in the determination of the geographic distribution of the saguaro.

[7] Shreve (1915:25) recorded observation of a single small individual at 5,100 feet in the Santa Catalina Mountains, Pima County, Arizona.

The winter night temperatures (nyctotemperatures) and the number of consecutive hours of temperatures below freezing appear critical. While much remains to be determined concerning the precise mechanism of control attendant to this critical datum, there remains little question but that the distribution of the saguaro is controlled northward and in elevation by extreme rather than average (mean or median) thermal conditions as recorded for 24-hour periods.

In summary, the experimental data obtained thus for the saguaro, a member of the Sonoran Desert biota derived from the warm-adapted Madro-Tertiary Flora of southern origin, supports Mason's (1936:183) concept that "Plant distribution is primarily controlled by the distribution of climatic factors and in any given region the extremes of these factors may be more significant than the means."

Precipitation

> "The distribution of the Giant Cactus to the westward of the Colorado River is undoubtedly limited by the low summer rainfall of interior southern California."--Forrest Shreve, "The Influence of Low Temperature on the Distribution of the Giant Cactus," 1911:138.

With the question of the role of precipitation as with that of temperature, the need for critical experimental work is indicated. The coefficient of variation for annual precipitation at Tucson is 28% and at Indio it is 67%.[8] The meaning of such high (60-70%) fluctuation to the relatively few plants and animals making a living in the harsh Lower Colorado region of the Sonoran Desert may be better appreciated when it is noted that the coefficients of variation for annual precipitation throughout the heart of our Eastern Deciduous Forest are on the order of 14-18%.

A large assemblage of desert plants and animals which flourish in the Arizona Upland region of the Sonoran Desert, *e.g.*, in the Tucson-Ajo area where mean summer (July-October) precipitation is on the order of 5-7 inches, disappear from the biota farther westward and few remain to make a successful living as far west as the Colorado River Valley, for example, in the Yuma region. There, the saguaro, an Arizona Upland representative of the general problem, reaches its known westermost distributional limit[9] where expected July-October precipitation is on the order of 1.0-2.0 inches.

The marked qualitative and quantitative differences in the biota of the Yuma and Tucson regions are undoubtedly expressive in large measure of the greater and critical effectiveness of the summer precipitation in the Tucson

[8] The coefficients of variation given are from recent and yet unpublished data for the United States, made available by Dr. James E. McDonald, Institute of Atmospheric Physics, The University of Arizona.

[9] The westernmost-known saguaros occur at widely scattered points in the Lower Colorado River Valley from the vicinity of Yuma to the mouth of the Bill Williams River near Parker Dam. The Saguaro occurs on the California side of the Colorado River between Winterhaven and Blythe.

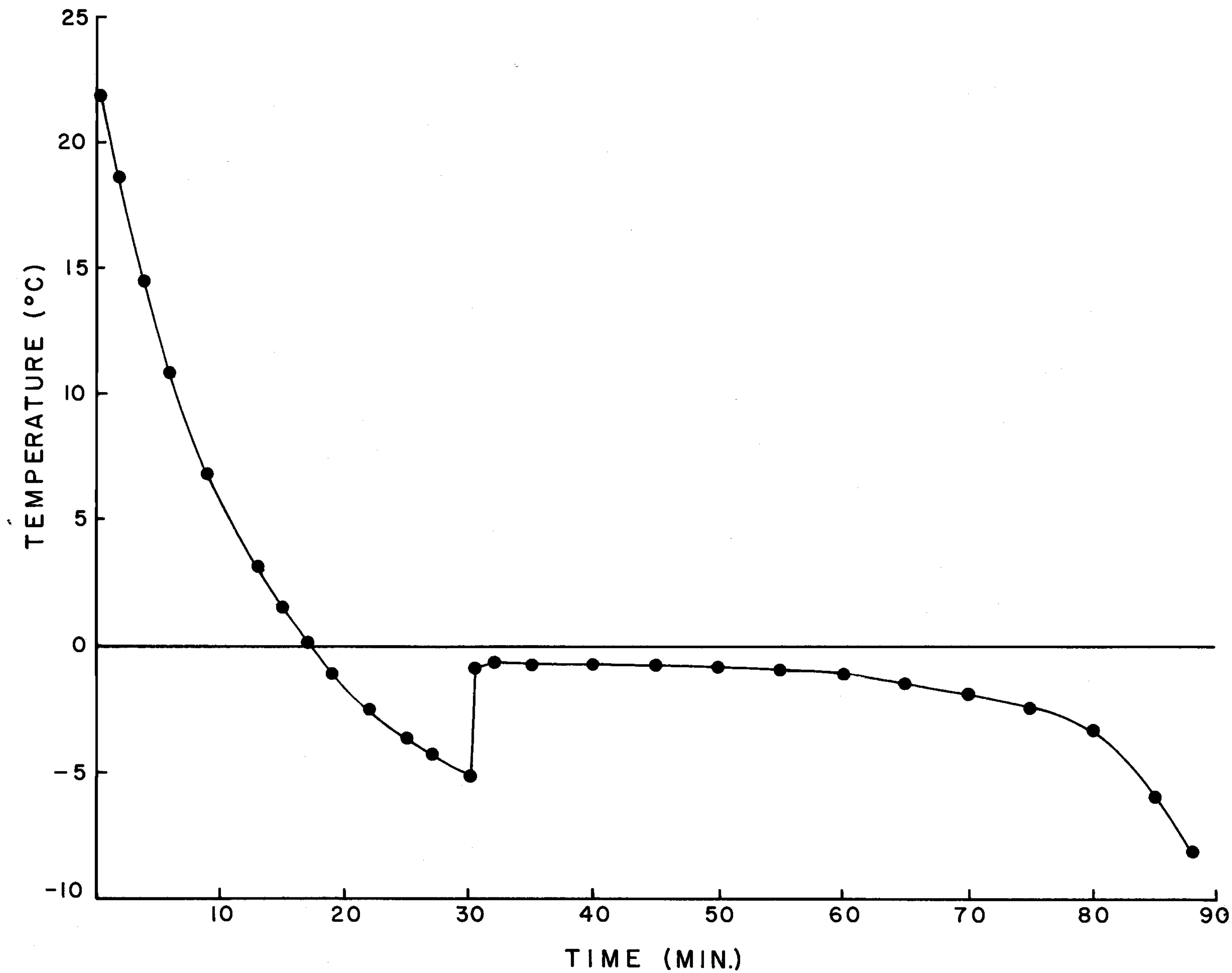

Figure 3. The internal tissue cooling curve for a young (2 yr. old) saguaro cactus in a -15°C experimental temperature environment, showing supercooling (=subcooling), temperature rise at freezing, and the freezing plateau followed by cooling of the ice.

region. Tucson lies near the northern (NE) limit of the Sonoran Desert and during the "summer rains" undergoes a change of general landscape dress from brown to green. This change is neither as extensive nor as intensive as the similar brown to green ("leafless to leaved") phenomenon of the desert and subtropical scrub vegetation of southern Sonora, but nevertheless it is just as real. Contrary to a long-standing generalization that has crept into the ecological literature (Humphrey, 1933; Shreve, 1934; Turnage and Mallery, 1941; Murray, 1959) summer rainfall in the Sonoran Desert about Tucson is particularly important to the vegetative growth as well as to the reproduction of many native plant and animal species.

Should one have studied ecologic events in the Tucson region only during the year 1905, he might well have been greatly impressed by the actual relatively greater biologic importance of the "winter" precipitation in that year in which the total annual precipitation was 24.17 inches and of which total only 1.6 inches were recorded for the summer months of July and August. By contrast, during the year 1921, with an annual total precipitation of 13.78 inches, 11.04 inches were recorded for the three "summer rainfall" months of July, August, and September (Smith, 1956). At Tucson, the average annual precipitation is 10.83 inches, and the coefficient of variation is 28%.

From consideration of the diverse life-form, community structure, and historical derivation of the components of the contemporaneous biota of the Sonoran Desert, I think that in our present studies we may find that species fall into one or more of several overlapping categories, three of which will probably concern (1) species in which growth and reproduction show high correlation with summer precipitation (and direct environmental and biological sequelae), (2) those in which there is high correlation with winter precipitation, and (3) those responding opportunistically to both phases of the essentially biseasonal rainfall regime.

In the study of stress and population distribution within arid lands, the general problem of factor determinants appears to be considerably more complex than the readily available average values for precipitation, temperature, evaporation, transpiration, etc., might alone or together indicate. For these values often mask the mechanisms by which critical factors operate (see the discussion under the subject of temperature, above).[10] In Wents' (1957) recent review of the experimental control of plant growth, he observes (p. 234) that "It is quite obvious that the average temperatures per 24-hour period, which is most easily obtainable from meteorological summaries, is of no value whatsoever when it has to be used in relation to plant growth." Moreover, it is obvious that the actual quantity of water available to terrestrial organisms is not adequately indicated by the precipitation alone (see Shreve, 1914, 1934).

In the Arid Lands Program a team of physiologists and ecologists are investigating an hypothesis concerning precipitation and critical time, viz., that the <u>variability</u> (fluctuation) of precipitation becomes critical for numerous species of plants and animals in the Sonoran Desert as approach is made in the two-inch summer rainfall line, and/or the three-inch annual

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[10]Also Daubenmire (1956) has recently shown that the climatic classifications of Koppen, of Thornthwaite, and of Swain have no value in this connection.

rainfall line. Experimental designs are directed toward an attempt to answer, first, the following questions: (1) What is the minimum amount of natural precipitation required to germinate saguaro seeds under natural conditions? (2) What is the maximum time following germination that the saguaro seedling will survive before additional precipitation of a given quantity is required to prevent death? That is, how much fluctuation in precipitation (under natural soil, thermal, and evapotranspiration conditions) is permissible to allow establishment after germination?

Quite the opposite problem also confronts us, and it is an especially interesting one. For species genetically adapted to desert conditions involving well-drained soils, too great an amount of precipitation may be limiting at one extreme of the geographic range in contrast to an insufficiency being limiting elsewhere in the distribution of the species. Many warm-blooded vertebrates adapted to desert conditions, as well as many plants, cannot long tolerate wet soil conditions (see above). From a brief study of ecologic compensating factors in Thorn Forest bordering the Sonoran Desert in extreme southern Sonora, it appears that further investigation may reveal that the relatively high summer (July-October) precipitation on the order of 11-13 inches (about twice that at Tucson) in conjunction with other factors, may have a critical limiting effect on Sonoran Desert species at the southern edge of the desert.

The Climax: Climate vs. Soil and Topography

> "It is not possible to use the term 'climax' with reference to desert vegetation. Each habitat in each subdivision of a desert area has its own climax, which must be given an elastic definition and must not be interpreted as having a genetic relation to any other climax."--Forrest Shreve, "Vegetation of the Sonoran Desert," 1951:21.

Both the Clementsian monoclimax theory of the peculiarly deductive American ecology, and its more popular version in the form of the polyclimax interpretation (which differ significantly only in the manner of emphasis on time) are incompatible with most of the information obtained thus far for desert vegetation.

Neither the older nor the modern textbooks on ecology substantially consider the literature on deserts, and, in particular, the data which bears directly on the problem of the climax. One of the reasons for this is the still-evident influence of Clementsian thought. Another is that while deserts are generally recognized as harsh environments, they are generally unrecognized as the markedly unique mid-latitude environments that they are.

In the Sonoran Desert in Arizona there are two major vegetation types (associations). One is a natural assemblage of shrubs dominated primarily by creosotebush (*Larrea tridentata*) commonly in association with bur-sage (*Franseria dumosa*), a few other shrubs, and a few herbs and occasional grasses (Fig. 4). The other is essentially dominated by trees; these are primarily foothill paloverde (*Cercidium microphyllum*) commonly in association with saguaro (*Carnegiea gigantea*), ironwood (*Olneya tesota*), other trees and several shrubs, herbs, and grasses (Fig. 5). It is clear that these two desert vegetation types differ markedly in life-form, complexity, biomass, and productivity. They also differ characteristically in their topographic positions and in the nature of their soils.

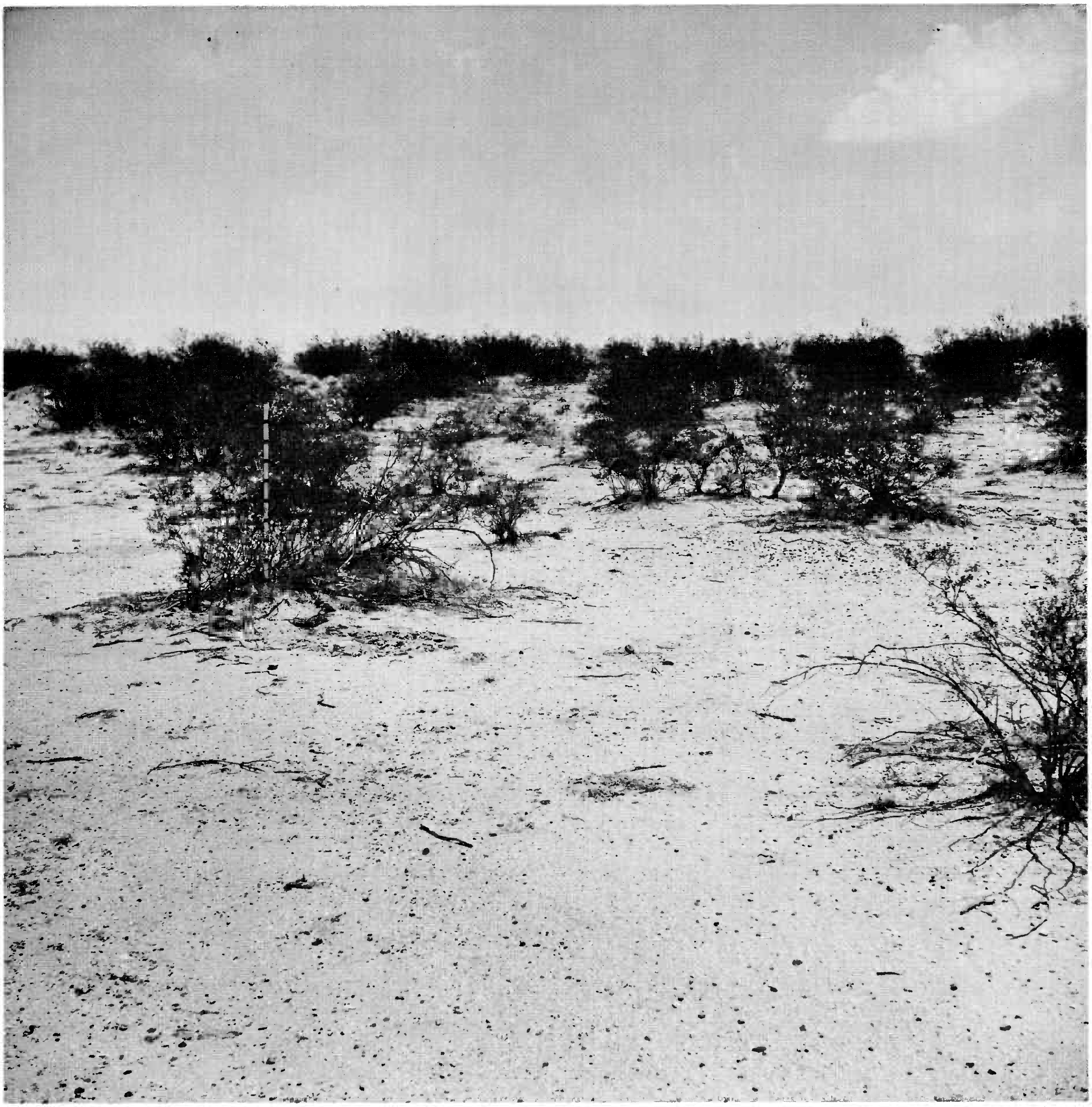


Figure 4. The relatively simple Sonoran Desert shrub climax dominated by creosotebush (Larrea tridentata) as on the finer soils of the lower slopes and floors of the Santa Cruz and Avra Valleys in the Tucson region (the Larrea-Franseria association). Meter stick indicates height of a large individual of Larrea.

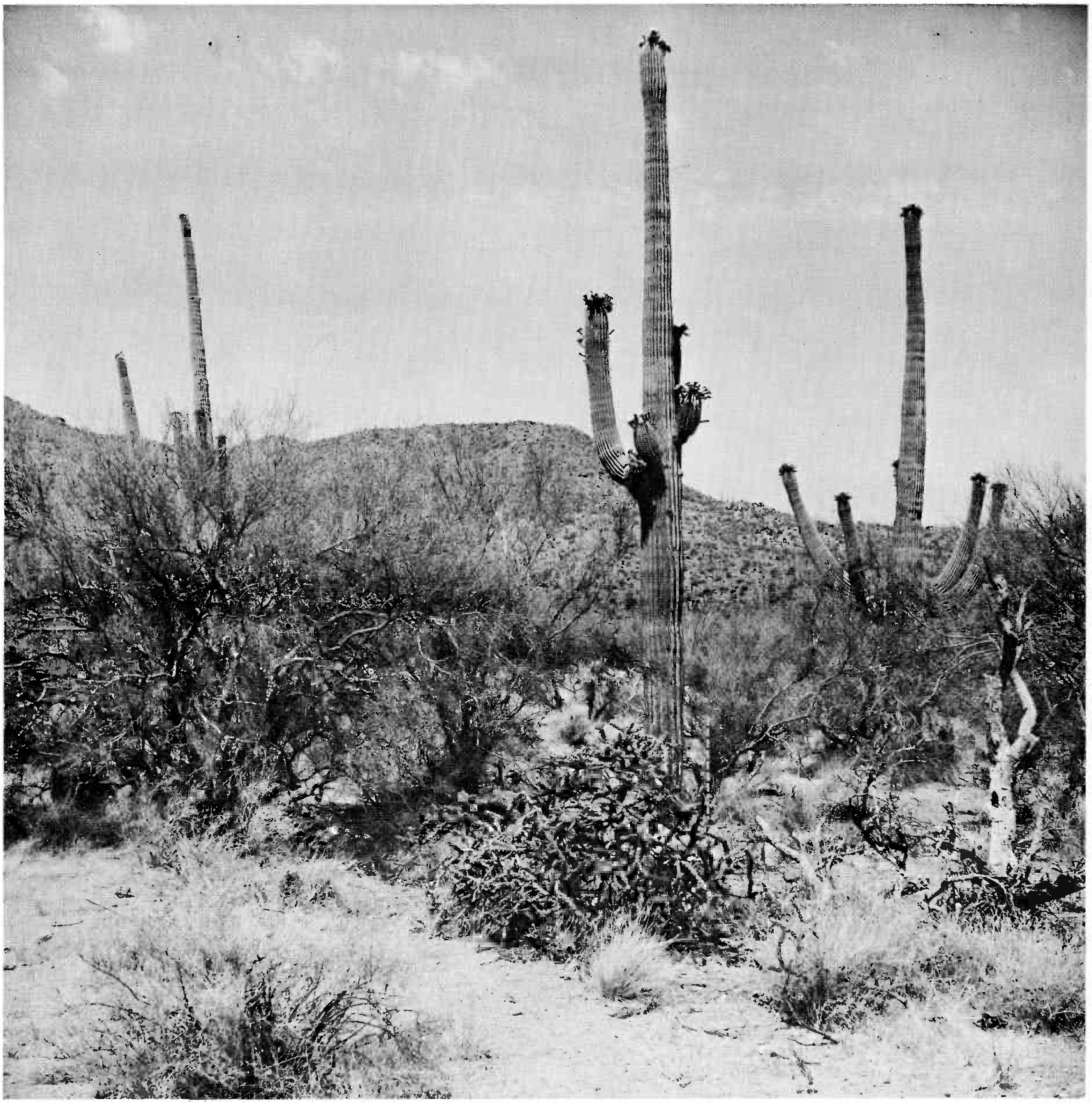


Figure 5. The relatively complex Sonoran Desert tree climax dominated by foothill paloverde (Cercidium microphyllum), saguaro (Carnegiea gigantea), and others, as on coarser soils of bajadas and slopes of ranges bordering the Santa Cruz and Avra Valleys in the Tucson region. A meter stick is near the saguaro in foreground. Note greater life-form complexity, and greater density and biomass than in the creosotebush community (Fig. 4).

Soil samples have been analyzed from a series of stations on transects in the Tucson Mountains and the adjacent Avra Valley, and from several other localities in the Tucson region. The vegetation of two such localities are represented by Figures 4 and 5. Standard determinations were made for soil texture (mechanical analysis), moisture equivalent, moisture content, capillary rise, dispersion rate, and total soluble salts. Results are given in Table 2, and graphed in Figures 6 and 7, for moisture equivalent and moisture content for the soils from the stations illustrated in Figures 4 and 5. Highly significant differences are obtained between the coarser, less colloidal soils of the upland paloverde type vegetation and the finer, more colloidal soils of the valley creosotebush type of vegetation.

TABLE 2

Comparison of Soil Characteristics of the Two Major Climax

Vegetation Types of the Sonoran Desert in Arizona

(Data from Yang and Lowe, 1956)

Frequency Distributions Graphed in Figures 6 and 7

Soil Characteristic	n	Creosotebush-Bur-Sage	n	Paloverde-Saguaro	t	P
Moisture equivalent (%)	24	12.2 ± 0.61	24	6.6 ± 0.14	8.9	<.001
Moisture content (%)						
Wet (ca. field capacity), Summer rainfall season, July.	12	9.1 ± 0.90	12	5.5 ± 0.16	7.3	<.001
Dry, Postsummer rainfall season, December	12	3.4 ± 0.41	12	1.4 ± 0.09	4.6	<.001

In summary, from analysis of pertinent soil characteristics and their correlation with climax vegetation types of the Sonoran Desert, it is concluded that here "specifically different soil attributes characterize, and are intimately associated with, distinctly different major climax vegetation types existing under the same macroclimate" (Yang and Lowe, 1956).[11] This may be termed a genetic climax interpretation.

[11]For classical theory demanding a "single climax" per "single macroclimate," see Weaver and Clements (1938; monoclimax) and Daubenmire (1956; polyclimax). For recent criticisms of both interpretations, see Egler (1951) and Whittaker (1951, 1956, 1957). Whittaker (1953) has recently presented an especially valuable and well-documented consideration of climax theory.

In his last paper, Shreve (1951) again set forth pertinent facts for deserts which are at variance with traditional theory. Similarly, the work of a few investigators since the early 1920's such as Shreve, Turreson, Clausen, Gleason, Cain, Epling, Mason, Stebbins, Egler, Curtis, Whittaker, and others, forms a sound basis for climax interpretation that involves a primary genetic basis rather than one which, traditionally, is more purely environmental in nature. Emphasis is placed on the genetic responses of organic systems oriented by adaptation through natural selection. In essence it is this: "The association owes its existence as such to the coincidence or overlapping of the tolerances of the component species and to the coincidental aggregation of its genetic lineages which have resulted from historical events" (Mason, 1947:204).

Moreover, I am reminded here of Egler's (1951:687) apt remark that "the study of American vegetation continues to worship at the altar of Oikos [meaning environment]. It might be well if a group of fanatics would 'reveal a new truth'; that vegetation is the sole result of the inherited characteristics of the plants, and that if we understand everything about the inheritance, then we would understand vegetation. The pendulum might move from its present extreme position."

The genetic climax, as I visualize it for desert vegetation, is set forth succinctly in the writings of Shreve (1915, 1950, and elsewhere) and Mason (1936, 1947, and elsewhere). Moreover, it is, in a sense, complementary to Whittaker's recent (1953) "climax pattern" idea, and partakes of the early interpretations of Turreson (1922, 1925, 1930) and Gleason (1926, 1927). The climax pattern, developed with the study of forest vegetation, places emphasis, in part, on vegetation as a continuum. It is to be cautioned, however, that desert vegetation is neither wholly nor primarily a continuum (<u>sensu</u> Curtis and McIntosh, 1951; Whittaker, 1951) nor is it wholly or primarily a mosaic (<u>sensu</u> Tansley, 1939; Daubenmire, 1952). In its essential biotic character, the North American Desert embodies both of these ecologic configurations, <u>i.e.</u>, continuity (the continuum) and discontinuity (the mosaic), and involves a multiplicity of little-understood climax types often existing side by side under the same macroclimate.

Under a particular climate in an area within a desert, the ecologic fundamentalist endlessly searches for the "climatic climax" rather than giving cognizance to the multiple forms of climax vegetation types forming the contiguous mosaic or the interwoven continuum, or both, as the particular case may be. Traditional polyclimax thinking requires the search for the average, undulating terrain with the average, loamy soil, etc., for, according to the creed, this is what supports <u>the</u> "climatic climax." According to this, and incongruously at variance with reality, the lowland, widely-spaced creosotebush <u>shrub</u> landscape in the Tucson region of the Sonoran Desert (Fig. 4) would represent <u>the</u> "climatic climax," rather than the adjacent upland foothill paloverde <u>tree</u> landscape (becoming "edaphic climax") with its vastly greater vegetation density and biomass, life-form complexity, and community productivity (Fig. 5). As pointed out above, neither one of these is an "edaphic climax" or <u>the</u> "climatic climax." Each, as a distinctive major climax vegetation type, is the plant part of a distinctive climax biotic community (Yang, 1957). Both of these stable, climax communities exist contemporaneously and contiguously--often forming a broad or narrow ecotonal continuum--under the same macroclimate. It is beyond reasonable doubt that neither is in any sense a stage of vegetation that is successional to the other, or to any other.

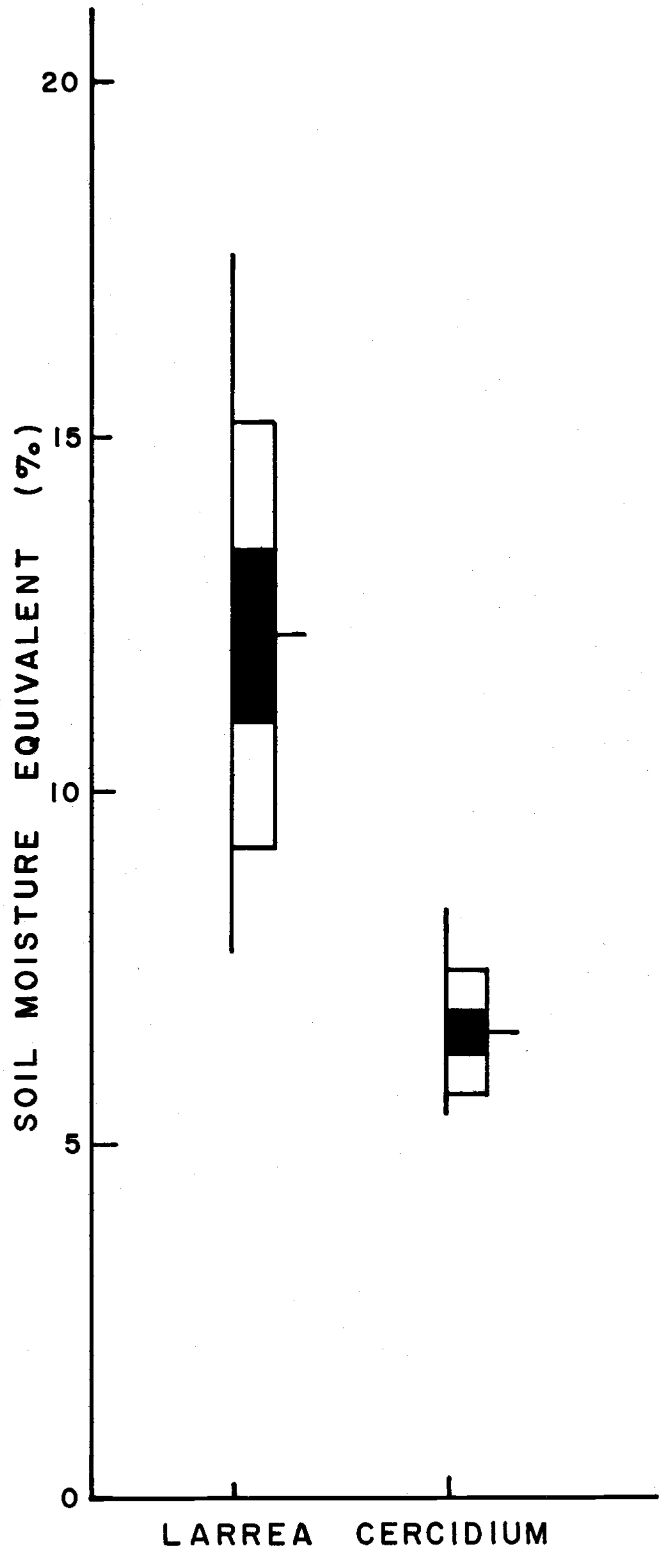


Figure 6. Frequency distributions of soil moisture equivalents for soil samples taken from trenches at *Larrea* and *Cercidium* localities as shown in Figs. 4 and 5. Range, mean, one standard deviation, and two standard errors (black) above and below the mean are shown.

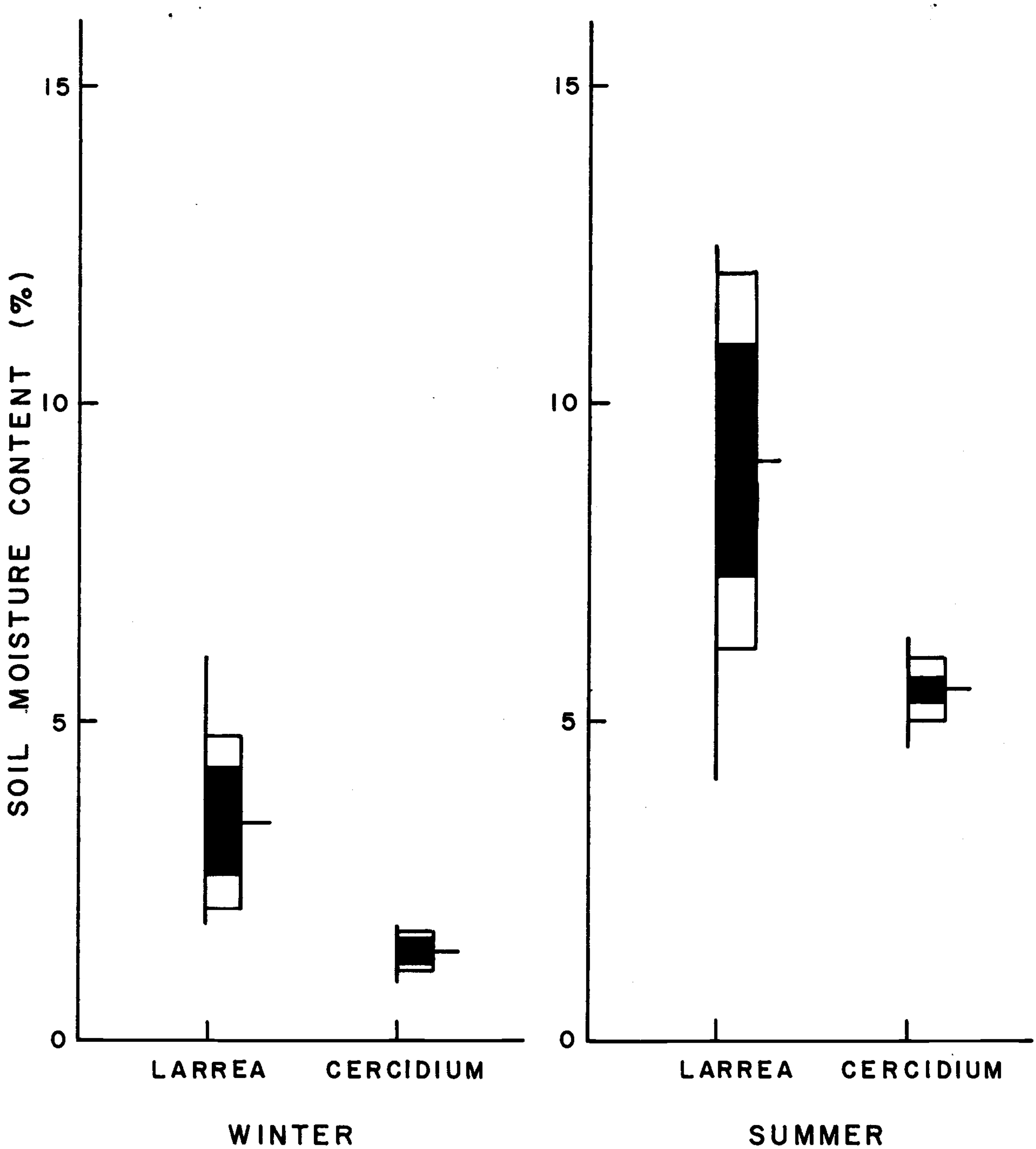


Figure 7. Frequency distributions for soil moisture content determinations for soil samples taken simultaneously from trenches at Larrea and Cercidium localities as shown in Figs. 4 and 5.

Stanley Cain's remark (fide Egler, 1951:683) on the "climatic climax" as the "edaphic climax" of the most favorable site of the region, with one term no more valid than the other, is precisely to the point for the vegetation of arid lands.

Under any single macroclimate in the desert (and often elsewhere, to be sure) the relationship is this: natural climax vegetation as a mosaic or continuum is the dependent variable which varies in co-relation with the independent variable of topography and/or soil as a mosaic or continuum. Thus desert vegetation varies over distance according to species response to the presence or absence of environmental factor gradients.

As major and unique middle-latitude environments throughout the world, the deserts remain in need of intensive biological investigation. From the foregoing, it is appreciated that within the desert the study of its characteristically abiotic and terminogenic "zonal" soils (Nikiforoff, 1937), as well as of its climate, is a primary consideration for the understanding of its vegetation and the general ecology and natural productivity of its plant-animal communities. The analysis and interpretation of desert soils is, therefore, one of our concerns in the Arid Lands Program.

In addition to being relatively little studied, the subject of desert soils is a desideratum in ecology textbooks (and most other general references on soils) which works, nevertheless, unfailingly refer to and often illustrate an extensive literature on forest, grassland, and other non-desert soils. This is, in part, a reflection of the uniqueness of desert soils which, for example, invariably defy conventional systems for the classification of soil profile. Table 3 gives comparative data for a coniferous soil from a high "desert mountain" and a desert soil from near the base of the same mountain. The data is taken from Martin and Fletcher's (1943) important studies on soils of the Graham Mountains and vicinity, in southeastern Arizona. This is one of remarkably few publications on soils giving actual description and illustration for the profile of a desert soil (Fig. 8). It is a classic work in which is proposed a meaningful set of horizon symbols (a, b, c) for desert soils as distinguished from those constituting the conventional soil horizon symbols (see Table 3).

Shreve (1951:4-17) has also presented a particularly succinct discussion of physical features of the Sonoran Desert including reference to soils.

The Community: Succession vs. Development and Change

"In a consideration of the dynamic aspects of the vegetation of a region in which the initial, sequential and final stages of a succession are characterized by the same species, and often by the same individuals, it is doubtful whether these conceptions, formed in regions with a very dissimilar vegetation, are of much real utility."--Forrest Shreve, "Ecological Aspects of the Deserts of California," 1925:102.

A prevailing tacit assumption in American ecology is that "succession is a universal phenomenon" (Oosting, 1956:239). This assumption is at variance

TABLE 3

Comparison of A Forest and Desert Soil from the

Graham Mountains and Vicinity in Southeastern Arizona

(from Martin and Fletcher, 1943)[1]

Fir Forest

Douglas fir and white fir
Elevation, 9860 feet; slope 7%; exposure, northwest
Soil group: Gray-brown podzolic

Horizon	Depth in Inches	Description
A_0	0 to 4	Partly decomposed organic debris. Matted with roots and mold mycelium. Spongy.
A_1 - A_2	4 to 9	Dark yellowish brown. Finely granular. Fibrous.
B	9 to 21	Moderate yellowish brown. Compact, Massive.
C	21 to 24	Strong yellowish brown substratum merging into rotten gneiss.

Desert

Mesquite and creosotebush
Elevation, 3360 feet; slope, essentially level area
Soil group: Red desert

Horizon	Depth in Inches	Description
a	0 to 3	No organic debris. Moderate yellowish brown; single-grain structure.
b	3 to 12	Strong yellowish brown; single grain structure.
c	12 to 30	Strong yellowish brown; gravelly; single grain structure; midly calcareous throughout the entire profile.

[1]Note horizon symbols (a, b, c) for desert soil profile.

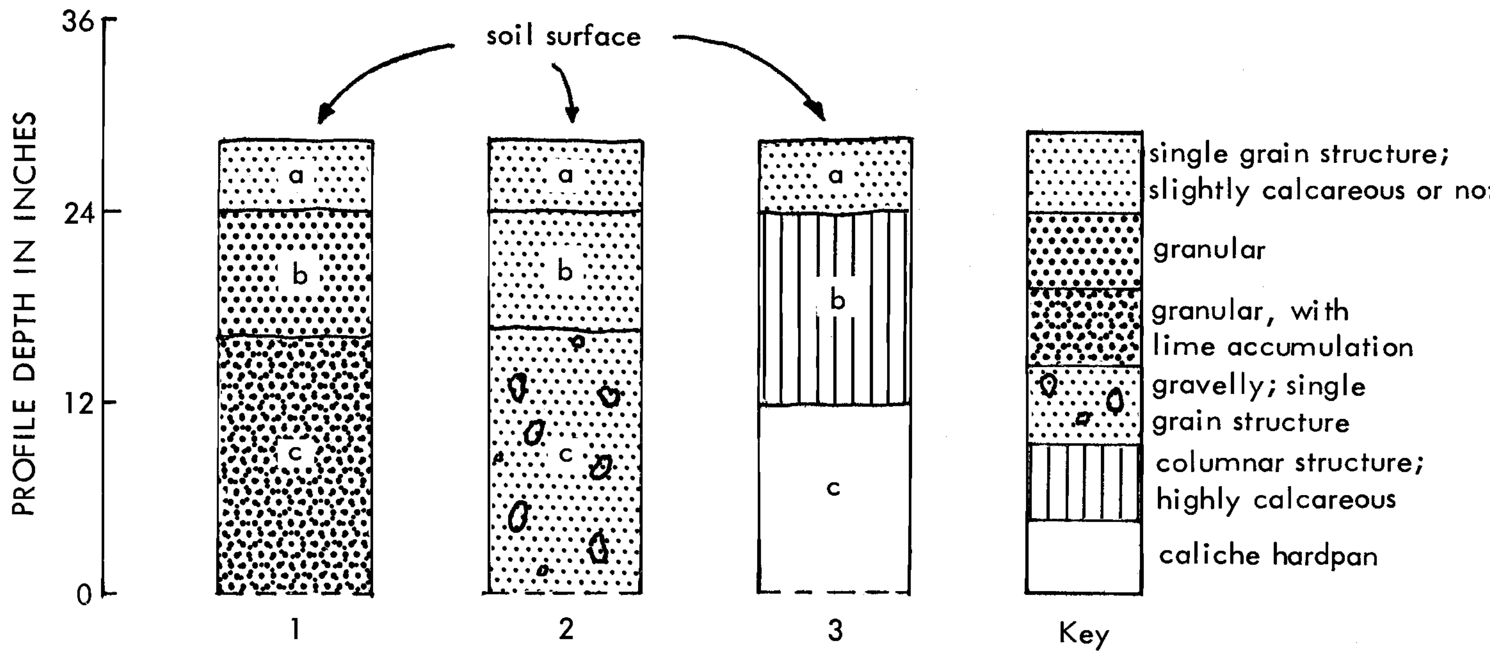


Figure 8. Profiles of desert soils, on essentially level areas in southeastern Arizona (adapted after Martin and Fletcher, 1943). Horizons (a, b, c) may also differ in color and other (e.g., chemical) characteristics. Vegetation at profile no. 1, chiefly saltbush with mesquite and snakeweed; profile no. 2, mesquite, creosotebush, snakeweed, burroweed, and cat claw; profile no. 3, chiefly creosotebush and Mormon tea. The relative simplicity of the profile is a characteristic of desert soils and a reflection of their essential abiotic nature. See Table 3.

with the evidence for desert environments. The fact that plant succession is not a universal phenomenon (Shreve, 1925, 1939, 1951) has been ignored by most other ecologists for the past quarter century (exceptions are cited below; see also McGinnies, 1955, and Shantz and Turner, 1958). In the desert, no true distinction exists between "climax" and "succession" (i.e., stages of seral vegetation).

In the desert there is no ordered plant succession (sensu Clements)--there is but development and change. It is suggested that the basis for this pronounced difference between forest and desert environments centers, in important part, in the limiting factors of light on the one hand and of plant-available soil moisture on the other, with both in relation to what is usually meant by the term "biologic competition." The striking environmental change from a "dark" (low light intensity) canopied habitat to a "light" and open one upon the "clearing" of forest dominants, and the subsequent long successional process of habitat conditioning to "dark" again, is not seen in the perennially "light" and open desert environment where, by additional contrast, keen underground competition for the relatively small amounts of plant-available soil moisture is a relentless primary competition.

Development

Direct development of desert vegetation to the climax is illustrated in Figure 9, which is a photograph of a plot in which the desert vegetation was removed by bulldozer three years earlier. The locality is in the Tucson Mountains, west of Tucson, Arizona, at ca. 2500 feet elevation. Note the direct establishment of the climax species on the bare area without a succession.

Shreve's (1925) early discovery (quoted above) of this phenomenon has never been incorporated into the fabric of American ecology. Moreover, I have been unable to find a reference to it in any of the numerous textbooks on ecology, even though it was published in the American journal, Ecology. It is also obvious that there has been actual resistance to the acceptance of these facts which are, of course, contrary to Clementsian interpretation.

Traditional opinion is well-exemplified by the maps in the editions of Weaver and Clements (1929, 1938) in which, for example, the entire Chihuahuan Desert is mapped as Grassland and classified as successional (non-climax) vegetation. In contrast, reference should be made to the important studies on the vegetation of the Chihuahuan Desert by Shantz and Zon (1925), by Shreve (1937, 1942), by Muller (1940), and by Rzedowski (1956); these reports are in full accord with Shreve's (1925) conclusion concerning "succession" in desert environments.

Change

Primary characteristics of desert vegetation include (1) a straightforward development without ordered succession, and (2) change. Forrest Shreve's (1929, 1937) early studies on vegetation changes in the Sonoran Desert employed, in part, the exceptionally informative field method of rephotography ("before-and-after" photography) for verification and illustration of long-term changes in vegetation. His matched photographs for a stand of saguaros taken in 1906 and in 1928 (Shreve, 1929), which clearly verify quantitative changes in community composition, growth, etc., represent a method that we are further developing for arid lands vegetation (Fig. 10, A-C).[12] Recently the method has been employed successfully in range management for grassland vegetation (Parker and Martin, 1952). Homer Shantz was, as were Forrest Shreve and D. T. MacDougal, among the early workers who carried the method forward (see Shantz and Turner, 1958) and who have left us a substantial record.

Figure 11 (A-B) depicts the vegetation at MacDougal Pass in the Sierra Pinacate region in northwestern Sonora, Mexico. The two photographs show nonseasonal or long-term landscape change in a harsh desert environment in which the mean annual precipitation is of the order of 2 to 3 inches, and the coefficients of variation for annual precipitation is of the order of 50-60%. These paired photographs (Fig. 11) were taken with the cameras set at the same sites, by the method of matching vertical and horizontal position relationships of landmarks. The first photograph of the pair was taken in 1907 by the late Daniel T. MacDougal, and the second in 1959 by Mr. J. R. Hastings during a recent study in our arid lands investigations. Note in these paired photographs the numerical, spatial, and size differences of the saguaro. Also note changes in these relationships for other trees (paloverde, ironwood, mesquite), shrubs, and the prevalent desert grass (*Hilaria rigida*). The climatic determinants of such changes in the desert landscape are being investigated in our present interdisciplinary program.

The "Non-agricultural" Landscape?

It is an increasingly frequent observation of many that desert range lands have been studied least and as a result are not well understood. Much of our work in the Arid Lands Program is directed toward those desert lands of a type not yet used for agricultural purposes in the southwestern United States and in northwestern Mexico. Here our problem is precisely as was stated by Gates, Stoddart and Cook (1957:155) in their study of soil as a factor influencing plant distribution on salt-deserts in Utah:

> "As human populations increase there will be additional need for agricultural production, and these lands may be put to higher use, perhaps even to irrigated crop production. Basic to management of these lands is an understanding of the vegetation they are now supporting, what they supported prior to their use of domestic livestock, and why the present vegetation grows to the exclusion of other vegetation types."

In the Sonoran Desert, insufficient previous attention has been directed to the seemingly "non-agricultural" soils and the organisms they support, particularly the natural vegetation and the native animals which have already solved the problem of making a successful living in an arid land. We are fortunate in this regard, however, to have available a groundwork established through the efforts of a few early workers who were dedicated students of the desert and who had the vision to see beyond the needs and

[12] In Figure 10 C, the arrow points to the stump of the saguaro which fell in 1958. The stump has been salvaged for tree-ring analysis by C. Wesley Ferguson, Dendrochronologist at The University of Arizona.

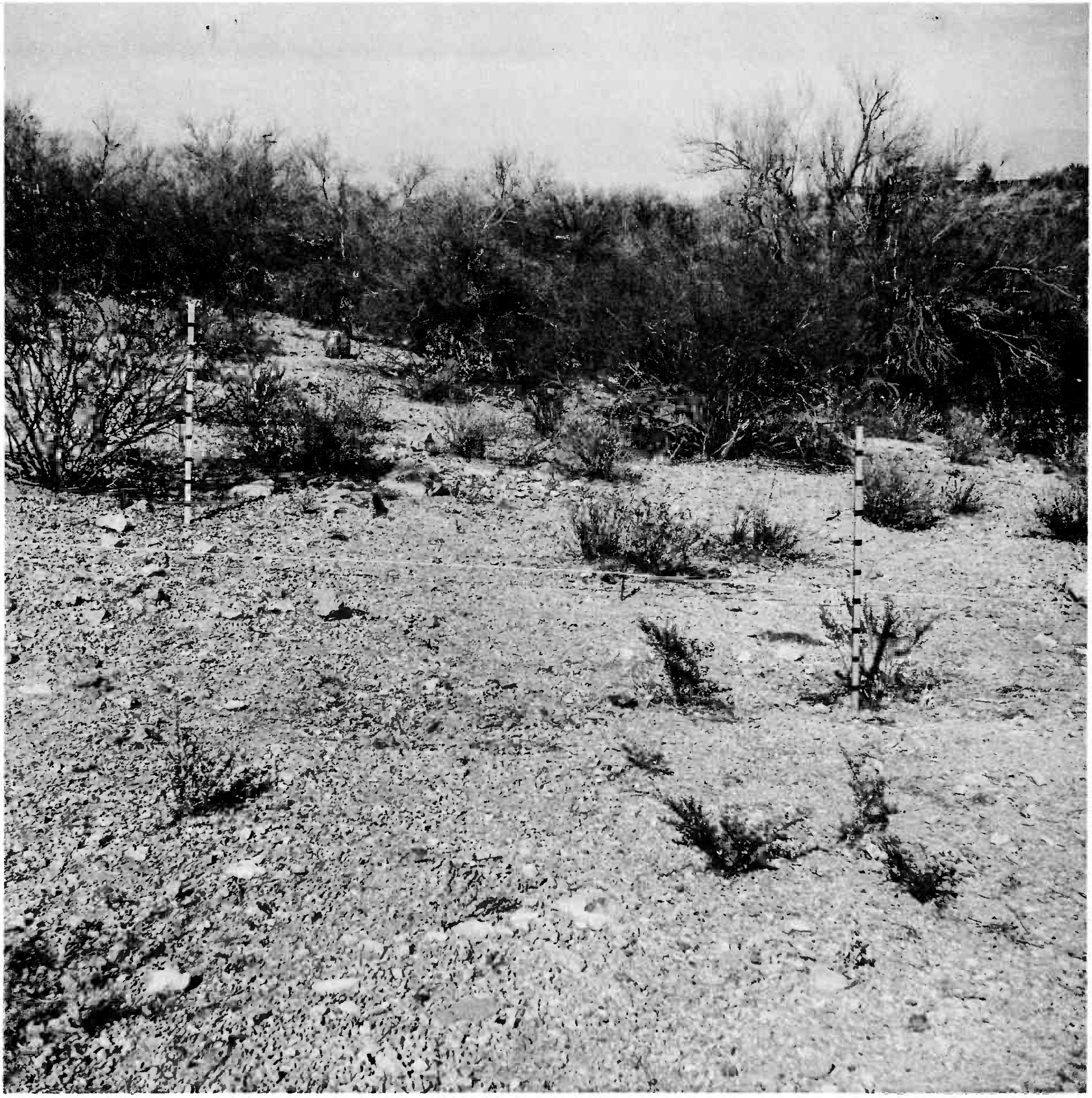
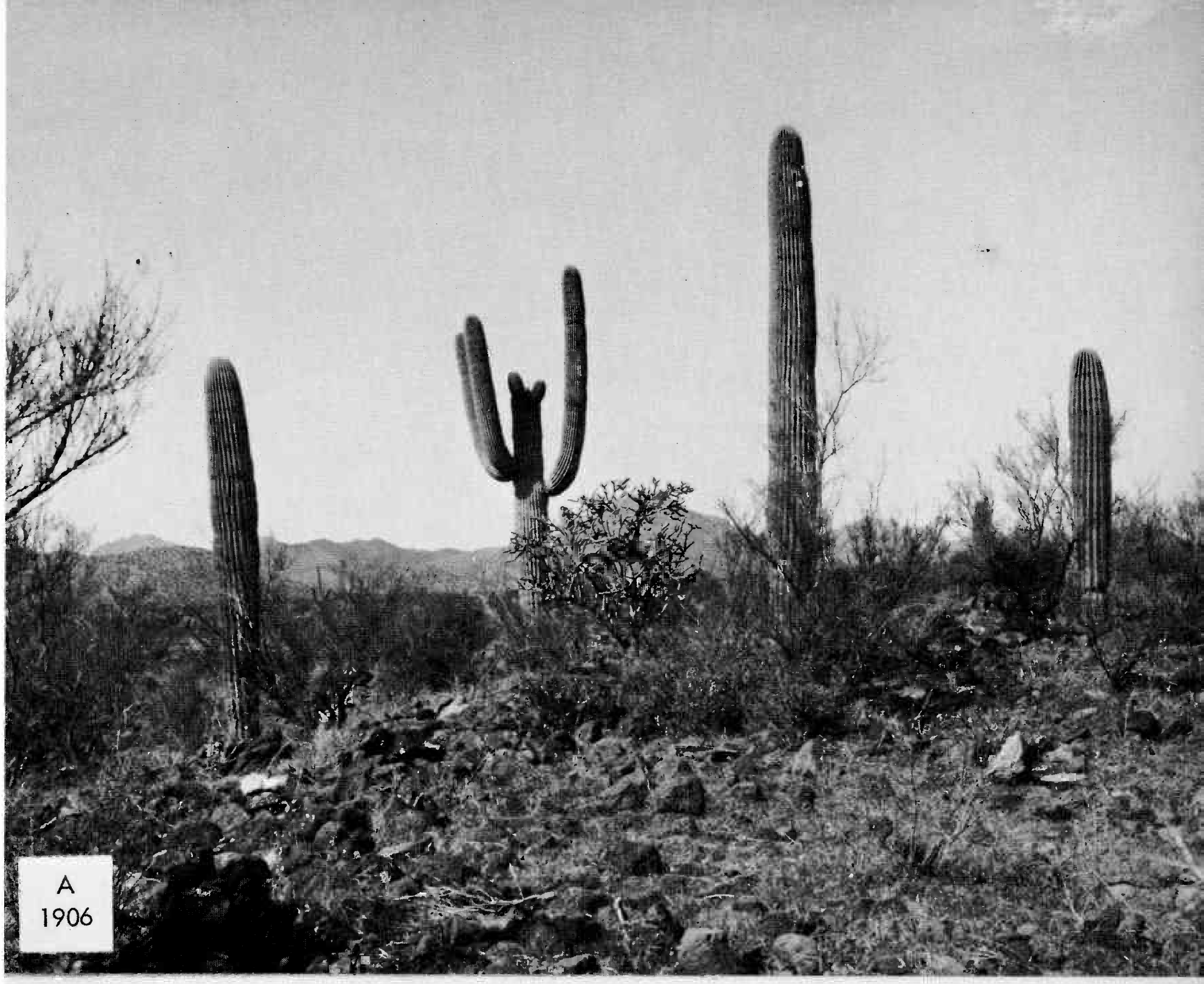
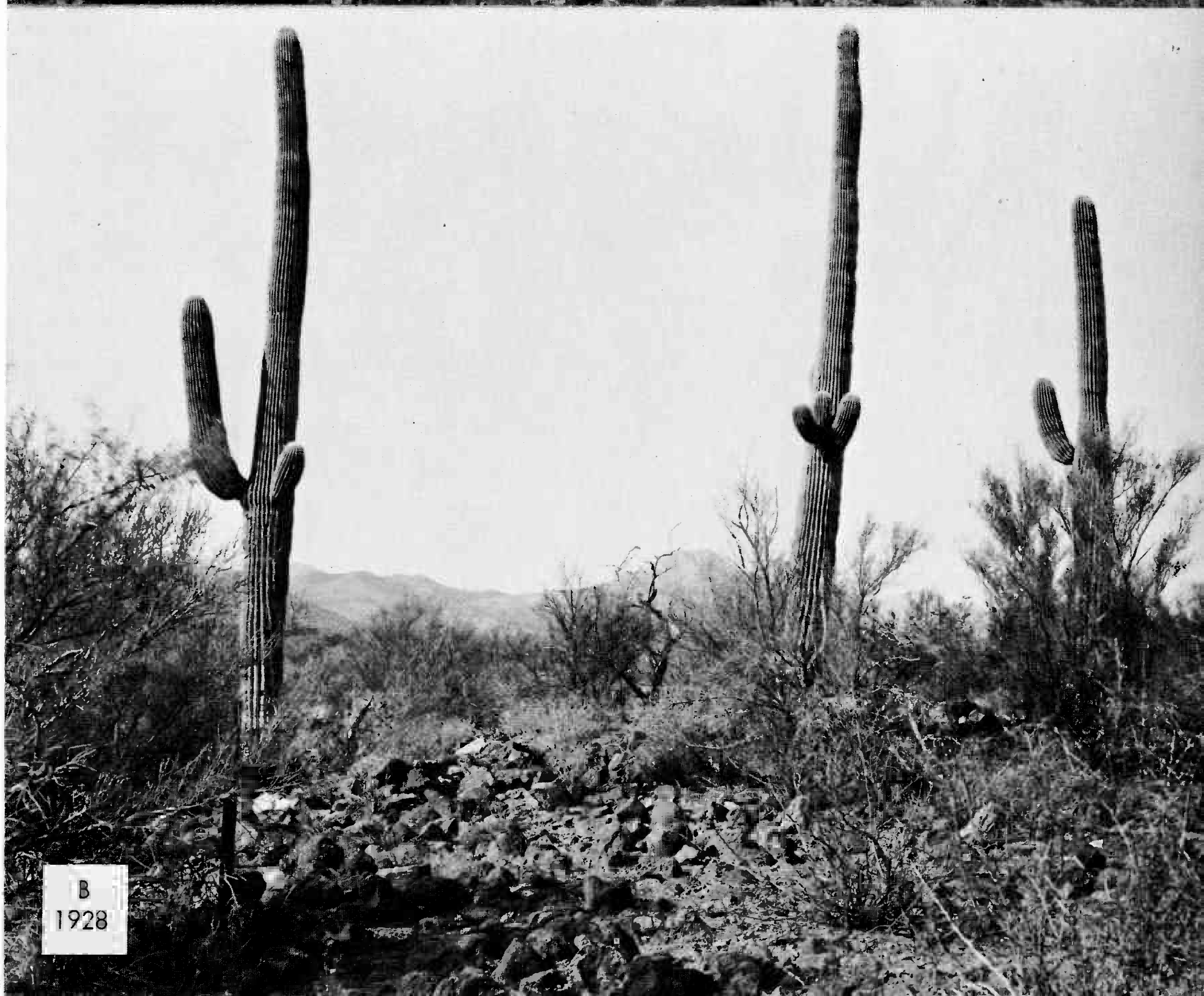


Figure 9. Study plot in foothills of Tucson Mountains, 2500 ft. elevation, showing a direct repopulation, without succession, of creosotebush (Larrea tridentata), foothill paloverde (Cercidium microphyllum), white bur-sage (Franseria deltoidea) and other species of the climax, following removal of the vegetation (foreground in front of white cord line) approximately three years earlier.


A
1906


B
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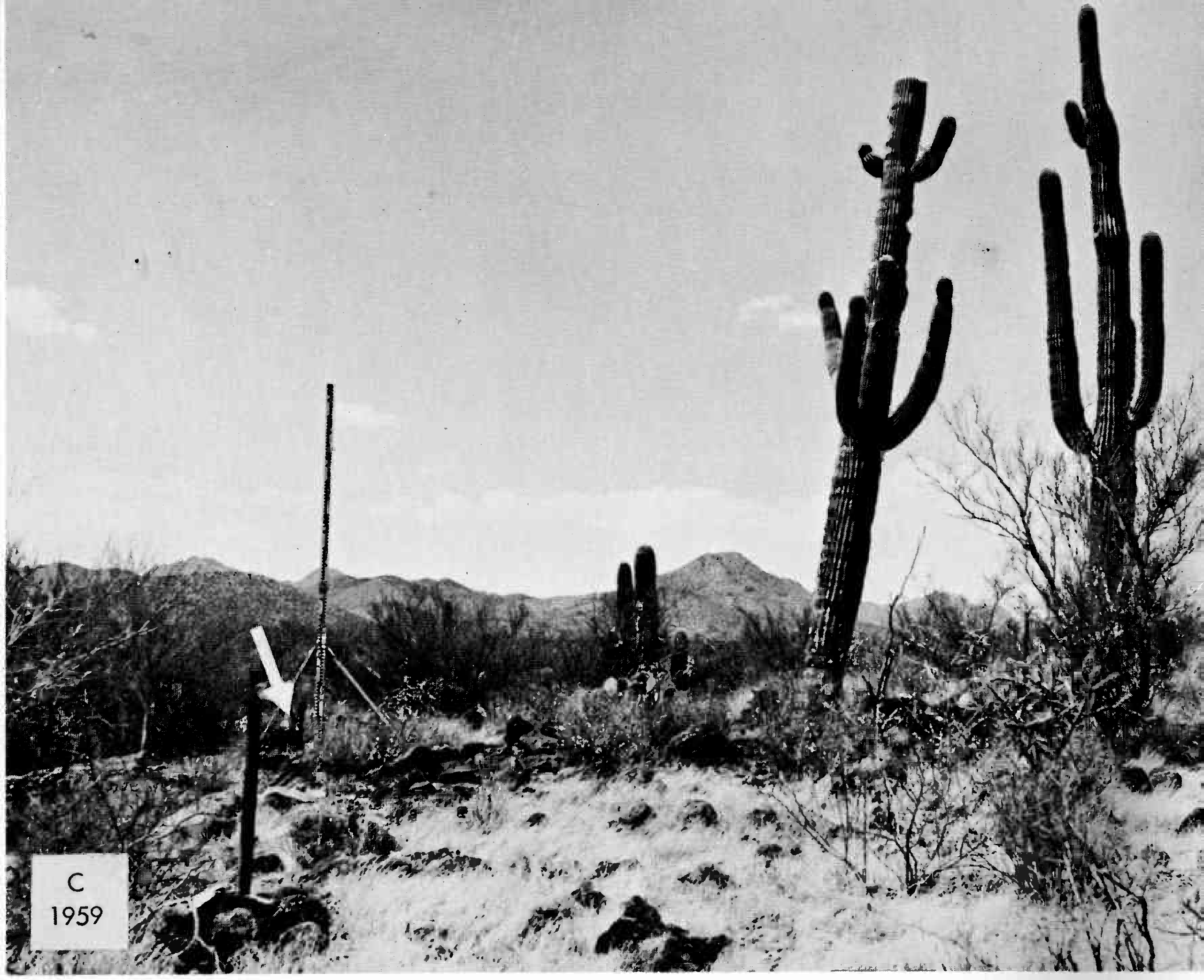

Figure 10. Rephotographs of vegetation on Shreve's Area 15 in the "Garden" of the former Carnegie Desert Laboratory at Tucson. A and B are from Shreve (1929). C, photographed by J. R. Hastings. Arrow in C points to stump of saguaro which fell in 1958; see text.

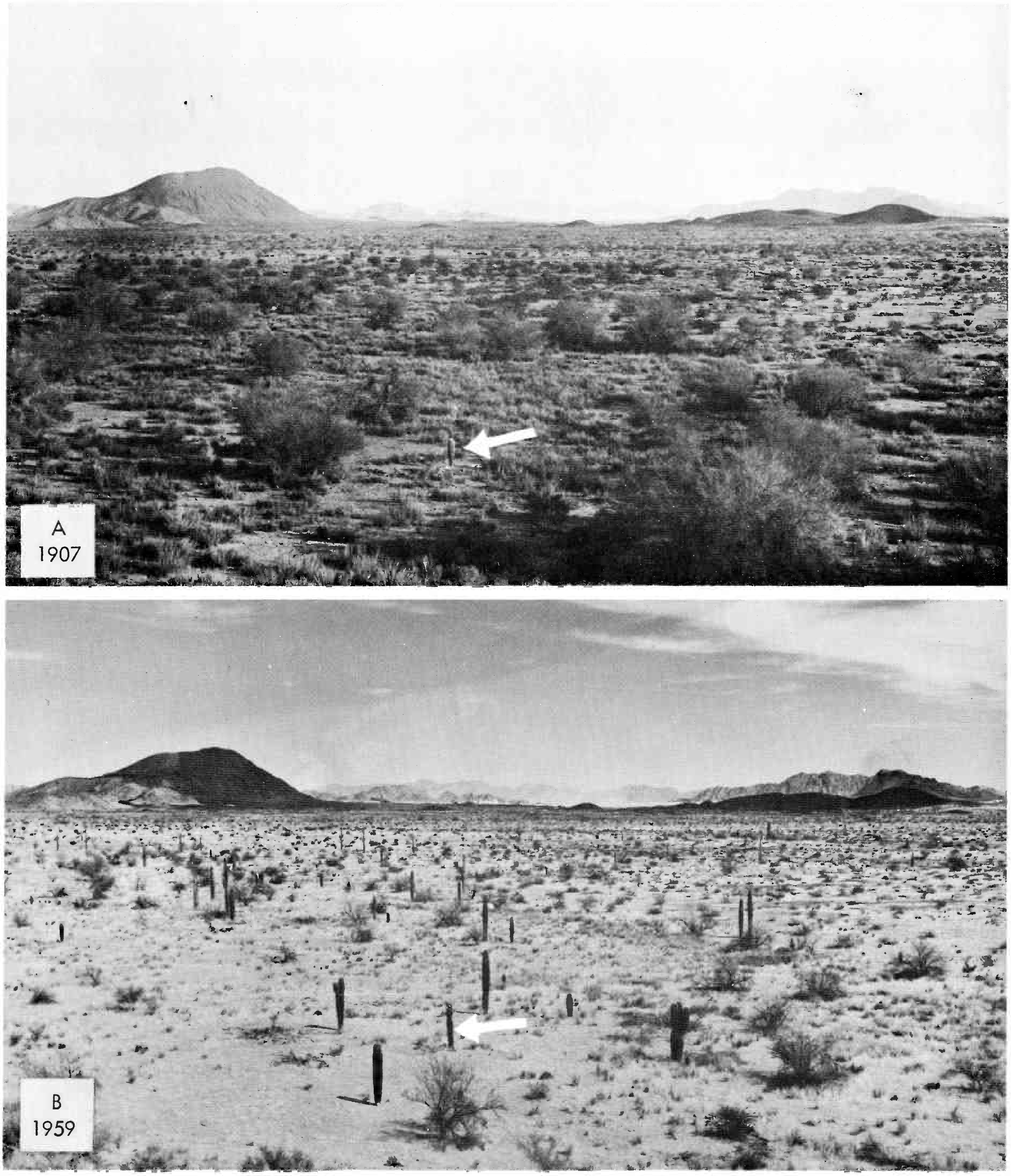

Figure 11. Rephotographs of vegetation in MacDougal Pass, northern gateway to the Sierra Pinacate in northwestern Sonora, Mexico. A, by D. T. MacDougal. B, by J. R. Hastings. White arrow in B points to a dead saguaro that is the live plant viewed in A. See text.

pleasures of their own generation. In addition to their writings they have left us a valuable heritage in the form of an excellent and painstakingly acquired photographic record of landscape events shortly after the turn of the century.

Summary and Conclusions

Deserts are unique environments and desert ecology is relatively little understood. The facts for populations and communities of desert-adapted species are often inconsistent with classical theory developed over the past half-century as the peculiarly deductive American ecology.

It is beyond reasonable doubt that characteristic species, if not the majority, of plants and animals living today within and marginal to the southern limits of the Sonoran Desert and other deserts in both the Eastern and Western Hemispheres, have been ultimately evolved from warm-adapted essentially tropical and subtropical stocks.

Organisms constituting major portions of the natural communities of the Sonoran Desert are controlled in their ecologic and geographic distributions by climatic and edaphic factors in which the extremes of these factors may be more critical than the means or other measures of central tendency.

Deductively arrived classical conclusions pertaining to the so-called community monoclimax and polyclimax are inconsistent with the facts for Sonoran Desert environments. In the Sonoran Desert specifically different soil attributes characterize, and are intimately associated with, distinctly different major climax vegetation types existing under the same macroclimate.

While a prevailing tacit assumption in American ecology is that "succession is a universal phenomenon," ordered succession (*sensu* Clements) in the desert environment is absent--there is but direct development and change.

Basic to the future management of desert lands is an understanding of the vegetation that desert soils are now supporting, what they supported prior to their use by domestic livestock, and why present vegetation grows to the exclusion of other vegetation types.

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METABOLIC PROBLEMS IN DESERT ORGANISMS

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Introduction

The self-maintenance of living material under the conditions of stress common to arid lands is importantly concerned with the presence of water and the ecological cycling of essential nutrients. Both water and essential metabolites may frequently be in very short supply in arid lands areas. Also to be fully appreciated are the vitally important influences of temperature, light, and population interactions upon the transfer of molecules needed for growth and maintenance in the desert.

It is the aim of these investigations to attempt to elucidate some of the mechanisms and rates of certain inorganic ion movements within the natural desert community. Initially, we have attempted to gain some information on ion accumulation and retention in desert homoiotherms (rodents), desert poikilotherms (lizards), and young cacti and other plants under isolated conditions. The following is a brief discussion of some pilot experiments.

Ion Retention in Desert-Marigolds (*Baileya multiradiata*)

Preliminary studies were first undertaken with young desert-marigolds planted in an adobe desert soil in laboratory jars, (1) in an attempt to evaluate the effect of this soil on ion availability to the plant when P^{32} was introduced with surface water, and (2) as a preliminary step in cycling through herbivorous animals. Although massive quantities of isotopes were used (up to 1 mc.), no accumulation within the plant was measurable even when water equivalent to two inches of rainfall was placed upon the soil surrounding the plant. This indicated a need for further study on ion movement through specific desert soils, an interdisciplinary study that is being undertaken.

Radioactive Retention in the Chuckwalla (*Sauromalus obesus*)

Although a considerable literature exists on the uptake, accumulation and release of radioactive iodine in the rodent and in man, only scant attention had been paid to iodine metabolism in cold-blooded organisms which are very desirable experimental subjects for the study of vertebrate response to thermal stress. The ecological aspects of iodine translocation also have been neglected in this group. In the desert environment where growth may be exceedingly slow, it is of the utmost importance to determine where metabolites are located, how long they stay where they are, and what kinds of biological competition they encounter, particularly under conditions of stress. Only then can life cycles be fully understood and the knowledge of them utilized.

Radioactive iodine is an isotope of choice in studies of ecological cycling because of its accumulation in specific tissues, its speed of turnover, and its easy measurement. Also, today, this element is part of the contamination burden coming from atomic detonations and reactor operations. In certain circumstances this material may enter very rapidly into the dynamic cycle between soil, plant and animal.

Sauromalus is a large, herbivorous iguanid ideally suited for laboratory investigations of this type. In this study, a series of eight animals was used. They were maintained in the laboratory for one month at room temperature (25°-28°C.) and fed prior to the introduction of I^{131} but not subsequently during the experiment. Four were males, three were females and one was a juvenile of undeterminable sex. During the experiment, cloacal temperatures varied from 25.9° to 28.8°C. Radioactive iodine, as the carrier-free isotope in sodium sulfite, was injected intraperitoneally about two cm. anterior to the vent through the left ventrolateral surface. Two concentrations were employed: 10^{-1} and 10^{-3} μc/gm of animal tissue.

Iodine concentration in the thyroid area was measured daily by means of a deep-well scintillation detector for periods up to sixty days. Analysis of the iodine accumulation in this area revealed that the maximum accumulation occurred in two days (Figure 1) and that the time required for the radioactive element to be diminished by 50 per cent (the effective half-life) varied from 11 to 17 days. Neither sex nor isotope concentration appeared to influence the effective half-life.

The effective half-life was influenced, however, by body weight (Table 1). As the weight of the animal increased, so did the effective half-life. Weight loss up to 33 per cent of initial weight was found unrelated to either isotope concentration or effective half-life.

TABLE 1

Iodine Metabolism in the Chuckwalla (Sauromalus obesus)

Specimen No.	Sex	Initial Wt. in Grams	Dosage I^{131} in μc/gm	Effective Half-Life in Days
1	Male	185.8	10^{-3}	11.0
2	Female	218.3	10^{-3}	12.0
3	Male	354.1	10^{-3}	15.0
4	Female	265.5	10^{-3}	17.0
5	Juvenile	77.1	10^{-1}	9.5
6	Female	260.5	10^{-1}	12.5
7	Male	303.1	10^{-1}	15.0
8	Male	327.8	10^{-1}	17.0

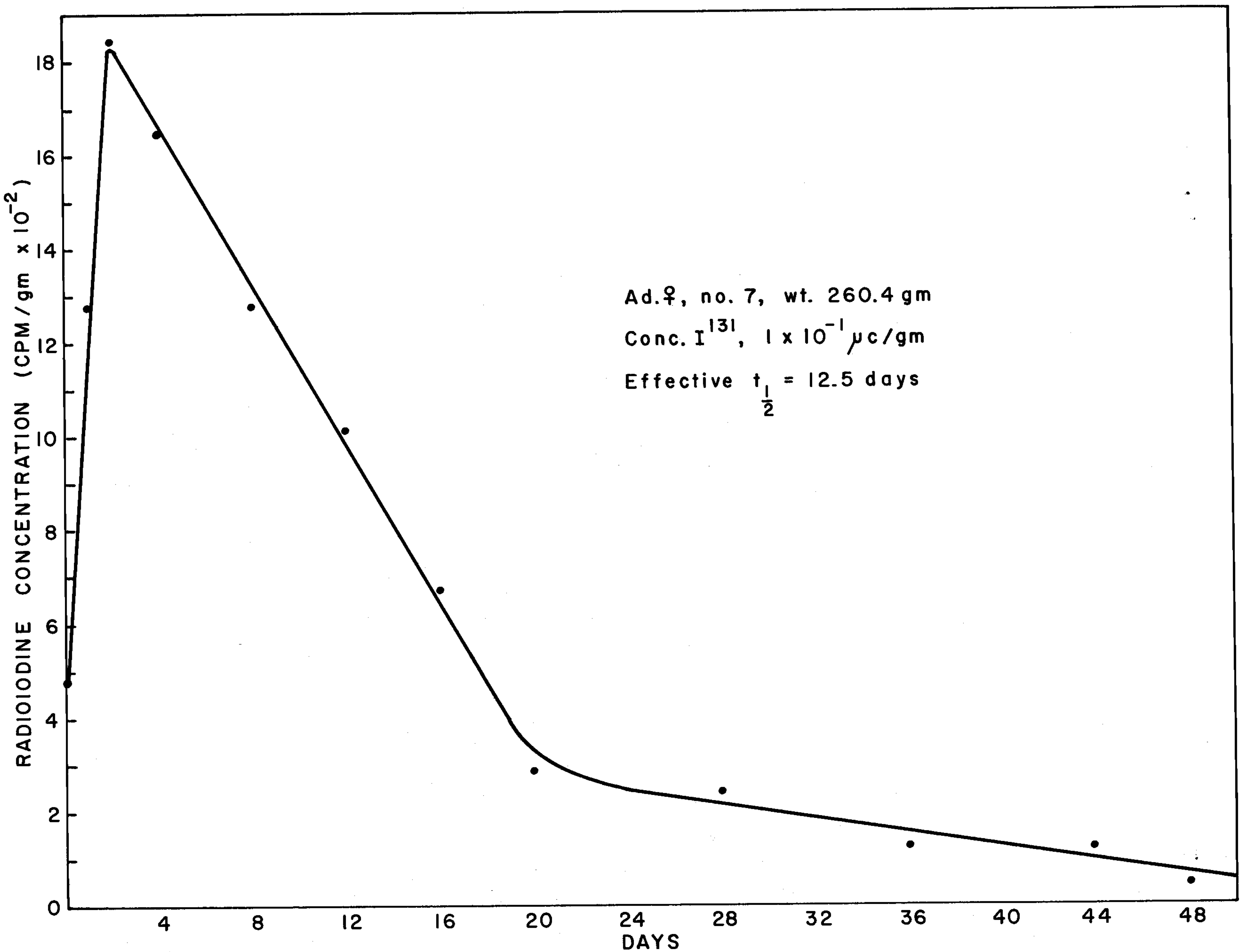

Figure 1. Radioactive accumulation in the thyroidal area of the Chuckwalla (Sauromalus obesus).

From two days to approximately twenty days after injection of the radioactive iodine, the amount of I^{131} in the thyroid area was found to decrease rapidly at a steady rate (0.8×10^{-2} cpm/gm/day). Since this curve after two days represents both the radioactive decay of the iodine plus the biological rate of turnover, its true meaning is not immediately apparent. However, since small amounts of I^{131} may damage thyroid tissue, the thyroid, after a few days, may no longer be active in the biological release of iodine. Thus the change in rate of iodine release after as much as twenty days is probably due only to radioactive decay. Further experimentation is designed to study this characteristic.

Localization of Radioactive Iodine in the Gila Monster (*Heloderma suspectum*)

Five adult gila monsters, varying in weight from 328.5 to 491.5 gm, were injected with 0.1 μc/gm of I^{131}. Injection procedure was the same as used with *Sauromalus* (above). One of the animals was kept at 21°C. (room temperature), two were placed at 5.5°C. and two at 35.5°C. After 48 hours the animals were measured for I^{131} content in the thyroid area (Table 2), then sacrificed samples of twenty different tissues and organs were removed, dried to a constant weight at 80°C., and then placed in plastic tubes for measuring I^{131} activity in a deep-well scintillation detector.

TABLE 2

Iodine Metabolism in the Gila Monster (*Heloderma suspectum*)

(Concentration I^{131} = 0.1 μl/gm)

Specimen No.	Body Temperature	Body Weight In Grams	48 Hr. Measurement cpm/gm Thyroid Area
1	5.5° ± 1.0° C.	328.5	5601
2	5.5° ± 1.0° C.	484.9	4520
3	35.5° ± 1.0° C.	380.4	4400
4	35.5° ± 1.0° C.	491.5	2480
5	21.0° ± 1.5° C.	480.6	6610

The activity of the structures measured was lowest in the tail fat from animals maintained at the two stress temperatures, and highest, as expected, in the thyroid (Table 3). The abdominal fat showed considerable activity in the animal kept at 21° C., (within the eccritic thermal range of the species), but this material was almost totally lacking in activity in animals under high and low thermal stress (Table 3). A further analysis of the data is summarized in Table 4.

TABLE 3

Iodine Localization in *Heloderma suspectum*

At 21.0 $\pm$ 1.5°C., and

During Stress at 5.5 $\pm$ 1.0°C. and 35.5 $\pm$ 1.0°C.

Tissue	cpm/gm X 10^3, 48 Hr. Exposure				
	5.5°C.		35.5°C.		21.0°C.
	No. 1	No. 2	No. 3	No. 4	No. 5
Tail Fat	24	36	27	29	346
Large Intestine	107	1083	320	771	925
Liver	222	355	91	157	1050
Abdominal Fat	239	12	2	14	4597
Abdominal Skin	381	489	330	324	416
Poison Gland	401	438	162	37	628
Pancreas	420	254	157	274	345
Ovary	546	---	340	849	---
Testis	---	777	---	---	742
Tongue	631	514	307	656	525
Ventricle	709	500	148	315	220
Lung	804	996	352	521	1695
Trachea	932	254	263	341	265
Gall Bladder	1019	1335	1797	326	1049
Ileum	1017	902	407	966	914
Buccalpharyngeal Membrane	1270	934	487	568	525
Bladder	1571	1083	327	824	9
Kidney	1587	704	482	737	1024
Spleen	1740	538	390	342	24
Stomach	3499	742	4892	588	812
Thyroid	----	---	42,290	87,742	---

Phosphorus^{32} Accumulation in Saguaro Slices (*Carnegiea gigantea*)

A series of ten young saguaros, measuring approximately 10 cm. in height, were used for this study over a period of two weeks during November, 1958. Two transverse slices were taken at the midsection of each plant stem. These were weighed and placed at room temperature in 100 ml. of distilled water containing 1 μc/ml of radioactive phosphorus. The average weight of the

TABLE 4

Summary of Iodine Localization in <u>Heloderma</u> <u>suspectum</u>

At 21.0 ± 1.5°C., and

During Stress at 5.5 ± 1.0°C. and 35.5 ± 1.0°C.

Ranges of Activity (cpm/gm X 10^{-3})	5.5°C.	35.5°C.	21°C.
Very Low (0 - 100)	Tail Fat Abdominal Fat	Tail Fat Abdominal Fat	Bladder Spleen
Moderate (300 - 1000)	Poison Gland Abdominal Skin Pancreas Tongue Gonad Heart Lung Trachea Gall Bladder Ileum	Large Intestine Abdominal Skin Gonad Tongue Heart Lung Ileum Buccalpharyngeal Membrane Bladder Kidney Spleen Poison Gland	Tail Fat Abdominal Skin Poison Gland Pancreas Gonad Tongue Gall Bladder Ileum Buccalpharyngeal Membrane Kidney Stomach
High (1200 - 1500)	Buccalpharyngeal Membrane Bladder Kidney Spleen	Gall Bladder	Lung
Very High (3000 - 90000)	Stomach Thyroid	Stomach Thyroid	Abdominal Fat Thyroid

slice was 10 gm. The slices were checked for radioactivity at 15 minute intervals for the first hour and at 2, 4, and 8 hours subsequently. Very rapid ion uptake was noted during the first half hour (Figure 2) with a secondary slower accumulation during the next 7-1/2 hours. Prior to each measurement (by scintillation detection), all slices were carefully washed free of external radioactivity in running tap water.

Further experiments are in progress (1) to localize the activity within the slice, and (2) to evaluate the efficiency of the standard washing procedure.

Phosphorus^{32} Accumulation in Young (2-Year) Saguaros (*Carnegiea gigantea*)

In this series, twelve intact plants were tested for the accumulation of radioactive phosphorus in distilled water over a period of 24 hours. The influence of the natural, fluctuating environment was also studied for its effect as compared to incubation in the dark at a constant chamber temperature of 25°C. (Table 5).

In both instances, the stems were discovered to take up similar amounts of activity. The roots, however, became nearly twice as radioactive when the plants were placed under outside conditions. Figure 3 illustrates the experimental apparatus employed in this and in other experiments on young saguaros.

TABLE 5

Comparison of P^{32} Accumulation in Saguaro Roots and Stems,

24-Hour Uptake (Concentration P^{32} = 0.1 μc/ml)

Environment	cpm/gm/hr	
	Stem	Roots
Incubator (25°C.; no light)	42.5	4205.0
Outside (April; sunlight)	42.6	9094.1

Phosphorus^{32} Uptake in Eight-Year-Old Saguaros

Eight-year-old saguaros were used to determine whether phosphate (P^{32} labeled) would be transported upward when injected into the root near the base of the stem. In the first plant, 10 μc of P^{32} were placed in a small hole made with a 5 mm. cork borer. An end-window Geiger tube and a standard Nuclear-Chicago Scaler showed no movement even after two days. Into the second plant, 50 μc of P^{32} were injected. No movement of radiophosphorus could be detected even after one month. Both of these experiments were conducted under ordinary room conditions.

Comparative Accumulation of Radioactive Calcium, Strontium, Iron, Yttrium and Zinc in the Saguaro

Small 2-3 year old saguaros were used in this study. The roots were carefully washed and were then placed in solutions of various isotopes. The isotopes (Ca^{45}, Sr^{89}, Fe^{59}, Y^{91}, Zn^{65}) were all used at 0.1 μc/ml concentrations. Counting efficiencies were calculated for the detection of these isotopes with a scintillation detector. After two days exposure, the plants were removed from the radioactive solution for determination of ion accumulation. The roots, as expected, exhibited the greatest amount of activity in all instances (Table 6), with yttrium taken up to the greatest degree (30.8×10^{-3} μc/gm/hr).

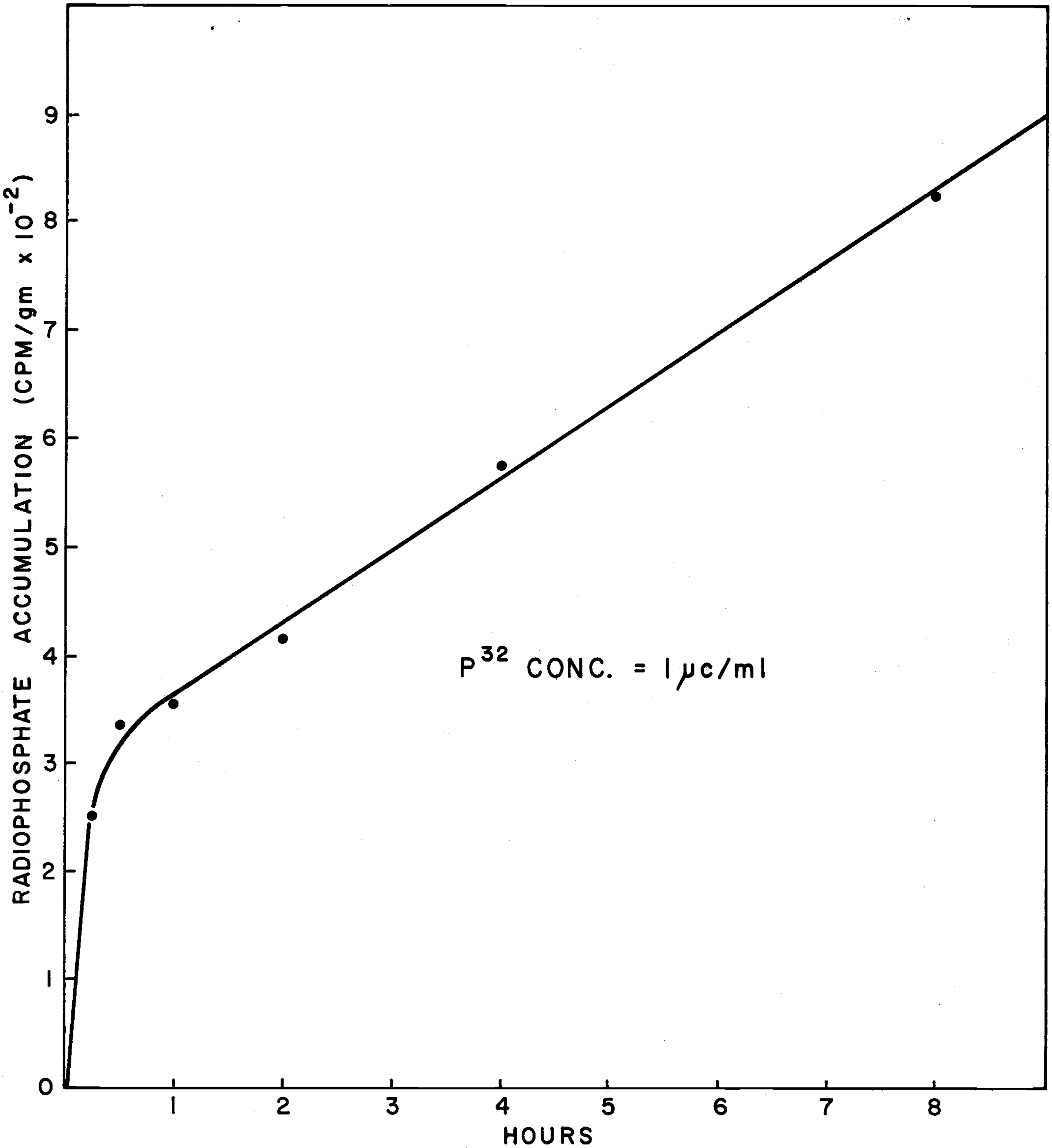

Figure 2. Radioactive accumulation in tissue slices of the Saguaro (<u>Carnegiea gigantea</u>).

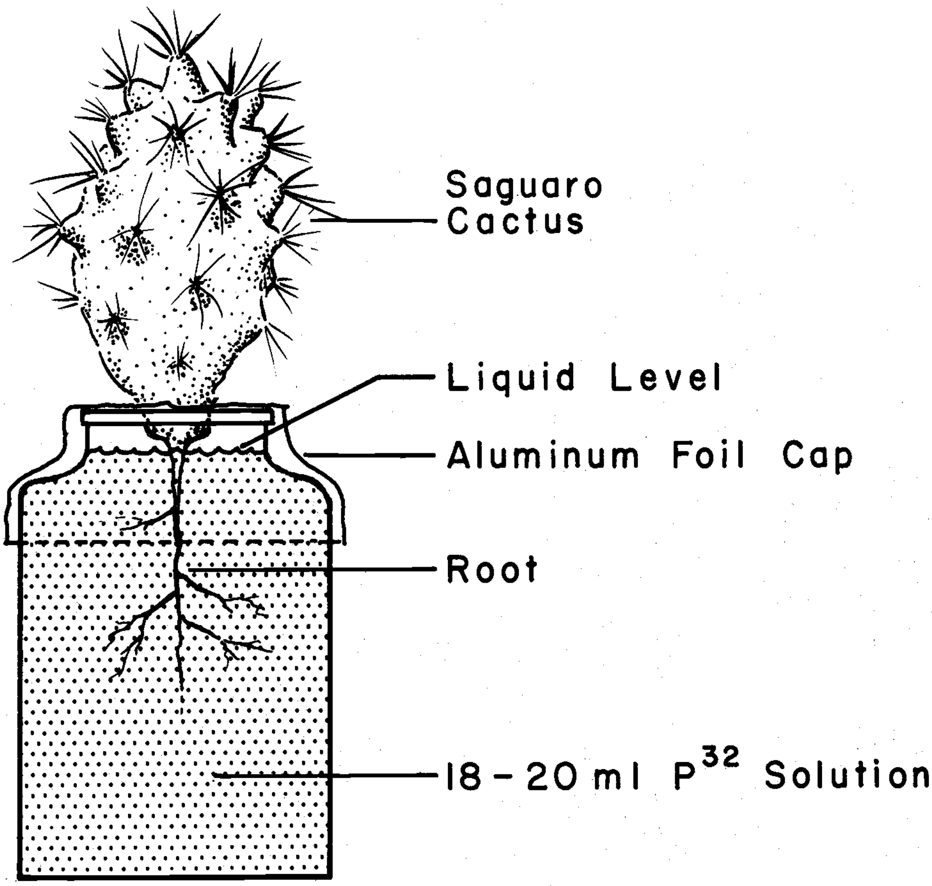

Figure 3. Experimental apparatus for studying P^{32} uptake in young Saguaros (*Carnegiea gigantea*).

TABLE 6

Comparative Ion Accumulation in *Carnegiea gigantea*

48 Hour Exposure

Isotope	t-1/2 (days)	$\mu c/gm/hr \times 10^{-3}$	
		Stem	Roots
Ca^{45}	163	1.1	2.0
Sr^{89}	53	0.4	15.6
Fe^{59}	45	0.3	15.5
Y^{91}	59	0.3	30.8
Zn^{65}	250	0.9	11.8

General Discussion

Isotopes of iodine, phosphorus, calcium, iron, zinc, strontium and yttrium were employed in order to study various aspects of comparative uptake and accumulation. Iodine, zinc, strontium and yttrium were selected because of their increasing importance as contaminants from atomic fallout and their possible subsequent entrance into ecological cycles.

Yttrium and iodine, in particular, are of interest here because of their rapid and selective incorporation into animal tissues and their availability to plants via urinary excretion. These properties of these elements make them especially interesting as tracers for ecological cycling. The degree to which Y^{91} was accumulated in cactus roots makes it also of considerable interest. Phosphorus, as an indicator of general metabolic activity, calcium, because of its role in growth and permeability, and iron, with the part it plays in respiration, are also of interest in evaluating general properties of protoplasm important in influencing biological cycling.

Pilot experiments have been partially successful in feeding radioactive plant material to desert-adapted rodents. The next phase of this investigation will involve a continuation of the labeling of small succulents with important trace elements and the study of their subsequent cycling in desert rodents. Retention time, effective half-life, and turnover rates of these elements will be studied in both plants and animals. It is planned that simulated natural communities may then be constructed in the laboratory in order to permit analytic evaluation of elemental presence and cycling. Factors possibly influencing this cycling such as population structure, temperature, light, moisture, and soil structure are to be investigated.

PRESPANISH HUMAN ECOLOGY IN THE SOUTHWESTERN DESERTS

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The following remarks do not represent final conclusions on the complicated subject of interrelationships between man and his environment in the arid Southwest, but rather are speculative and programmatic. It should also be mentioned at the outset that human ecology is fundamentally different from plant or animal ecology because of the important fact that man can change his behavior systems rapidly and profoundly through changes in his culture--the infinitely adaptable learned patterns of action that distinguish human activities from those of all other organisms. Therefore, human behavior is not a near-constant in its relation to a given environment, but can change radically and almost instantaneously.

The Southwestern desert is a particularly promising area for human ecological analysis. This promise derives from the fact that research into prehistoric periods has already provided the general outlines of a long span of human occupation.[1] Furthermore in historic times and even to the present day, some of the descendants of the desert-dwelling population have survived and their cultures are known in far more detail than could ever be known through the archeological record.[2] By inference from these recent data, it is possible to sketch in man's past in the area with some confidence.

In order to understand the ecology of the past it is convenient to divide the known span of human occupation into several phases or periods each characterized by cultural attributes distinct from those of the other periods and derivable from the evidences of the archeological record or from other disciplines. For our purposes it is fortunate that subsistence techniques comprise an aspect of human activity that archeologists are usually able to define in some detail, since they also are basic to understanding man's relationship with his environment. For convenience, the following four large time periods can be defined for the Southwest.

1) Period of hunting big game from the time of man's first arrival in the area more than ten to twelve thousand years ago to about 6000 B.C.

2) Period of gathering food from wild plants (with hunting continuing on a limited scale), from about 6000 B.C. to about 2000 B.C.

3) Period of initial agriculture (with hunting and gathering both continued), from about 2000 B.C. to about A.D. 500.

4) Period of developed agriculture (with hunting and gathering continuing), from about A.D. 500 to the present.

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[1] Convenient summaries will be found in Wormington, 1947, 118-47; Haury, 1945, 204-13; Haury, 1950, 3-21; Haury, 1957; Gladwin and others, 1937, 247-69. A somewhat divergent interpretation of the data is presented in Di Peso, 1956, 559-68. The shortcomings of ecological analysis in an area lacking such full prehistoric data are illustrated well by Rochefort, 1957.

[2] See, for example, Spier, 1933 and 1936; Gifford, 1933; Underhill, 1939; Spicer, 1949; and Russell, 1908.

Since the changes in subsistence patterns were gradual, with older techniques persisting together with the new, these periods merge at the boundaries. Also, agriculture could never be practiced as widely as could the gathering of wild foods, so that the third and fourth periods also involve a smaller area, with older techniques persisting in marginal areas.

In order to make valid inferences about the human ecology of these four periods, the following classes of information are needed:

1) Data on the environment of each period, and on the resources available to man--regardless of how they were exploited.

2) Data on the subsistence basis or bases of the human population in each period, including details of the foods used and the techniques by which they were acquired, stored, and prepared.

3) Data on the localities preferred by the human population for each period, for its subsistence activities and its dwellings. This would include information on movements of a seasonal or long-term nature, and on settlement patterns.

4) Estimates of population density in each period.

5) Evaluation of the effects on the environment of human activities in each period.

Although we are far short of having all these data for each period, we can proceed to a consideration of the human ecology of the region, using such information as is available and recognizing the uncertain nature of some of the guesses with which facts must be supplemented.

Period of Big Game Hunting

Data from the Naco (Haury, Antevs, and Lance, 1953), and Lehner (Haury and others, 1959) sites in Arizona indicate that large grazing animals, particularly the mammoth, were regularly hunted and killed. A single mammoth would feed a family or band for a couple of weeks or more, assuming that techniques were known for drying and curing the meat to retard spoilage. We cannot be sure, however, to what extent these hunters also made use of the many wild plants of the region; it is probable that the hunting of big game was the focal point of their life but that a very important part of the diet was vegetal. At the Lewisville site in Texas (ignoring the controversial nature of its chronological assignment) seeds of the hackberry tree and a large assortment of small animals were used to judge from the hearth and refuse material (Crook and Harris, 1958). Similar evidence will probably be found in the Southwest, if a camp-site, rather than a kill-site, should ever be discovered.

The climate of this period was cooler and more moist than at present, (Miller, 1958) so that a sizable population of large game animals could be supported. A human family or band probably had a number of favorite and habitual camping areas convenient to the streams and ponds where they knew that game could be found. In addition, it undoubtedly roamed over a considerable area in search of berries and seeds, and with an intimate knowledge of the area and its resources could arrive at each productive locality at the particular time its plant products were ripe.[3]

Population density can only be estimated in the roughest way. If the southern half of Arizona has largely grassland, supporting herds of herbivores, we can assume a population at least as dense as that of the Caribou Eskimo of inland Canada, whose mainstay was the large caribou herds. The Caribou Eskimo density was about one person per 100 square miles, (Kroeber, 1939: 134) which would permit a population of 500 to 600 people in a region the size of half of Arizona. Since vegetal resources were greater in the Southwest than on the tundra, temporary fluctuation in animal population would have a less drastic effect on human inhabitants, and the regularly available food supply would be more varied and abundant. Thus a density three to five times greater is not unreasonable; the buffalo-hunting Kiowa and Kiowa Apache had a density of about seven per 100 square miles, (Kroeber, 1939: 139), but the exact figure is less important than the fact that small groups of people were very widely scattered, therefore having minimal contacts. Also, the mobile way of life with a simple technology prevented the development of large groups, thus inhibiting social complexities and technical specializations. Therefore, over a long period, few innovations in the way of life would be expected, and these few would spread only slowly.

Finally, considering the effect of man on his environment, there is little doubt that man at least hastened the extinction of such large animals as the mammoth, bison, and horse, (Sellards, 1952, 115-16; Jelinek, 1957; Williams, 1957) even though the reduction of grasslands and water supplies as a result of climatic change may have been the more important cause. As desiccation became more severe, culminating in the Altithermal, the dwindling herds may have been quite rapidly killed off by man--a drastic and irreversible change in an aspect of his environment that was of a particular importance to him.

Period of Gathering Food From Wild Plants

Whether gradual or rapid, the extinction of the major game animals necessitated a profound readjustment in the life of mankind in the area of the Southwest that was developing into the modern desert. Whereas plant foods had formerly been a supplement, they were now the major dietary resource. Hunting of small animals continued, and in restricted areas where large game lingered a bit longer the old life-ways could have continued. However, technological innovations may have also influenced man in his shift to greater use of plant food; many kinds of small seeds available in quantity are palatable only after proper preparation, and the discovery of these techniques was essential. Seeds with a hard exterior will pass through the human digestive system unmodified, but after parching (by deftly rolling a few hot coals among the seeds for example) they are a quite satisfactory food. Over the centuries the potentialities of each plant came to be known, through experimentation motivated sometimes by curiosity and sometimes by the threat of starvation, and the result was more and more complete use of the total plant resources of

[3]Such inferences are based on aboriginal groups in many parts of the world; see, for example, Howitt, 1904; Spencer and Gillen, 1927; Okada, 1955; Peabody Museum, 1958; Marshall, 1958; and Thomas, 1959.

the region. Castetter (Castetter, 1935) has listed 210 native wild plants used by the Southwestern Indians, of which a large number were available and used in the desert area.

Archeologists have recently applied the term "Desert Culture" to this way of life, recognizing its importance as the basis of a number of later locally elaborated patterns of culture (Jennings and Norbeck, 1955; Jennings [ed.], 1956). In Southern Arizona the Cochise Culture, studied in detail for the past quarter century by several archeologists (Sayles and Antevs, 1941), is now seen to be a manifestation of this widespread Desert Culture. The characteristic remains of Cochise camp-sites are large grinding stones, used in the preparation of many kinds of vegetal food. But in the earliest stage of the Cochise sequence, the Sulphur Spring stage, hunting was still a relatively important activity, as indicated by the presence of bones of mammoth, horse, dire wolf, and camel, as well as deer, rabbit, and coyote. In later stages the emphasis on plant foods steadily increased, however, and from Central Mexico to the Columbia Plateau, life was primarily focused on the search for fruits, seeds, roots and shoots.

With surface water much more scarce than in the previous period, man's movements were quite closely controlled by his need for drinking water at frequent intervals and by his lack of large-scale or permanent storage facilities. A pitch-lined basket or a gourd could at best give a family only a few sips of water, and weight would preclude the carrying of water in quantity any great distances. With knowledge of the seasonal characteristics of all the streams, springs, and seeps in its neighborhood, a group could move confidently over a well-planned annual circuit in order to make maximum use of plant resources. The modern Papago exemplified such a life until recently, except for his partial dependence on agriculture (Castetter and Underhill, 1935; Castetter and Bell, 1942). Tribes of the Great Basin of Utah and Nevada, prior to recent acculturation, provide a closer analogy; their numbers and movements have been reported in detail by Steward (Steward, 1938, see especially 14-49, 230-7, and 258-62) who states that a typical range for a family was about 20 miles in all directions from their winter camp. Local topographic and vegetation conditions would cause variations from this average figure, but it is important to realize that "free wandering" is probably a figment of the imagination (see Meggers [ed.], 1956). Nevertheless, each group would be able to move over terrain that offered a variety of resources which the gradually elaborating technology would provide means for using effectively.

On the basis of Steward's figures for the Great Basin (Steward 1938, 46-9) and Kroeber's summary (Kroeber, 1939, 136-7) of Mooney's estimates, a population density of five or six people per 100 square miles is probably the minimum figure for the less attractive parts of the Southwestern deserts, and in some regions as many as twenty-five per square mile may have lived successfully. The increase in population density can be regarded as a reflection of man's more effective use of his environment, plant food being more widely available and often more plentiful in a dietary sense than game animals ever were.

The effect of the desert cultures on their environment was relatively slight. A widely dispersed population using a great variety of plant foods would not cause the extermination of any species, and indeed might disperse it more widely, even though a particularly popular plant might be temporarily scarce in a few localities.

Period of Initial Agriculture

Archeological evidence for the first stages of agriculture is slight, but several cave sites with C-14 dates suggest that by 2000 B.C. a few groups of people were growing maize, squash, and the bottle gourd.[4] These plants, however, were probably insignificant in food value and unimpressive in size, in comparison with their descendants today, and they were also probably grown only in small numbers, so that initially they formed only a minor supplement to the numerous wild plants in use.

It should be noted in passing that there is great difficulty in deciding whether a group practiced agriculture, unless the lucky accident of preservation in a dry cave plus indentification by a botanist provide sure evidence of domestic plants. With the introduction of agriculture, the assortment of grinding tools, basketry trays, collecting baskets, and so on changed little, and so gradually, that artifact types are not a safe basis for assuming the presence of domestic plants except in much later times. In reporting on caves in Tamaulipas (at the twenty-fourth annual Meeting of the Society for American Archaeology, Salt Lake City, April 30 - May 2, 1959) MacNeish commented that milling stones were so scarce in levels with radio-carbon dates of 5000 to 6000 B.C. that he would have inferred a hunting economy were it not for the presence of domestic peppers, pumpkins, gourds, and beans.

Gradual as it may have been, the introduction of agriculture eventually permitted (and required) groups who came to depend on it to spend much of the year at a place where moisture and soil made the growing of crops possible. Between planting and harvesting, most of the group could move away in search of wild plant foods, but the stored harvest could not easily be moved more than a short distance and would require a less mobile life. It was in these small groups which exploited agriculture effectively that cultural diversity and complexity developed most rapidly, as each adapted to a chosen locality.

The preferred areas for agricultural life would have been the mouths of small arroyos where moisture from the mountains spread over flat, silty areas, and also narrow strips along the permanent streams, the Gila and Salt, where spring flooding or abundant underground moisture permitted a crop to mature (Bryan, 1922 and 1929). It is important to realize that these favorable localities made up only a small fraction of the entire area--a nonagricultural life was the only possible existence for many groups depending on the perhaps 99 per cent of the region not included in these favorable localities. Because the area of farming was so small, the overall increase of population was probably slight, in spite of the concentrations that were beginning in favored areas. Likewise, man's effect on his environment in this period was little different from before, with the introduction of new species proceeding slowly and not involving the wide-spread distribution of weeds that characterizes present-day farming. (However, compare Anderson, 1952).

Period of Developed Agriculture

Up to this point the development in the Southwestern desert was little different from the developments that were occuring in much of the New World--slow and rather slight technological changes and the gradual development of somewhat larger, more settled groups in a few favorable spots. (See, for example, Willey and Phillips, 1958, 151-5). But from here on, highly distinctive cultural developments occurred, resulting in the unique cultural

[4]Cutler, 1952; Mangelsdorf and Smith, 1949; Dick, 1954; Whitaker, Cutler, and MacNeish, 1957; MacNeish, 1955 and 1958.

complex that has been termed the Hohokam, situated along the Gila and Salt and their tributaries and desert flanks.

The basis for intensive agriculture here was a suitable water supply and its control. Although the term "irrigation" is generally used for the techniques by which water is brought to the crops in arid regions, it is too specific a word for our discussion here, and implies certain techniques that may or may not have been used by particular prehistoric groups. Therefore the general term "water control" is preferred, with its implication of management of water regardless of the special techniques.

Water control in general may be considered as serving three main purposes: first, the diversion of excess water, to protect crops from flood damage in much the same fashion that protection from wind damage is accomplished in arid areas; second, the improvement of water distribution and retention on areas already being farmed, through the use of small spreading ditches, simple terracing, and small impermanent diversion structures in stream channels--all of this usually carried on by a single farmer during brief periods of rain or run-off; and third, the transport of water to areas otherwise not arable, by means of larger and more permanent ditches or canals. Very simple techniques would suffice for the first two purposes, and may have been practiced with the initial introduction of domestic plants from the south; in fact, in the Great Basin area simple water distributing techniques were used to improve the growth of wild plants, by people raising no domestic crops at all (Steward, 1929). The third kind of water control presumes an increasing dependence on agriculture, so that the need for additional farm land would justify the building of sizeable canals; it also presumes a population sufficiently large and socially unified to plan, build, and administer the program of agricultural expansion.

Archeological evidence for small scale, temporary water control systems will be almost impossible to secure. By analogy with modern Indian groups, such systems can sometimes be assumed, but their extent and details will be unknown. In Southern Arizona our first certain information on large scale canal building comes from the cross section of the Snaketown canal, dated to the Santa Cruz phase of the Colonial period, about A.D. 800 (Gladwin and others, 1937, 50-58). It is reasonable to assume that canals of possibly lesser extent were being built as early as A.D. 500, since the Snaketown canal is a large and complete structure, over ten miles long, and dug to a depth of about two meters, and a width of over three meters. If this canal provided water for a strip of fields extending a quarter of a mile each side of the main channel, it would have watered approximately 3000 acres. Many other canals as large as this have been recorded, although all were not contemporary (Halseth, 1932; Hodge, 1893).

Away from the Gila and Salt, major canal systems were impractical, but smaller systems of channels were developed to collect and distribute water from mountain slopes or ephemeral streams and to water farm plots a few acres in extent. Where possibilities for agriculture were limited, the gathering of wild plant foods continued as a major activity, so that a great variety of subsistence patterns was possible, each adjusted to a local situation (Castetter and Bell, 1942; see also Withers, 1944).

Population in the areas of intensive water control undoubtedly grew quite rapidly, although the large Hohokam towns were always rather widely dispersed. At its peak the population probably equalled and may have exceeded the figure of 10,000 estimated for the Pima and Papago of recent decades. In peripheral areas only slight increases over the previous period can be assumed.

In the areas of most intensive agriculture there may have been a major, and ultimately disastrous, effect on the soil, due to water-logging and the accumulation of minerals (Hayden, 1957, 113-15). Direct evidence of this is lacking, but comparable effects occur today. The decline in population which began by the fifteenth century may have been due in large part to the damage to farm lands that continuous irrigation brought about. Technological means were inadequate for bringing water to new and unaffected areas or for restoring the damaged fields, and agricultural productivity must therefore have declined sharply.

In summary, two major changes in man's adjustment to and exploitation of the Southwestern desert region have taken place, the first with the disappearance of large game and the climatic change to more arid conditions, the second with the development of elaborate water control techniques and the consequent great increase in production of food crops. This second change was made possible by an increasing population without which the division of labor, specialized technical skills, and necessary man power would have been lacking. At the same time, population growth and its social and technological concomitants were possible only with the water control techniques that have been briefly discussed. Thus a delicate balance between environment and cultural development grew up, only to be upset when man produced a change in his farm lands that he was powerless to prevent.

Two important questions have been omitted, mainly because they cannot be satisfactorily answered at present. First, what water control techniques were introduced from Mexico, either with the first domestic plants, or later to initiate the period of intensive agriculture? Studies of prehistoric irrigation in central Mexico have only recently been begun, (for example, Millon, 1957; Palerm, 1954 and 1955) and northern Mexico is still a major gap in our knowledge of water control. Second, how far were the techniques of water control that we have discussed for the desert area common in the mountain and plateau areas to the North? A partial survey of archeological literature suggests that canal, terrace, and ditch systems were more widely used in the Southwest than has been realized, and further research should make it possible to appraise desert farming techniques in the larger perspective of the entire prehistoric agricultural west.[5]

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[5]Such an appraisal was begun by the Soil Conservation Service, but has not been followed up by anthropologists; see Stewart, 1940, and Stewart and Donnelly, 1943.

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