UNITED STATES DEPARTMENT OF THE INTERIOR

Geological Survey

Effects of Nuclear and Conventional Chemical Explosions on Vegetation

by

H. L. Cannon, M. E. Strobell, C. A. Bush, and J. M. Bowles

Open-File Report 81-1300

CONTENTS

TABLES

ILLUSTRATIONS

Page

Page

Introduction

Studies in the Basin and Range Province of the elemental uptake by plants rooted in sediments and soils of variable salt content, by the U.S. Geological Survey, led inevitably to a study of the uptake of radionuclides and their effects on plant growth at the Nevada Test Site. In addition to studies at the Nevada Test Site, observations were made of nuclear explosions in northern Nevada, in Mississippi, and of large dynamite explosions at depth. The purpose of this report is to present a pictorial record of the observed effects on plants made from 1962-1970 above and around contained underground nuclear and chemical explosions, atmospheric nuclear explosions, cratering nuclear explosions, and partially contained nuclear explosions.

This report is a partial review of the observations of others and the observations made by members of the U.S. Geological Survey during the course of basic studies of the vegetation and soils in the Basin and Range. The study presented here is an attempt to establish criteria that could be used to identify and to separate physical effects from those of radioactivity on vegetation. It is not intended to supercede or to negate the work of others, but to supplement and to extend by a slightly different approach the ecologic studies that have been made at the Nevada Test Site. The senior author was responsible for field observation, collection of samples, and interpretation of results, Mary Strobell for autoradiographs, Charles Bush for isotopic analyses, and Jessie Bowles for wood sections. The authors wish to thank Frank Stead for his technical advice on the nuclear events and Richard Phipps for review and consultation on the wood sections.

Two basic studies are described in this report. First, the physical and radiation effects of contained and released nuclear explosions were studied over a period of 8 years as time and funds permitted. Locations of the study sites on the Nevada Test Site (NTS) are shown in figure 1. Second, the purely physical effects of geophysical explosions of 245-4,545 kg of dynamite exploded at depths of 14-150 m in various locations in Arizona were studied over a period of 4 years. The second study provides a background against which the effects of nuclear explosions in Nevada and Mississippi can be evaluated.

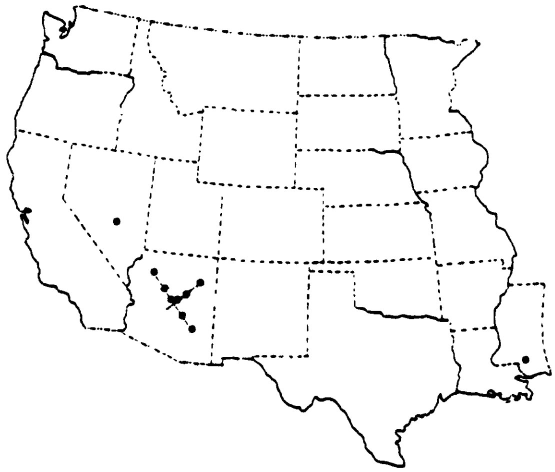


Figure 1.--Map showing botanical stations on Nevada Test Site with index map showing stations elsewhere in Nevada, Arizona, and Mississippi.

Glossary

alpha radiation--radiation from alpha particles that consist of a helium nucleus with a double positive charge, which is converted into an atom of helium by the acquisition of two electrons

atmospheric nuclear explosion--nuclear charge exploded above ground, as from a tower

autoradiograph--record of radiation from radioactive material in an object, made by placing the object in close proximity to a photographic emulsion

beta radiation--radiation given off by radioactive substances consisting of electrons that move with velocities varying from 30,000 to 180,000 miles per second. (More penetrating than alpha rays)

contained explosion--an underground nuclear explosion with no release of radioactivity to the atmosphere

count--(as by geiger or scintillation counter) external indication of a device designed to enumerate ionizing events

curie--amount of radioactivity generated by 1 gram of radium per second or 37 billion disintegrations per second

dose--radiation delivered to a specified organ or whole plant, measured in roentgens

event--the occurrence of a planned nuclear explosion

fallout--radioactive debris from a nuclear detonation, which has been deposited on the surface of the ground after atmospheric transport

gamma radiation--short wavelength radiation given off by radioactive substances, with a range of 10^{-8}-10^{-11} cm wavelengths emitted from the nucleus

gas erosional crater--crater in the ground surface created by underground erosion and elemental desintegration of soil and rock by gases formed during underground nuclear explosion

genetic mutation--a change in the characteristics of a plant produced by an alteration of the hereditary genes

half-life--time required for radionuclide to lose 50 percent of its activity by decay

rad--a unit of absorbed dose of radiation equal to 100 ergs of ionizing radiation per gram of the absorbing material

released explosion--a nuclear explosion accompanied by a release of radioactivity to the atmosphere

roentgen--that quantity of gamma radiation (or X-rays) which give rise to the formations of 2.08 x 10^9 ion pairs per cubic cm of dry air at standard temperature (0°C) and pressure (one atmosphere)

spectrograph, mass--a device for analyzing a substance in terms of the ratios of mass to charge of its components

subsidence crater--a crater in the ground surface over a contained nuclear explosion formed as a result of a primary surface mounding and delayed cavity collapse

throwout crater--a crater produced by the ejection of material above the explosion at a high acceleration

tree ring--annual increment in growth of wood composed of summer and winter vessels, which can be seen in cross section

Abbreviations used in report

c	-	curie
dps	-	disintegrations per second
dpm	-	disintegrations per minute
gm	-	gram

prefixes
k - kilo, 10^3
m - milli, 10^{-3}
M - mega 10^6
- micro 10^{-6}
p - pico 10^{-12}

pci/g	-	picocuries per gram
r	-	roentgen
t_o	-	time of explosion
t_o + 1 hr	-	1 hour after explosion etc
t + 1 d	-	1 day after explosion etc
$T_{1/2}$	-	half life

Effects of nuclear explosions on native vegetation

A nuclear explosion exerts a physical force and is accompanied by radiation that is released to the environment in varying degrees. Positive identification of physical effects on vegetative growth as opposed to effects from radiation is not always possible. In general, the effects are largely physical around a contained explosion that may result in extensive fracturing, and conversely are largely due to radiation in the extended path of the radioactive dust cloud of a vented explosion. The effects of radiation from long-lived radionuclides within plants continue for a much longer period of time than do many physical effects, so that coniferous trees may reach their limit of tolerance and die many years after the radioactive release at distances of several miles from ground zero, as observed at Blanca and Des Moines and reported herein. Deciduous shrubs subjected to large amounts of radiation, on the other hand, defoliate quickly in the immediate vicinity of the explosion but may, if not completely killed, recover after a prolonged period of dormancy. After the Palanquin explosion (NTS) sage was observed to be burned near the crater and the leaves of sage were wilted, and starting to die at distances as much as 600 feet from ground zero in the direction of radioactive cloud movement within 12 days after detonation. The latter did not appear to be burned but effected by high doses of radiation. Plant growth aberrations observed at the Nevada Test Site are much more diffult to interpret than those observed in laboratory or field experiments because they depend on the following variables: (1) containment and wind direction at time of detonation; (2) physical force of the explosion, both below ground and above ground; (3) thermal effects; (4) plant species composing the vegetative cover; and (5) distance of individual plants from ground zero. Rather than controlled radiation from a single source, we had at the Nevada Test Site alpha, beta, and gamma radiation from a series of fission products, radioactive tracers that had been added to the nuclear explosion, activation products induced from the natural rock materials overlying the device, and from the steel casings, wires and so forth that encased or were attached to the nuclear explosive during emplacement. The radiation levels were extremely high at the time of the explosion and decreased rapidly according to the half lives of the various radioisotopes. In this report, the word "contained" refers to underground explosions for which no radiation was detected at the ground surface immediately after the detonation or after the collapse of the ground in cratering explosions. If the explosion is not contained, then important effects on the vegetative cover are the number and quantity of the radionuclides that are released from the bomb or induced from the overburden, the distance that a given radionuclide can travel through the geologic materials above the explosion and through the atmosphere before disintegrating to a stable daughter nuclide, and the energy released by the various nuclides in radioactive decay. Finally, the species of the plant community are important, as those with furry or sticky leaves will catch and hold dust more effectively than smooth-leaved species, and each species varies in its ability to absorb and translocate particular radionuclides within the plant. These characteristics will affect the total dosage received. For these reasons, various kinds of plants growing near explosions that were detonated in different kinds of material were studied outward from ground zero wherever possible in order to observe and evaluate the different, and in some cases interdependent, factors affecting plant life.

Nearby plants are exposed to extremely high levels of radiation (measured in rads) immediately after a released explosion in which radioactive gases and dust are released to the atmosphere, and continue to receive a high degree of radiation insult as long as radioactive fallout remains on their leaves. Rhoads and Platt (1971) and Rhoads, Kantz and Ragsdale (1972) have shown that plants covered with a plastic tent before a released explosion continued to survive, indicating that fallout at time zero gave far greater doses of beta radiation than gamma radiation to plants. Both plant mortality and the beta levels decrease rather rapidly in the first few months (see data given in description of Palanquin explosion), suggesting that beta radiation from ^{45}Ca with a half-life of 165 days and ^{32}P with a half-life of 14.3 days are initially moe than that of ^{90}Sr with a half-life of 28 years, as curies of Sr^{90} at the time of detonation are only 127th that of the combined curies from ^{45}Ca and ^{32}P. (See table 7.) Long-lasting effects on vegetation however, result from the actual absorption of radionuclides, and, in this context, ^{90}Sr with its long half-life is indeed a harmful element of fallout. Leafy shrubs and trees near ground zero may defoliate and then remain dormant for considerable periods. When radiation levels in the plants and soils are sufficiently reduced--in some cases years after the explosion--dormancy is broken and the plants again leaf out, as in the case of oak near the Blanca crater. Conifers, however, are very sensitive to radiation and when their relatively low tolerance level is reached, the trees die. The time period also may be measured in years, depending upon the distance of the conifer from ground zero. Each year the areas of affected trees continue to increase outward from vented explosions on Rainer mesa.

Plant tolerance for radioactive soils

The ability of herbaceous plants to reestablish colonies in radioactive soils after nuclear explosions varies greatly depending on several factors. These factors include the physical characteristics of the seeds of a particular species, whether the seed remains undisturbed in the irradiated soil or is carried in by the wind after the explosion, the amount of actual throwout (cratering explosions) covering the existing seeds, and, finally, whether the seedlings can withstand the gamma and beta radiation that occur at that particular location. Salsola and the annual Bromus are among the most tolerant adventives.

A number of investigators from UCLA (the University of California at Los Angeles), who studied the late effects of the Palanquin explosion, suspected that beta rays might be more important in killing vegetation than gamma rays (Rhoads, Platt, Harvey, and Romney, 1968; Rhoads, Ragsdale, Platt, and Romney, 1970; Rhoads and Platt, 1971; Rhoads, Kantz, and Ragsdale, 1972). To test this theory, they covered certain plots with polethylene sheeting prior to the detonation of the Schooner explosion that was detonated in 1968. They found that the shrubs under polyethylene received 15 percent less gamma irradiation and 69 percent less beta irradiation and survived, whereas after 4 months the plants outside put out no new growth, after 5 months some vegetation was abnormal, dead or dying, and after 15 months were completely dead. Measurements with dosimeters at Schooner showed a ratio of 10-15 times beta to gamma measured in rads, and that plants were killed with only 150-200 rads of gamma. They concluded that beta damage is greater than gamma but that it is possible to protect from beta damage. The underparts of a large shrub may be protected from severe irradiation by the canopy afforded by the rest of the plant. It should be pointed out that the shrubs that were covered were also protected from the highly radioactive (beta and gamma) dust fall that otherwise would have been in direct contact with the plants.

The atmospheric explosions of the Plumbob series removed vegetation and a layer of soil, and at the same time covered the area with a layer of radioactive glass created from silica sand that had been added to the bomb. In spite of such adverse circumstances, Mentzelia albicaulis came up thickly the next spring as near as 0.3 km from ground zero, and species of Chaenactis, Gilia, Amsinckia and Cryptantha as near as 0.6 km. The summer annual Salsola iberica then invaded the denuded area and was dominant in subsequent years; Eriogonum nidularium later invaded the disturbed ground.

At the Palanquin site, an escaping radioactive cloud went north across an otherwise undisturbed mesa with the result that there was no throwout on the south side and plants were completely unaffected. Throwout was present for 180 m to the west and Chrysothamnus and Cowania died but Lupinus flavovaculatus and Phacelia fremonti, were in flower 75 days after the explosion 330 m from ground zero in soil reading 12 mr/hr. To the north, a scintillometer reading of 2 R was taken 180 m from ground zero where the first live but wilting sage was observed 12 days after the explosion. All vegetation was blackened and dead nearer to ground zero from heat as well as radiation.

Twelve days after the Palanquin explosion and 180 meters from ground zero, the ground was covered with 5 cm of fused glass and white dust, and the leaves of the sagebrush were hanging limp--the plants were dying. Thermal insult from the fused glass is not known. A reading of 2 R/hr (roentgens per hour) was taken 1 meter above the ground surface. The sage appeared healthy 300 meters from ground zero where a reading of 1.5 R/hr was taken. Seventy five days after detonation, the sagebrush was defoliated and appeared to be dead for 640 meters from ground zero. Beyond this zone the sage was yellowed and not fruiting. After 550 days, Cryptantha sp. Eurotia lanata, and Artemisia arbuscula (seedlings) were growing 330 m north of ground zero in soil measuring 60 mr/hr beta and 40 mr/hr gamma. Some plant tolerance observations are given in table 1. At the Sedan crater where all vegetation was decimated and the area was covered with layers of throwout for a distance of 2.4 km to the north, the plants, except for Salsola iberica, grew back slowly, and no herbs were observed to be growing in soil registering more than 4 mr/hr (see fig. 60).

Twelve samples of Salsola from different areas of Yucca flat, radioactive and nonradioactive were analyzed for 20 elements (table 2). Salsola appears to have an extremely low content of phosphorus and relatively high contents of potassium and nitrate compared to average herbs. The contents of zinc, aluminum, barium, boron, iron, manganese, and nickel are all low. Yellowed Salsola contains less nitrate than healthy green specimens from the same area.

Absorption of radionuclides by plants

The uptake of radioactive elements by plants was established several decades ago by the work of Stoklasa and Penkava (1928), Kunasheva (1939), Hoffmann (1941, 1943) and others, using uranium and radium. Later studies by Cannon (1957, 1964), and Moisenko (1959) showed that the content of uranium in plants can be used in prospecting for uranium deposits. Hill (1962) identified alpha emitters in normal biological materials, and Anderson and Kurtz (1955) proposed the measurement of alpha emitters in vegetation as another means of prospecting. Penna-Franca and Gomes de Freitas (1963) reported on the radioactivity of biological materials from Brazilian areas rich in thorium compounds. Concern for environmental effects of nuclear explosions has led to observations and studies of the absorption by plants of radioactive nuclides from fallout throughout the world (Chandler and Wieder, 1963; Beasley and Palmer, 1966; Kauranen and Miettinen, 1967; Watters and Johnson, 1968; Gulyakin and others, 1968; Gabay and others, 1965).

Table 1.--Maximum soil radiation levels recorded for some plant species at Palanquin site (measured by Scintilation counter .9 m above ground surface)
[mr/hr = milliroentgens per hour, Leaders (--) indicate no data]

Plant species	mr/hr in soils gamma	beta
Grasses:		
Stipa speciosa	50	105
Sitanion hystrix	8	--
Oryzopsis hymenoides	30	50
Poa sanbergii	5	3
Hilaria jamesi	30	50
Forbs:		
Cryptantha sp.	40	60
Sphaeralcea emoryi var. *variabilis*	30	50
Machaeranthera canescens	40	60
Astragalus purshii var. *tinctus*	30	40
Lepidium lasciocarpum	30	50
Eriogonum nidularium	30	50
Lupinus flavovaculatus	12	--
Astragalus lentiginosus	10	--
Salsola iberica	5	6.3
Phlox stansburyi	2	2.5
Shrubs:		
Artemisia arbuscula (seedlings)	40	60
Eurotia lanata	40	60
Atriplex canescens	16	40

Table 2.--Percentages of some chemical constituents in the ash of *Salsola* (Russian thistle)

[Analysts: K. A. Leong, M. E. Hinkle, G. H. Vansickle, T. F. Harms, J. B. McHugh, H. M. Nakagawa (chemical) J. C. Hamilton, H. G. Neiman, Barbara Tobin, A. L. Sutton, Jr. (spectrographic) Leaders (---) not determined. M = million]

Ion	Content in average herb	Laboratory Numbers D406533 Jefferson County, Colorado (background)	D406306 Sedan site 19b	D406524 Plumbob Diablo	D406525 Plumbob Diablo	D406530 (yellow) Smokey site	62-1655 (yellow) Area A crater	62-1656 (yellow) Area A 150 ft N (45 m)	62-1657 (green) Area A 150 ft E (45 m)	D405831 Galileo	D408649 Galileo	D408652 Sedan site 19b	D408671 (green) Smokey site
Chemical analysis													
Ash in dry weight	7.2	20.	25.9	15.4	20.1	22.1	24.7	26.0	20.3	17.9	22.8	23.	24.
Calcium	12.	13.8	5.	10.2	10.6	8.8	11.0	7.7	11.0	13.0	8.6	5.1	7.5
Nitrate (water soluble)	0.1	1.1	.94	.25	.37	.94	.11	.11	.63	.50	.375	.5	1.25
Phosphate	3.3	.9	---	.5	.6	.4	.44	.9	.6	.32	.44	.6	.44
Potassium	26.	19.8	28.	31.2	35.2	33.4	30.	33.	32.	31.	27.2	36.5	30.2
Sodium	4.2	.14	1.8	2.4	1.9	1.7	.98	---	.92	4.8	.35	.92	2.5
Sulfate (water soluble)	---	.44	---	.39	.52	.60	---	---	---	---	.34	.37	.34
Zinc	.065	.015	.005	.005	<.005	.005	.005	.005	.005	.005	.005	.005	.005
Spectrographic analysis													
Aluminum	0.44	1.0	1.0	.2	0.15	0.3	0.7	0.7	0.7	0.005	0.5	0.15	0.3
Barium	.05	.07	.015	.003	.003	.01	.01	.01	.01	.015	.01	.005	.01
Boron	.06	.015	.01	.015	.015	.015	<.002	<.002	.01	.02	.01	<.002	.01
Chromium	.0012	.001	.0007	.0002	.0002	.0005	.0005	.0005	.0007	.0002	.0005	.0005	.0003
Copper	.012	.007	.003	.002	.015	.002	.02	.03	.02	.003	.002	.003	.002
Iron	1.0	.5	.3	.07	.07	.15	.15	.2	.2	.03	.07	.05	.03
Lead	.004	.01	<.001	<.001	<.001	<.001	.002	.002	.002	<.001	.0015	.0012	.0015
Magnesium	3.5	M	1.5	2.0	2.0	3.	3.	3.	3.	2.	1.5	2.0	2.0
Manganese	.327	.05	.02	.02	.02	.02	.02	.03	.05	.03	.02	.03	.015
Nickel	.0035	<.003	<.003	<.003	<.003	<.003	<.003	.0007	.001	.0003	<.003	<.003	<.003
Strontium	.192	.02	.05	.1	.07	.07	.1	.07	.07	.15	.1	.1	.15
Titanium	.034	.02	.03	.007	.005	.01	.01	.015	.02	.007	.01	.005	<.002
Vanadium	.002	<.001	.002	<.001	<.001	.007	<.001	.002	<.001	.003	<.002	<.001	<.001

The Atomic Energy Commission has supported laboratory studies of the absorption of fission products at the Oak Ridge National Laboratory, Tenn., Brookhaven National Laboratory, Long Island; Emory University, Atlanta, Georgia; Laboratory of Medicine and Radiation, University of California at Los Angeles; and at the Nevada Test Site. Pioneer greenhouse studies by E. M. Romney and others (1960) at UCLA of the movement of fission products in soils and the uptake of ^{90}Sr, ^{91}Y, $^{106}Ru\text{-}Rh$, ^{137}Cs, and ^{144}Ce by plants showed that different plant species vary in their accumulation of radionuclides from the soil and that most crop plants remove only a portion of the total concentration in the soil depending on the soil type. The percentages of the various radionuclides removed from the soil were:

^{90}Sr	5.0 - 10.0
^{137}Cs	0.1 - 0.5
^{91}Y	0.01 - 0.3
$^{106}Ru\text{-}Rh$	0.05 - 0.13
^{144}Ce	0.01 - 0.05

^{90}Strontium was more concentrated in the leaves than in the other parts of the plant and uptake was greatest in acidic soils and lowest in high calcium soils. Crop uptake of ^{137}Cs was inversely proportional to the level of available potassium.

Work by Brown (1964) at the Oak Ridge Laboratory has shown that ^{137}Cs in the sap streams of woody species is primarily in the ionic form; that much ionic ^{137}Cs probably occurs in intracellular fluids other than sap; and that a small quantity forms ionic bonds with organic compounds, probably as salts of carboxylic acid. Although most of the ^{137}Cs was in the phloem, some was dispersed throughout the sapwood and even in the dead xylem of the heart wood.

Our analyses and autoradiographs are intended to contribute to an understanding of the degree of contamination and uptake by plants of radionuclides at the Nevada Test Site.

Radionuclides in background soils and vegetation

A considerable quantity of radioisotopes occurs normally in plants; ^{40}K (beta, gamma) has been reported to amount to 15-30 ppm (parts per million), and there are also several parts per million of thorium, radium-uranium and their daughters. These radioisotopes naturally interfere with low-level detection of radionuclide contaminants and vise versa. Only gamma isotopes were measured on most of the samples that were collected. Background gamma values could be detected only in the plant samples when they were not masked by large amounts of radionuclide contaminants from the nuclear explosion.

Soils that were collected at a distance from nuclear explosions for background information were seldom analyzed by gamma spectrometer for individual radionuclides as the gamma count on the sample was below the limits of detection. Specific plant genera were studied from areas having different radiation levels, however, and the radionuclide analyses show interesting variations and some unexpectedly high values.

On April 12, 1963, branch tips of pine, juniper, and sage were collected in advance of any man-made disturbance on Pahute Mesa, Nevada. Only low levels of ^{137}Cs (possibly from earlier Danny Boy explosion) and natural U and ^{40}K were detected. A pre-explosion sample collected at Cabriolet on Pahute Mesa on November 7, 1966 contained a little $^{95}ZrNb$ which may have come from nearby Palanquin. In soils collected for data on plant-soil relationships from Yucca Flat, but not closely related to nuclear detonations, small amounts of ^{54}Mn, ^{60}Co, $^{65}ZrNb$, ^{125}Sb, ^{137}Cs, and ^{144}Ce were detected in some samples. The extent of air-blown contamination on Yucca Flat can be seen in the analyses of soils at the old Smokey atmospheric explosion detonated in 1957. A sample that was collected in 1964 contained considerable ^{60}Co and ^{144}Ce and some ^{137}Cs. In 1965, ^{60}Co and $^{65}ZrNb$, ^{125}Sb, and ^{144}Ce were 26 times higher in soil collected from the same sample locality, which completely masked any contamination from the original detonation. Pre-explosion collections of oak, pine, sweet gum, and sour gum that were made on the Tatum salt dome, Mississippi on May 20, 1963 far from the Nevada Test Site contained small amounts of ^{137}Cs and ^{54}Mn in one or two samples, but ^{144}Ce ranging from 11.9 to 80.6 pci/g (pico curies/gram) in the entire suite of samples. The distribution of ^{144}cerium was measured on dry ground plant material as follows:

	Leaves (pci/g)	Wood (pci/g)
Oak--------	59.5	40.0
Pine-------	56.7	42.5
Sweet gum--	74.7	58.3
Sour gum---	80.6	11.9

Similarly, samples collected in Owyhee Co., Idaho in 1963 at a planned explosion site that was later abandoned, contained ^{64}Mn, ^{95}Zr, ^{137}Cs and considerable amounts of Ce^{144}. These radionuclides unrelated to NTS explosions may have originated from the Chinese explosion in 1963 and demonstrate the difficulty in establishing background levels for radioisotopes that travel thousands of miles within days of an explosion, as ^{144}Co.

In soil sections that were sampled to depths of 2 or 3 m in trenches bulldozed across the Yucca fault, ^{54}Mn, ^{60}Co, and ^{137}Cs were confined to the top 2.5 cm of soil except in samples collected from the leached zone around shrub roots (table 3). Roots of shrubs growing along the fault have been able to penetrate an indurated caliche layer from 100 to 132 cm in depth that was cracked during a period of movement along the fault. Live roots were observed to a total depth of 254 cm in the trench and are apparently responsible for the downward movement of ^{144}Ce and concentration in the soil at this depth.

All Grayia spinosa roots with recognizable annual rings that were collected from open fractures at depths ranging from 1 to 5 m in trenches A and E, appear to have an age of about 9 years. Roots of the same shrub that were collected from the soft material above the indurated layer, are considerably older but show wider rings for the past 9-year period on the side of the root toward the fracture as shown in figure 2. Grayia roots, then, give positive evidence of movement along the Yucca fault in 1955 that permitted the roots to penetrate the caliche. Chrysothamnus also grows along the fault but does not produce annual root growth rings that can be used in dating.

Table 3.--Gamma radionuclides in soil samples collected from Trench A on Yucca Flat

[Analysts: C. A. Bush and C. M. Bunker, U.S. Geological Survey. Date of collection: September 14, 1964. Tr, trace, leaders (--) indicate not detected]

Depth of soil in cm	^{54}Mn (pci/g)	^{60}Co (pci/g)	^{106}Ru (pci/g)	^{125}Sb (pci/g)	^{137}Cs (pci/g)	^{144}Ce (pci/g)	eTh (ppm)	eU (ppm)
0 - 2.5	12.1	3.7	Tr	Tr	9.1	Tr	17	8.1
2.5- 10	--	--	--	--	--	--	16	3.3
10- 40	--	--	--	Tr	--	8.3	23	3.3
40- 70	--	--	--	--	--	--	20	2.7
70-100	--	--	--	Tr	--	--	22	8.5
100-132 (indurated caliche)	--	--	--	--	--	--	14	3.8
132-162 (gravel)	--	--	--	--	--	--	17	Tr
162-192 (gravel and caliche)	--	--	--	--	--	--	13	2.6
192-220 (caliche)	--	--	--	Tr	--	--	17	3.3
220-254 (gravel	--	--	Tr	.24	--	25.5	23	3.1
ground roots *Grayia spinosa* tips	3.06	--	--	--	4.3	25.9	--	25.9

A nuclear explosion of 1.2 kt (kiloton) was detonated at a depth of 20 m in north Yucca Flat on March 23, 1955. An earthquake on December 16, 1954, with an epicenter north of the Nevada Test Site was recorded with an intensity of Richter magnitude 6 on Yucca Flat. Either may have resulted in the fracturing described--later studies have shown that movement on the Yucca fault does result from nuclear detonations in the Yucca alluvial basins.

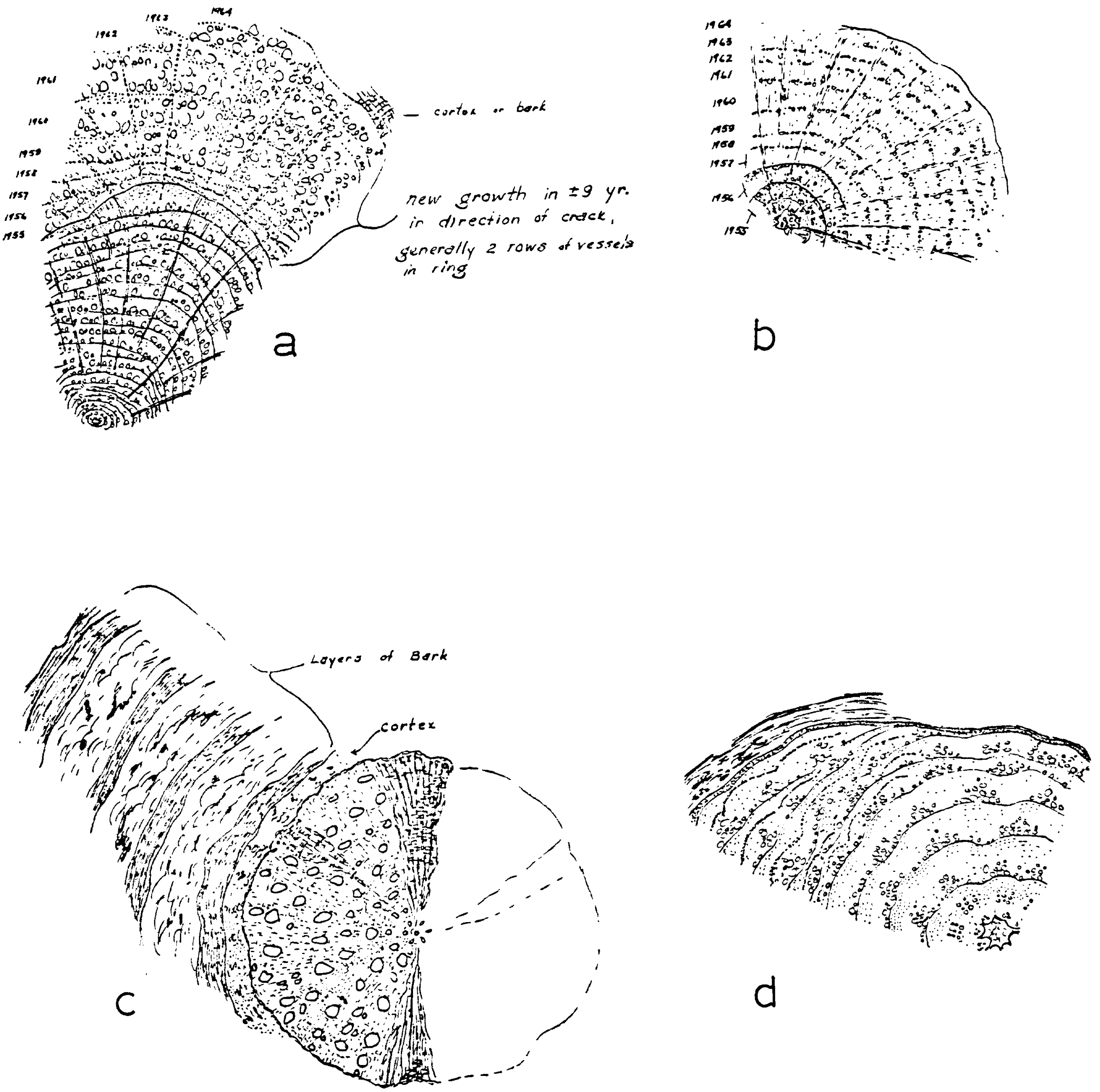


Figure 2.--Dating of Yucca Fault movement by increased shrub growth along fractures: a, Unidentified root; b, unidentified stem; c, *Grayia* root; d, *Grayia* stem.

A study of vegetative growth changes or the uptake of radionuclides in relation to atmospheric, contained, or released explosions requires, then, recognition and evaluation of any background contamination and also of any physical disturbances emanating from other explosions in the vicinity.

Absorption of radionuclides by plants growing near nuclear explosions

Analyses and autoradiographs of new growth on shrubs at several sites provided evidence of actual absorption and translocation of radionuclides after the Pinstripe, Palanquin, and Danny Boy events at the Nevada Test Site. The absorption of radionuclides by annuals or grasses could be compared with the soil contents around the old tower explosions. *Oryzopsis hymenoides* (rice grass) contained more ^{144}Ce than the soil (92/2.6 pci/g). *Salsola iberica* normally contains considerably less radionuclides than the soil, which may explain its tolerance to radioactive soils.

On-the-ground hand-counter measurements showed 2 times more beta than gamma within a mile of the Palanquin cratering nuclear explosion and a gradual change to more gamma than beta with time. The data suggest the initial presence of large amounts of shorter-lived radionuclides that produce beta, such as ^{32}P (14 day half-life), ^{45}Ca (165 day half-life), and ^{131}I (8 day half-life), although long-term effects from ^{90}Sr (28 year half-life) absorbed by conifers may be a factor in their eventual death, observed west of the Blanca site to occur as much as 8 years after the explosion. Mills and Shields (1961) found the absorption coefficients $\left(\frac{\text{uc/100 g plant part}}{\text{uc/100 g soil}} \times 100\right)$ for *Bromus rubens* to be 29.13 for ^{90}Sr, 6.54 for ^{106}Ru-Rh, 1.75 for lanthanide rare earths and only 0.61 for ^{95}ZrRb.

Martin and Turner (1965) found that ^{89}Sr on D+5 (5 days after the Sedan detonation) was 100 times higher than ^{90}Sr in non-washed plants samples. ^{89}Sr on dried twigs and foliage of shrubs ranged from 6,487 pci at sites where readings of 75 mr/hr were recorded to 228 pci where 1.5 mr/hr were recorded. By D-60, the values were reduced by about 1/6. Correcting for a half-life loss of 14 days due to rain and wind, they calculated the effective half-lives from D+5 to D+60 to be 18 days for ^{89}Sr and 28 days for ^{90}Sr, and from D+30 to D+60 the effective half-life of ^{89}Sr to be 38 days and of ^{90}Sr more than 100 days.

In our studies, a few plants and soils were analyzed for ^{90}Sr by ashing, dissolving the ash in hydrochloric acid, and then following the procedure for water analysis, described by Johnson and Edwards (1967). In this procedure, strontium is finally precipitated as the oxalate and the amount of radiostrontium is determined by measuring the beta activity on a low-background beta counter. The chemical recovery is determined gravimetrically. As a considerable period of time elapsed between collection and analysis, the values do not include a measureable amount of ^{89}Sr. The data are given in table 4. Contamination from the air burst of Jackass Flat reactors in 1962 probably accounts for the pre-explosion levels at Tiny Tot. The percentage of external to internal ^{90}Sr is not known but the loss from rain and wind should have reduced the external amounts in samples collected years after the event and have no effect no annuals or deciduous plants. The largest amount that was measured in a plant sample (23.9 pci/g) occurred in dead limbs that were killed by either heat or radiation on oak at the time of the Blanca explosion (accidentally atmospheric); the humus under the trees, which consists of rotted leaves, also dating from the time of the explosion, contained 53 pci/g ^{90}Sr. New leaves put out several years after the event on limbs that were not killed contained 1.25 pci/g ^{90} Sr. As the half-life is 28 years, there should be little measureable difference in quantity from the leaves dropped at the time of the explosion and that in later leaves. Probable causes for the difference are two. First, dead wood samples were not washed, and although subjected to several years of rain and wind probably still contained surface contamination. Second, a certain amount of ^{90}Sr would have leached from the soil and be thus unavailable for uptake by the trees and transport to the leaves.

Gamma radionuclides were measured by gamma-ray spectrometry. The spectrometer system consisted of a 400-channel pulse-height analyzer and two 5-inch diameter by 4-inch-thick NaI crystal detectors each viewed by a 5-inch photomultiplier tube. Each detector was routed into separate 200-channel groups of the pulse-height analyzer and the analyzer was adjusted with standards of known energies so that each detector measured energies in the 0 to 3 million electron-volt (Mev) range. The spectra were plotted on an XY plotter. The radionuclides were determined from the photopeak energies located in the spectra and the quantitative data were interpreted from the height of the peaks per unit time with a method similar to the analysis of potassium described by Bunker and Bush (1967). The analyses were restricted to gamma-ray emitting radionuclides. Alpha particles were absorbed by the sample containers and were not detected by the crystal. Beta particles were sensed by the detectors as a continuum but photopeaks were not formed.

Table 4.--^{90}Sr contents in plant and soils samples*

[Analyst: V. C. Janser, U.S. Geological Survey; values shown in pci/g of dried sample]

Event	Interval between event and date of collection	Distance from ground zero (in meters)	Sample description	Part of plant	^{90}Sr in plants	^{90}Sr in soil
Largely contained						
Tiny Tot	Pre-shot	--	*Purshia*	Tips	6.14	5.93
Do.	1 year	150	do.		1.11	
Gumdrop	5 1/2 months	360	*Artemisia*	do.	2.91	
Do.	3 months	360	do.		2.20	
Marshmallow	3 1/2 years	30	*Pinus*	do.	.904	
Shoal	7 months	800	*Artemisia*	do.	5.76	
	13 months	800	do.		4.66	
Atmospheric						
Smokey	7 years	300	*Salsola*	Above ground	8.80	22.0
Teapot Apple	9 years	915	*Sphaeralcea*	Tips	2.55	
Cratering						
Danny Boy	4 years	225	*Atriplex can.*	do.	.704	
Small Boy	9 months	2400	*Eurotia*	do.	2.90	
			Larrea	do.	1.44	
Partially contained						
Pinstripe	11 days	1600	*Larrea*	do.	1.50	
Blanca	6 years	300	*Quercus*	Dead wood	23.9	53.0 (humus)
			do.	new Leaves	1.25	53.0 (humus)
Des Moines	2 years	9	*Cowania*	Tips	11.5	
	2 years	60	*Pinus*	do.	5.19	

*^{90}Sr half life is 28 years, beta radiation.

In earlier samples, the nuclides were measured in plant material that had been dried and then ashed, but later analyses were made on pulverized dried plant material because the results were found to be more reproducible.

Because no radionuclide standards were available in plant or soil matrices, the quantitative values were obtained by comparing the measured sample spectra with those of calibrated single radionuclide point sources. The derived values were then adjusted for geometric differences between the point sources and the collected samples by empirical methods. This made no provision for differences in density (self-absorption), so no absolute method for measuring the accuracy was available. An accuracy of 10-15 percent seems reasonable, but, in any case, the values should maintain a good relative relationship to each other.

Because of the time lag between date of collection and date of analysis, reported values for all nuclides were calculated back (by computer) to the date of collection and also to the date of nuclear detonation.

Each radionuclide has its own behavior pattern at the time of detonation. ^{144}Ce, ^{137}Cs, and other direct fission products with long half-lives may travel thousands of miles within days after an atmospheric explosion and can be detected around the world. Radionuclides such as ^{54}Mn and ^{24}Na with very short half-lives may occur in large quantities at the time of the explosion but their effect is local. ^{106}Ru-Rh occurs in five valence states, which permits action as either cation or anion, with rapid movement through ground water. ^{125}Sb also is commonly concentrated in ground water. Algae collected from a pond draining a radioactive tunnel detonation on Rainier Mesa (Sta. 43) had absorbed 11,050 pci/g of ^{106}Ru-Rh and 2780 pci/g of ^{125}Sb from the water. ^{54}Mn, ^{60}Co, ^{65}Zn, and ^{59}Fe that are induced from metal casings and cables, do not travel far from the area of release. Thus time elapse, depth of emplacement, and disintegration rates are all involved in the eventual distribution of radionuclides in the vicinity of a detonation and their availability in soil and water for plant absorption. Only the longer lasting radionuclides were detected by spectrophotometer, as rarely was it possible to collect immediately after the explosion nor could the laboratory analyze the samples promptly. Commonly, also, large quantities of one radionuclide will mask the presence of another. The data available for study are therefore confined principally to long-lived gamma radionuclides that represent only a small part of those actually present at the time of the detonation. Recorded radioactivity levels at some of the early atmospheric explosions were as much as 10,000 rads for the first 2 hours. Maximum amounts detected in the earliest collections are shown in table 5. No adjustment has been made for half-life loss owing to wind and rain.

Table 5.--Maximum concentrations of radionuclides measured in dried plant and soil samples, shown in pci/g.

[Analysts: C. A. Bush and C. M. Bunker, U.S. Geological Survey]

Radionuclides	Half-life in months	No. of samples	Background off and on Test site* Plant	Background off and on Test site* Soil	Explosion contained at time of detonation Plant	Explosion contained at time of detonation Soil	Generally contained but with small escape Plant	Generally contained but with small escape Soil	Explosion with large-scale release of radioactivity Plant	Explosion with large-scale release of radioactivity Soil
			17	23	51	1 (at 5-1/2 mo.)	18	4	112	68
^{54}Mn pci/g	9.3		11.3	19.5	11.3	---	5.85	19.5	171.	2,600.
^{60}Co pci/g	62.4		---	4.33	2.66	0.44	2.54	6.93	280.	3,720.
^{65}Zn pci/g	8.1		---	---	---	---	.26	---	93.6	422.
^{88}Y pci/g	3.5		---	---	---	---	---	3.08	10.5	1,010.
^{90}Sr pci/g	336.		6.14	5.93	5.76	n.d.	6.14	5.93	23.90	53.00
$^{95}ZrNb$ pci/g	2.2		3.29	---	18.1	3.0	9.89	31.0	5,970.	157,000.
^{106}Ru pci/g	12.		155.	---	240.	54.2	155.	343.	11,050.	37,800.
^{124}Sb pci/g	2.		---	---	---	---	---	---	943.	2,910.
^{125}Sb pci/g	27.		4.88	.31	9.32	---	20.1	---	2,720.	164.
^{137}Cs pci/g	319.		25.	27.1	10.4	---	25.0	53.2	754.	786.
$^{140}La\text{-}Ba$ pci/g	.055		---	---	---	---	108.51	97.63	4.435.	3,410.
^{144}Ce pci/g	9.7		82.0	137.	80.6	2.09	82.0	577.	233,000.	746,000.
^{152}Eu pci/g	156.		---	---	---	---	0.87	---	---	---
eRaU** ppm	---		89.1	28.	51.0	---	7.5	12.0	123.	440.
eTh** ppm	---		22.	26.	110.	---	4.6	---	37.	230.

* These samples collected off Nevada Test Site and also on Yucca Flat away from shot points.
** eRaU, eTh mean the amount of uranium and thorium that would be present if the measured daughter products were in equilibrium with the parent.

n.d.--Not determined.

The differences between the radionuclide content of washed and dried shrub samples in background areas near contained explosions and that of shrubs near released explosions are considerable and would be vastly greater if the shrub material had been collected immediately after the released explosions and analyzed at once. Contents of radionuclides that were measured in various parts of the plant are given in table 6. No unusual concentrations were reported in roots. The twigs of oak contained more ^{54}Mn, ^{125}Sb, and ^{144}Ce than the leaves. New green branches of rabbitbrush contained more ^{95}Nb, ^{125}Sb, ^{137}Cs, and ^{144}Ce than the old wood but less ^{54}Mn, ^{60}Co, and ^{65}Zn. These data cannot be considered to be as significant as observations made on plant uptake in controlled experiments by other workers.

Physiological effects on plants

Many physiological effects of radiation on plants have been observed by other workers in controlled experiments, near unshielded reactors, and at the Nevada Test Site. These include: harmful effects to the apical meristem, lateral bud differentiation, growth inhibition, and leaf abnormality. We have also observed and report throughout this paper similar effects near released nuclear explosion at the Nevada Test Site.

Miksche, Sparrow, and Rogers reported in 1961 on the pattern of meristem development of two gymnosperms that were grown at Brookhaven National Laboratory under several dose rates of chronic gamma irradiation from a Co^{60} source. In both *Pinus strobus* and *Taxus media* 20 days exposure at 3.5-15 r per 20-hour day resulted in distinct, anatomical abnormalities in the apical (main shoot) meristems. At higher levels of gamma radiation, the main shoot meristems became broad disorganized structures with adventitious meristemic regions and fasciations.

Table 6.--Distribution of radionuclides within the plant, shown in pci/g
[Analysts: C. A. Bush and C. M. Bunker, U.S. Geological Survey]

Plant	Parts	^{54}Mn	^{60}Co	^{65}Zn	^{95}Nb	^{125}Sb	^{137}Cs	^{144}Ce
Pinus----------	Twigs and needles-	---	---	---	---	---	9.05	10.6
	Roots------------	---	---	18.6	---	---	---	---
Ephedra--------	Stems------------	1.14	---	---	115	---	---	40.3
	Roots------------	---	---	---	---	---	---	3.13
Chrysothamnus nauseosus----	Twigs and leaves--	---	---	---	543	4.03	754	35.6
	Old wood---------	9.51	6.61	93.6	---	---	27.6	21.0
	Roots-------------	---	4.35	--	261	3.59	---	411.0
Quercus--------	Leaves------------	2.09	---	---	---	1.95	1.88	15.5
	Twigs-------------	18.5	---	---	---	10.9	---	128
Pinus----------	Twigs and needles--	---	---	---	---	---	4.41	16.2
	Older branches-----	---	---	---	---	---	.52	.92
	Roots-------------	---	---	11.3	---	---	1.22	---
Juniperus------	Twigs and needles--	---	.35	7.04	---	---	5.40	8.59
	Roots-------------	---	---	---	---	---	.24	---
Atriplex canescens	Twigs and leaves---	1.45	---	---	997	---	---	44.8
	Roots-------------	---	---	---	Tr	---	---	---

*---in columns indicate below limits of detection or masked by other radionuclides.

At Brookhaven National Laboratory, a forest ecosystem of *Quercus alba*, *Q. cocinea*, and *Pinus rigida* has been irradiated from a ^{137}Cs source over a long period of time. Radiation has produced zones of (1) total kill: (2) sedge; (3) heath-shrub; (4) oak; (5) oak-pine forest. Insect defoliation is more than 10 times as severe as in the control forest (Woodwell, 1962). Exposures of less than 5 r per day for several years killed 90 percent of the pine whereas exposures of 1-3 r/day inhibited the radial growth of needles. Shoot elongation was inhibited in oak at 35 r/day and in pine at 15 r/day. In 1963, Sparrow, Schairer, Sparrow, and Campbell reported that dormant white pine seedlings were much more resistant to radiation than actively growing plants. Woodwell and Miller (1963) reported that the reduction in radial increment in pitch pine stems irradiated at 1-5 r/day for 9 years was greatest near the base of the trees and greatest in years of high stress. Smaller trees were more affected than larger. After 10 years of exposure, 20 percent of the trees had been killed by a cumulative dose of 5.0 kr at 2.5 r/day and 50 percent killed at 3 r/day. No trees survived a dose of 13 kr (Sparrow, Schairer, Woodwell, 1965). The number of mature seeds per cone was reduced to 10 percent of the control after 9 years at 3.5 r/day. No cones were produced above a dose of 7.4 kr. Studies of *Quercus alba* and *Q. velutina* exposed to the same radiation levels showed oak to be more tolerant than pine (Mericle, Mericle, and Sparrow, 1962). Effects of radiation on oak included sparseness of foliage due to death of lateral and terminal buds, reduced internodes, fewer leaves which were often enlarged, distorted, leathery, and occurred in tufts along the branches, and abnormal inflorescences. Histological studies showed that many terminal buds lacked meristemic tissue, a lower number of floral primordia and a reduction of viable pollen. On the other hand, lateral buds had unusually active meristemic tissue suggesting a stimulative effect.

Similar observations were made by Pedigo (1963) in Georgia where neutron and gamma rays were released from a partially shielded reactor on loblolly pine (*Pinus taeda*) at irregular intervals. Exposure of 1,000-2,000 rads produced red-brown discoloration, death of terminal buds, and inhibition of reproduction. A greater exposure resulted in complete browning, defoliation and death; the lethal dose being computed at 7,500 rads. Terminal buds were inhibited by 1,000 rads and laterals by 3,000-4,000 rads. Pedigo suggested that these effects were caused by interference with auxin metabolism in meristemic tissues as radiation reduces the biosynthesis of auxin.

In order to test the effects of acute gamma radiation on *Pinus monophylla*, Brandenberg, Mills, Rickard, and Shield (1963) irradiated a tree for 8 hours in April, 1960, with 10,000 R from a ^{60}Co source at the Nevada Test Site. The tree was studied for 15 months after irradiation. They found that needles browned within a month at a calculated dosage of 8,000-10,000 R (roentgen) and were dead within 10 weeks at 2,000 R. At 500 R there was a slight elongation but terminals were dead after 4 months although laterals were developing. At 100 R there were no needles on 1960 stems and at 80 R the number of needles was reduced and one-half of them were dwarfed. Sections showed abnormal vascular tissue and a decrease in the width of the growth ring for 1960 depending on exposure. The stem tip was affected at exposures as low at 15 R. They concluded that "lateral branching assumes a significant role in shoot recovery from radiation damage, particularly at exposures great enough to affect the actively growing regions of the stems."

Although we did not make cytological studies for this report, the macroscopic effects of damage to the apical meristem of pine and oak in the Blanca area and also the effects on Russian thistle of the reactor runs on a 480-m tower in Yucca Flat were observed and are described in those sections of the report. In many cases, the cessation of terminal growth is accompanied by stimulation of lateral stem tips which Brandenburg, Mills, Rickard and Shields (1963) believed was significant in shoot recovery. Platt (1962) observed a sharp difference in sensitivity between apical and lateral meristems or growth tissues. Vasilev (1962) reported that the stimulation in growth was accompanied by an increase in oxidation-reduction potential, decrease in viscosity, increase in permeability and an increase in respiration rate. Janice Beatley (1966) observed a stimulation in growth in *Chaenactis stevioides* after the Sedan event. The plants were larger and had thicker darker leaves than any observed elsewhere on the Nevada Test Site. Among these plants were a few abnormal plants that lacked a corolla and other flower parts.

Our observations included studies of oak at Blanca (an accidental atmospheric explosion) and at Clearwater and several other contained explosions. No leaves were observed on the oak that grew nearest to the edge of the Blanca explosion crater for four years and for the next three years shoots at the base came up and then died before the end of the summer. In the 8th year deformed curled leaves appeared on the upper older branches and the trees are now leafing our normally. Stimulation of lateral growth was observed in oak at the contained Clearwater explosion (fig. 3) in *Artemisia* at the contained Shoal explosion and in *Atriplex canescens* near the Duryea explosion. In all three of these areas, where no radiation was detected at the ground surface after the explosions, the stimulated plants were the nearest vegetation to ground zero (at edge of scraped area) growing along large fractures caused by the explosion. Probably the stimulation in these areas was caused by the rise in the water table (perched or actual) along the fractures at the time of the explosion. After some explosions the rise in water table has been measured at several hundred feet. *Atriplex canescens* near Duryea put out lush wet leaves 23 days after the explosion but dry and small leaves the following year.

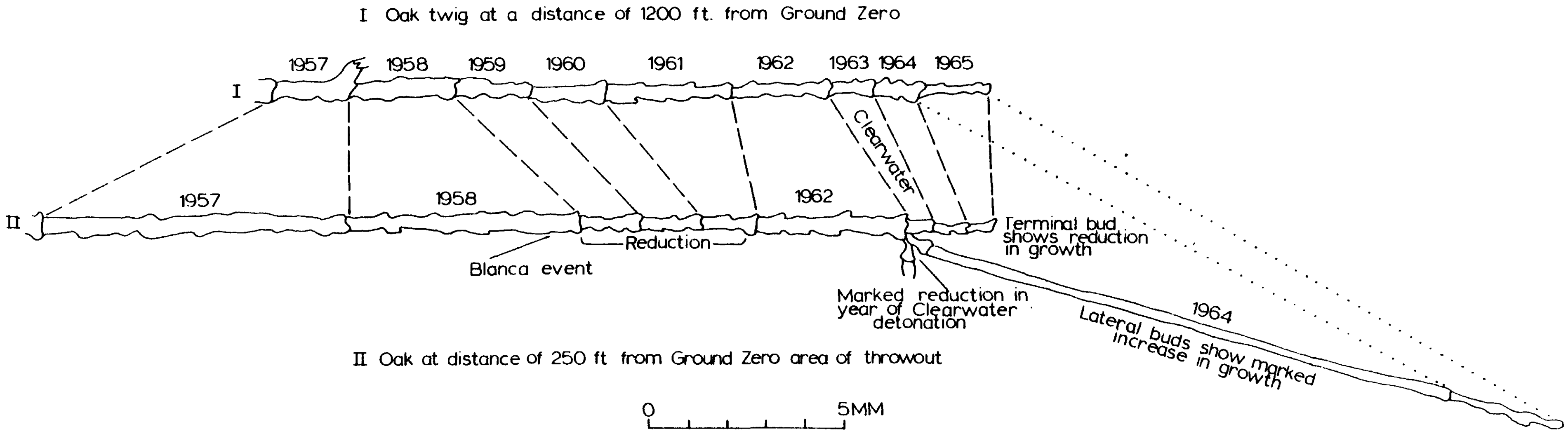


Fig. 3 Effect of contained Clearwater event of October 1963 and Blanca vented explosion of 1958 on oak. Normal difference in growth of trees I and II are shown by 1957 and 1962 growth

Damaging shock to roots and the destruction of root hairs is most severe along fractures in the ground that either result in open cracks or shear laterally. At the Shoal event in Churchill County, Nevada, the shrubs located along large fractures extending out from ground zero were severely damaged. Grayia spinosa and Ephedra nevadensis along the fractures were dead one and one-half years after the explosion. Artemisia was less affected. Damage and eventual death of Quercus, Pinus, and Ephedra were also observed along faults produced at the Clearwater event. The trees along faults turned color earlier in the fall following the event than did the main body of the forest.

The stress effects of root shock from a landslide were studied in Colorado. The effects of a landslide on pine and its recovery could be observed in wood sections (fig. 4). Slow colluvial creep affected a Prunus shrub over a period of years and finally killed half of it; the other half was not affected and has continued to grow. The effect on the development of spring cells in one area of the wood for five years could be seen (fig. 5).

Earthquakes also provide information concerning shock effects. Wood of Chrysothamnus collected near the Derby, Colorado, earthquake center in 1965 shows well-developed traumatic canals or resin ducts resulting from stress (Esau, 1965) in both the stem and the root (fig. 6a and 6b). Similar canals were observed in stems and roots of Haplopappus growing near the Yucca Fault at the Nevada Test Site, which had had very recent movement (fig. 7a and 7b).

Radiation also affects wood growth and can be observed in wood sections. Woodwell and Miller (1963) reported that exposure of pitch pine trees to chronic ionizing radiation of .1-5 roentgens a day for several years causes reduction of the radial increment throughout the stem, the reduction being most severe near the base of the tree. As buds are most sensitive and as auxin movement from the buds produces cambial activity, greatest effect at base of tree farthest from buds. They were able to demonstrate that both the size of the crown and the climate influence the severity of the effect, trees with large crowns showing little effect at low exposures except in years of environmental stress. Environmental stress, in turn, is greatest in dry sites or during the years of low moisture and high temperatures (Fritts, 1966). Trees growing near the top of their climatic range may produce multiple or false growth rings in a single year and show damage along the growth ring produced in a particularly severe year. This evidence of frost damage shows as a rope-like line of collapsed cambial cells followed in the next annual ring by highly distorted cells (Glock and Agerater, 1963) and is similar to that commonly produced in the nearest trees to survive at the time of a nuclear explosion. Sparrow and Miksche (1961) observed that the larger the nuclear volume, the more radiosensitive the plant. Chappell (1963) found that species with underground vegetative structures are able to withstand greater amounts of radiation. The ability of certain plant species to go into dormancy for periods of time proportional to the dose of radiation also protects deciduous shrubs from death (Platt, 1962).

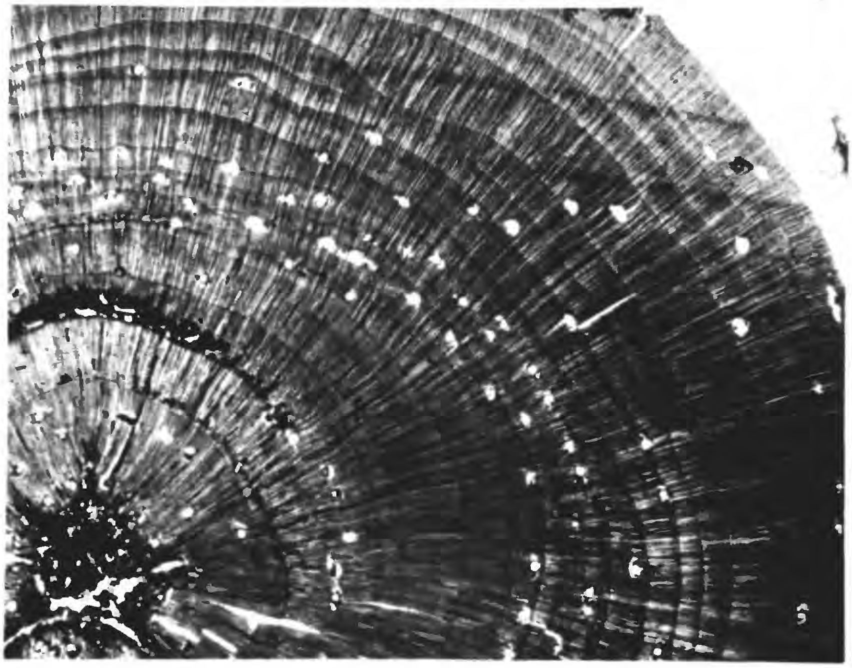


Figure 4.--Pine from landslide area showing severe shock in 2nd year of growth.

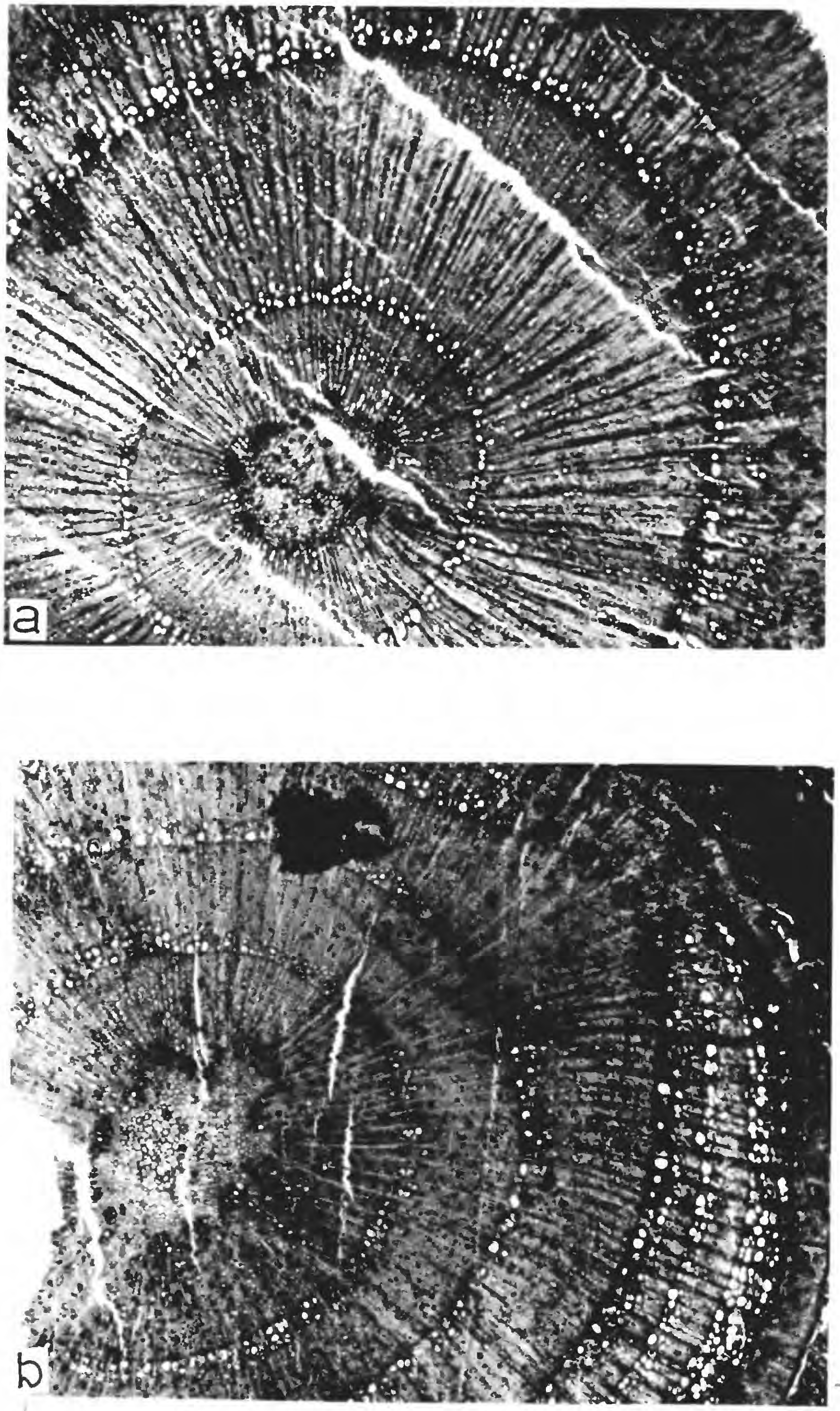


Figure 5.--*Prunus americana* in landslide. a, Unaffected live stem; b, affected stem through a 5 or more year period (that eventually died).

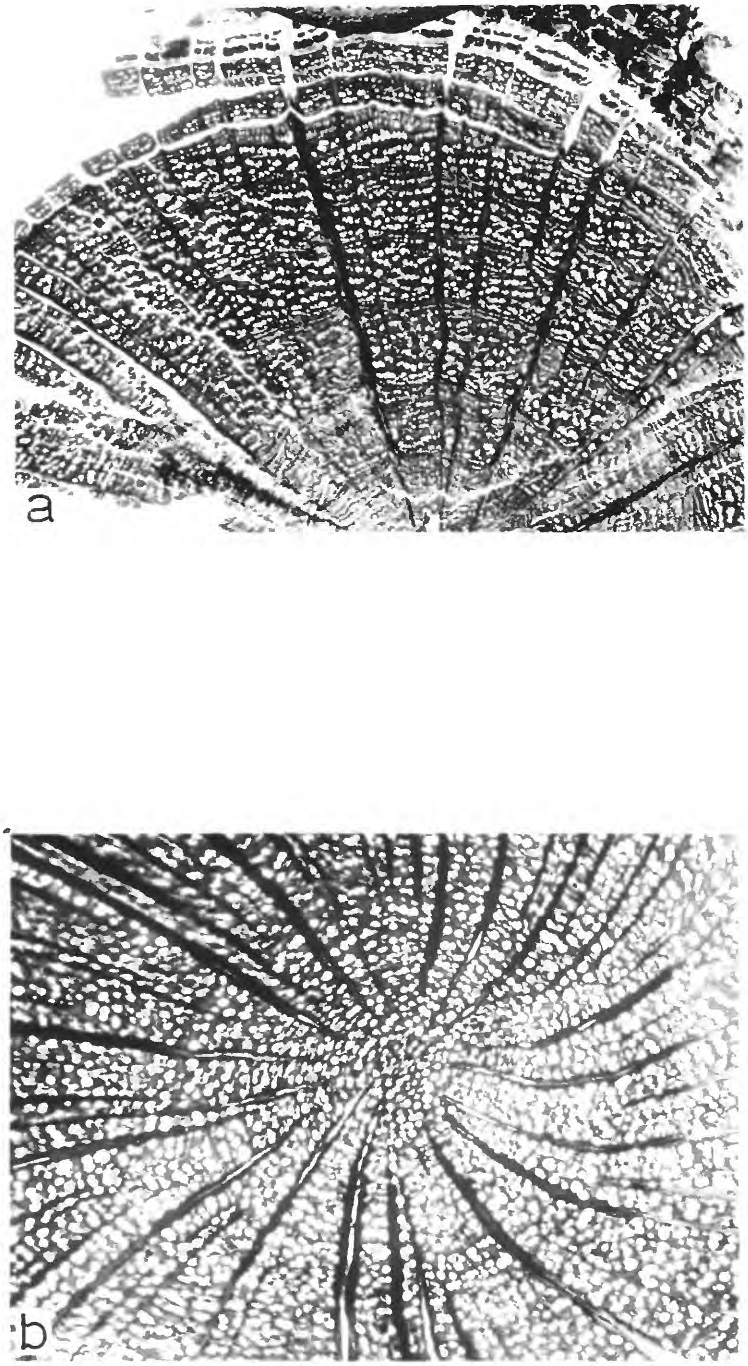


Figure 6.--Chrysothamnus collected near Derby, Colo. earthquake. a, Wood; b, root of same shrub.

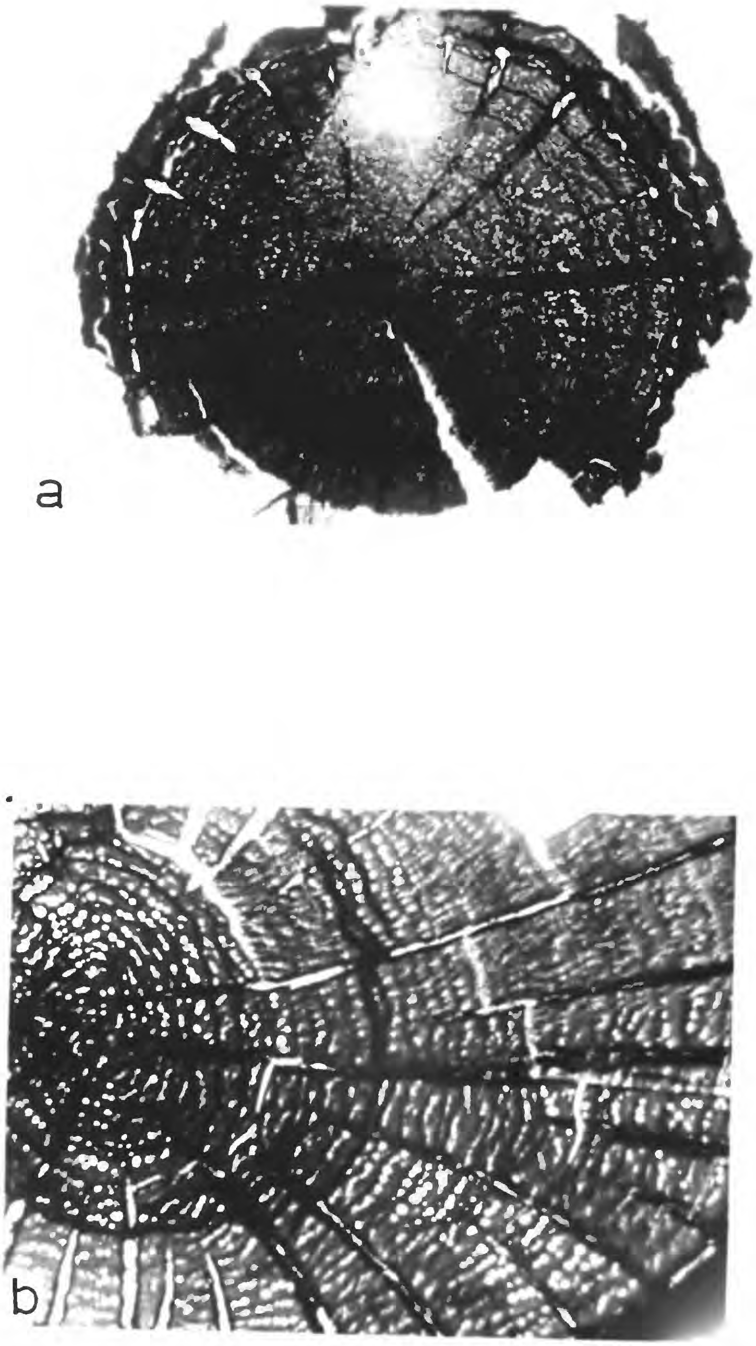


Figure 7.--Haplopappus growing near Yucca Fault. a, Stem; b, root of same shrub.

The growth history in trees and shrubs after a detonation can be followed by examination of wood sections. Four distinct changes have been observed:

1. A dark line may be observed within the annual ring at the time of the explosion similar to that produced in trees nearly killed by freezing. This line occurs only in specimens within 100 meters of ground zero and represents a near-death condition that may be related to blast and heat rather than to radiation.

2. An increase in "spring" vessels is commonly noted to the complete exlcusion of "summer" vessels during the first year or more after the explosion. This phenomenon hs not been noted in plants disturbed by earthquake, landslide, or underground conventional (dynamite) explosions.

3. Changes in width of annual ring. Trees and shrubs for a radius of more than 1 1/2 miles from the detonation appear to have increased growth immediately following a vented explosion but to be retarded or to go into dormancy for several years after the event.

4. Traumatic deposits of ergastic substance in rays of the wood (fig. 8). These deposits were most pronounced in shrubs of the alpha area in Area 9 and in Artemisia at Palanquin--both areas of high radiation but little physical shock.

Traumatic canals were noted in wood collected from shrubs that were growing near undisturbed uranium deposits at Yellow Cat, Utah, and hence due to radiation rather than to physical shock (fig. 9). Coniferous species, which are relatively sensitive to radiation, die back farther from a fixed gamma source each year as their tolerance limits are reached (Mericle, Mericle and Sparrow, 1962). Although the radiation levels do not remain constant but are massive at the time of the explosion and decay rapidly, radiation effects on trees are certainly evident at NTS. Injured oak trees, that appeared to be leafless and certainly had no apical growth for as long as 6 years, near the Blanca crater finally put out curled deformed leaves and the next year relatively normal leaves. A marked reduction in the width of the annual rings shows clearly in wood section and then eventual recovery (see fig. 47). Photographs and more detailed descriptions, of wood sections are given in discussions of individual explosions.

Morphological effects on plants

Morphological effects on plants have been studied intensively at Brookhaven National Laboratory, Upton, New York, by irradiation of many species of plants from a ^{60}Co source. Sparrow and Pond (1965) were able to induce both genetic effects in the form of mutant spots on petals of snapdragon and cytological effects resulting in an increase in the number of micronuclei at the quartet and microspore interphase and also a high frequency of bridges in somatic cells. An exposure of 3 to 4 weeks with dose rates of as low as 2.2 r/day caused significant changes. Sparrow and Christensen (1950) reported spontaneous chromosomal fragmentation in Trillium erectum of up to 30 breaks per cell in radiation experiments although there was considerable variation from anther to anther. Sparrow and Pond (1956) also reported tumors on Nicotiana, which developed on lateral buds after 5 weeks and could be produced either by irradiation from a ^{60}Co source or by feeding the plants the beta isotope ^{32}P in the form of PO_4. After 385 r/day for 64 days, an average of 53 percent of the fresh weight was tumorous and the

Figure 8.--Dying trees that contained great numbers of traumatic canals filled with resin.

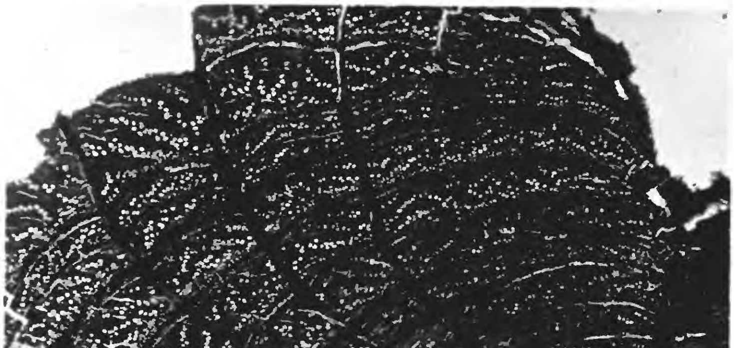


Figure 9.--Development of traumatic canals in Artemisia rooted in carnotite ore.

tumorous masses continued to grow for several weeks after all leaves were dead.

Morphological effects of radiation on plants have been noted in several areas of atmospheric nuclear explosions on the Nevada Test Site. A large number of tumors were observed on Atriplex linearis accompanied by misshapen leaves in the first of these shrubs to grow at the edge of Sedan crater 8 years after the explosion when the radiation levels had been reduced to about 1 mr/hr gamma. The effects of radiation from the Sedan explosion on the flowering parts of Chaenactis stevioides have also been described by Janice Beatley (1966). The first plants to appear were unusually large with thick green leaves. However, certain of the plants were dwarfed, bushy, and failed to develop a corolla and other flower parts, which she attributed to either chromosomal aberrations or gene mutations. We noted radiation effects on the growing tips of oak and pine and the development of a witches' broom effect on Morman tea near the Blanca crater in an area that received more than 9 r/hr of beta + gamma radiation at the time of the event. These are more fully described in the section on the Blanca explosion. Cowania stansburiana that is growing above the Des Moines tunnel explosion of 1962, which vented and contaminated the mesa with both beta and gamma radiation, has absorbed large amounts of radionuclides and has produced deformed fruits over a period of years (see section on Des Moines event). Similar fruits were observed on Cowania at Palanquin.

Effects noted in a drainage area, which have not been described elsewhere in the report were apparently caused by alpha contamination. A small seep dammed by a fault scarp on Yucca Flat is draining an area that was contaminated by alpha radiation in 1959 from T9E, S9E, and S9F events. Because levels of more than 100 alpha dpm (disintegrations per minute) were measured in 1959, the surface layer of soil was scraped into windrows and oiled. Current readings of only 8 dpm were measured on the soil of the catchment area in 1965; the level of beta radiation is not known. All shrubs growing in this area appeared to be affected however, and exhibited the following unusual growth habits (fig. 10):

Grayia spinosa, enlarged thickened leaves
Eurotia lanata, knobby extended stalks, owing to affected terminal buds
Atriplex confertifolia, small fine leaves of delicate texture
Salsola iberica, extremely lush growth, 1.3-1.5 m high

Similar growth habits in Eurotia and Atriplex were noted at Palanquin.

No production of flowers or seeds was observed on these shrubs. Haplopappus produced thickened heads with enlarged involucres on elongated stems. Stanleya pinnata produced fasciated and divided spikes with completely abnormal flowers. The latter included no petals or stamens but enlarged thickened sepals and a pistil which reproduced a new plant asexually. In some cases the second plant then produced a third plant asexually as shown in the accompanying drawings (fig. 11 a, b, c, d, e).

In an area of 610 m^2 on Frenchman's Flat, we found 85 of a total of 105 Stanleya to be abnormal. Teretological Stanleya more than 2 m high were growing in an area of northern Yucca Flat where 700 mr/hr of radiation (beta + gamma) had been recorded 24 hours after the Sedan detonation.

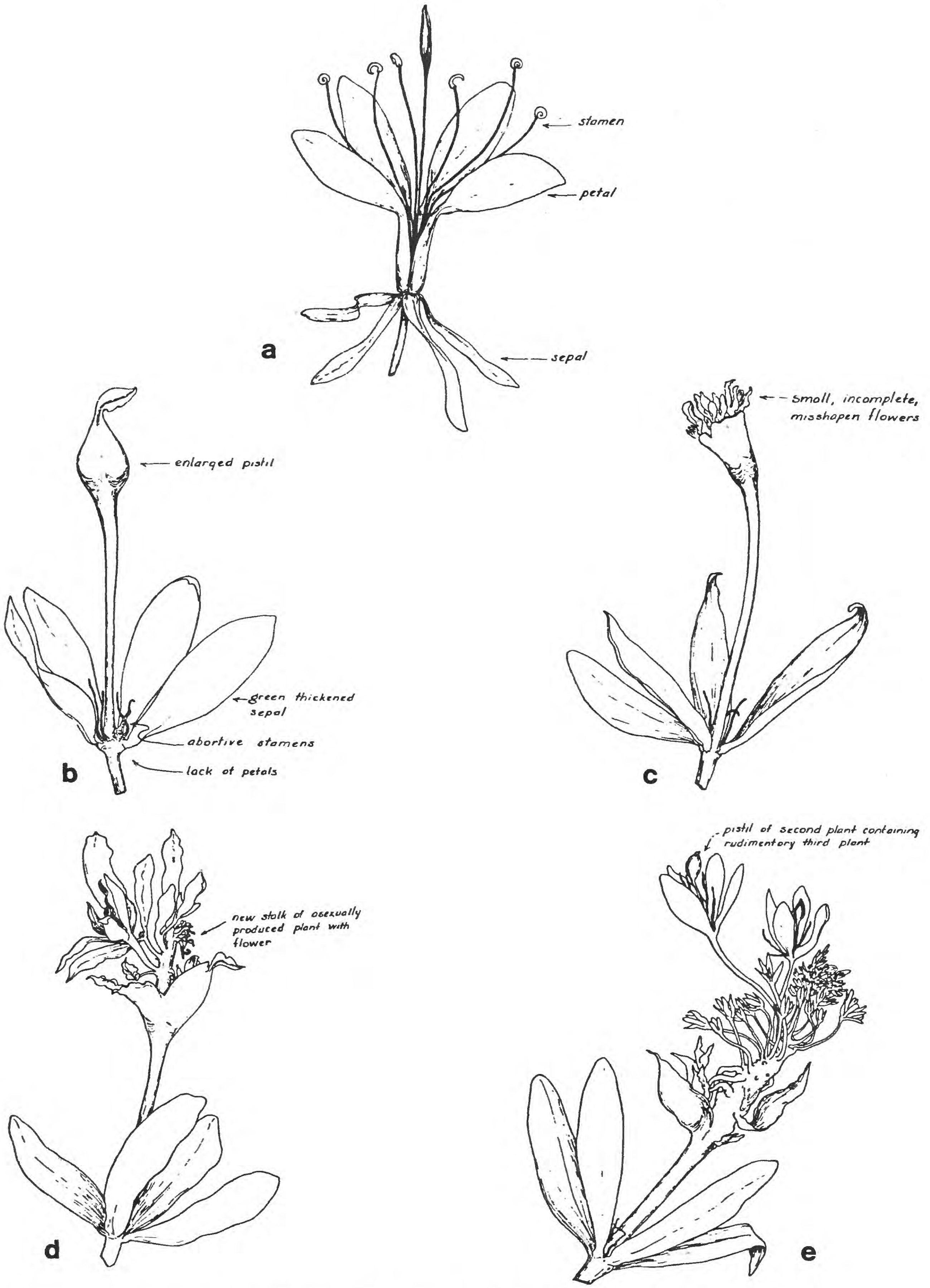


Figure 11.--Asexual development in irradiated Stanleya. A, Normal flower; b, First stage in irradiated Stanleya; c, second stage; d, third stage; e, fourth stage.

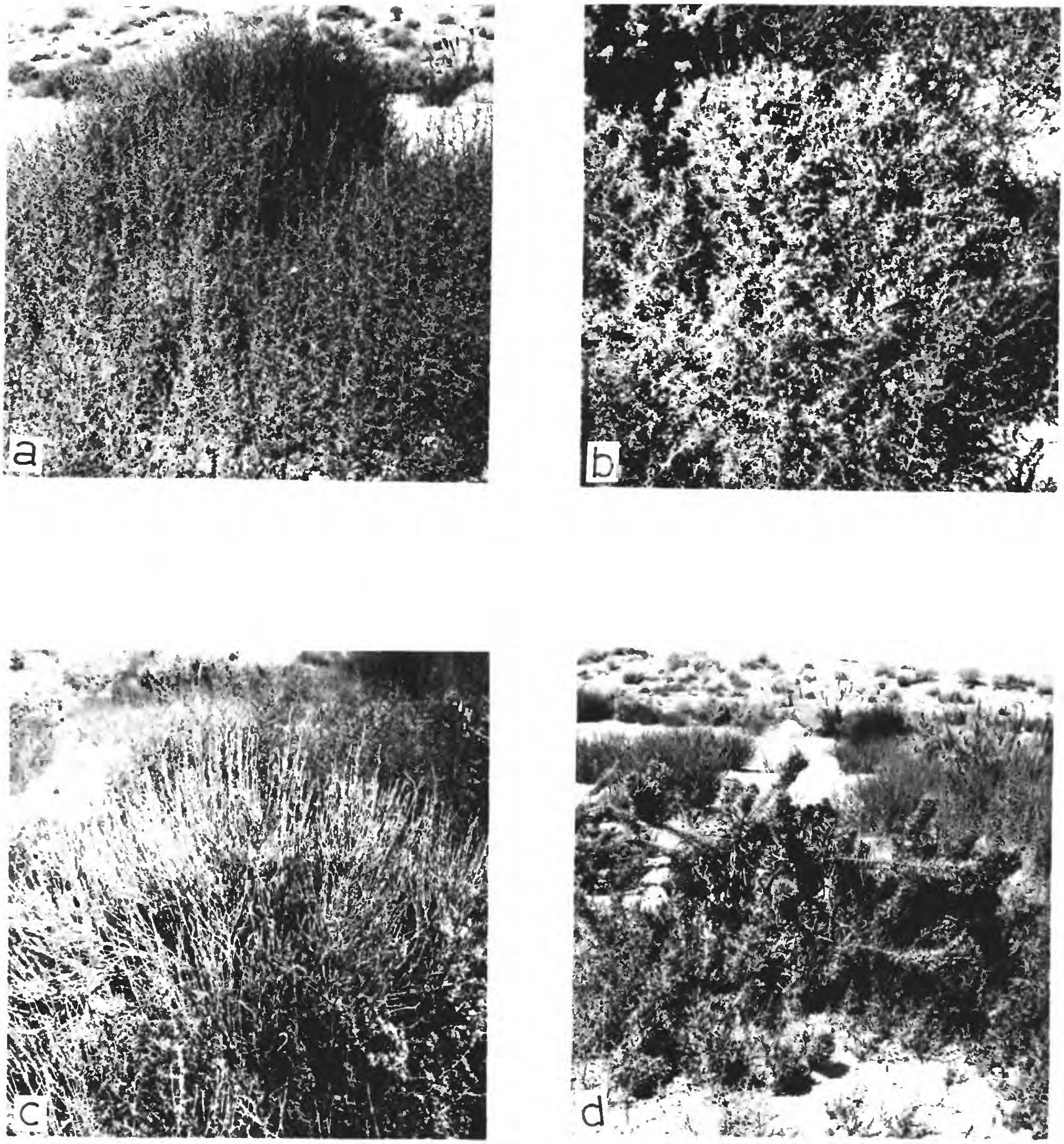


Figure 10. Anomalous shrub growth in seep draining alpha contaminated area.
a, Salsola iberica stimulated to grow to height of 1.5 m.
b, Atriplex confertifolia with abnormally fine leaves.
c, Eurotia lanata, knobby spike growth. d, Stanleya pinnata, spikes of apetalous flowers with thick green sepals and no stamens.

Shields and Rickard (1959) described Stanleya pinnata on Frenchman's Flat as being fasciated and branched into as many as 6-8 branches from one stem. They reported that the stamens produced anthers but no pollen, the petals were green, the siliques were recurved, abortive, and some had analoid crowded masses of tubercles. In 1960, they reported on an irradiation experiment. Stanley plants were irradiated in May from a ^{60}Co source of up to 10,000 R. In July, the plants flowerd and a few produced abnormal branches with vegetative growth from flower parts. One plant produced whorled fasciated leaves.

Intolerance of radiation by Stanleya pinnata (a selenium indicator plant) was previously noted in the Yellow Cat uranium district on the Colorado Plateau. Although Stanleya grew down-drainage from the uranium ore, which contained selenium, the flowers were abnormally imperfect and hence stands of Stanleya did not occur around the surface deposits of high radiation intensity. Because morphologically affected plants were observed, experimental plot studies were conducted. Seeds were sown in control plots, and in plots to which sodium vanadate; carnotite $(K(U_2)(VO_4 \cdot nH_2O)$; carnotite plus sodium selenate; and sodium selenate had been added. The seeds germinated and matured only in plots that contained sodium selenite, as was expected. In the plot that contained carnotite ore in addition to sodium selenite, the plants developed no petals or stamens but greatly thickened green sepals. To test whether this phenomenon was due to radiation or to some chemical element in the ore, a radioactive thorium ore (vanbergite) of completely different chemical composition but with a similar radioisotopic disintegration series was added to the selenium plot in which the Stanleya was already in bloom. After about a week the flowers that were opening at the top of the spike resembled those of plants growing in the carnotite plot--that is, they had no petals or stamens and thickened sepals. Also the spike divided (fig. 12 a, b, c). Following a heavy rain, which presumably lowered radon levels in the soil and perhaps washed radon out of the plant, the spikes produced normal flowers for a short period and then reverted to their anomalous growth habit. These experiments proved that the morphological effects noted in Stanleya (morphological changes along the spike with changes in radioactivity are cytological effects of radiation rather than genetic mutations, as has been suggested.

Contained nuclear explosions

The locations of the nuclear explosions that were studied and are described in this report are shown in figure 1. Subsidence craters are the end result of collapse of a deeply buried nuclear explosion cavity extending to land surface, where the volume of the surface subsidence is essentially equivalent to the volume of the nuclear explosion cavity. Initially with the primary shock wave the ground is elevated for a few meters and radial and concentric cracks develop. Then the rocks above the cavity collapse resulting in a subsidence crater at the surface. Subsidence craters have little observable effect on the vegetation growing in the central area of initial uplift and eventual subsidence. Generally the plants show no evidence of water loss and are able to withstand root shock and to continue to grow normally; only plants that are rooted along concentric and radial fractures associated with the movement are disturbed. Careful studies of two explosions were made on Pahute Mesa by Rhoads (1976). He found Cowania to suffer greater

Figure 12. *Stanleya* grown in experimental plots in 1955 in connection with uranium exploration research. Plants developed apetalous flowers, no stamens, and thickened green sepals in radioactive soil. a, Normal *Stanleya* in control plot. b, *Stanleya* in plot treated with vanbergite (Th) ore during growth of spike. c, *Stanleya* in plot treated with carnotite (U) before seed germination.

damage than either juniper or sage. The Handley event was a 1 megaton charge exploded at a considerable depth in March of 1970 in the volcanic sediments of Pahute Mesa. The area was visited by the senior author one month after the detonation when the ground was still mounded and the collapse had not yet occurred. The plant association of juniper and sage was completely undisturbed; no damage to shrubs that were growing along fractures in the ground surface was observed. There was no opportunity for the authors to revisit the area after the collapse. Several subsidence craters in the alluvium of northern Yucca Flat were examined but no followup schedule of visits was considered to be necessary.

The effects on vegetation around eight contained and partially contained detonations emplaced from 110-839 m (not designed to produce subsidence craters), were studied at various time intervals (figure 13) depending on accessibility and time available to the senior author. Of these, six were located at the Nevada Test Site, one in Mississippi and one in northern Nevada. Three of the explosions, Marshmallow, Tiny Tot, and Duryea had small escapes of radioactive gas through vents or up the access shaft. A total of 38 site inspections were made and analyses for radionuclides were made by gamma spectrometer of plant and soil samples collected on 29 site visits. After scanning, the plant and soil samples were analyzed by gamma spectrometry and a few samples were analyzed in addition for ^{90}Sr. The results were calculated by computer back to the date of collection and the date of detonation. No analyses for tritium were made nor are the levels known.

Physical effects on vegetation were noted along rock fractures where actual damage to roots had occurred. Commonly only the side of the shrub died from which roots had been actually torn apart by fracture movement, and the remaining portion of the shrub quickly recovered from shock.

Washed plant samples collected from control areas produced no autoradiographs, and those collected near contained explosions produced less bright autoradiographs than samples collected in the path of radioactive gases from explosions. With time, autoradiographs of certain species indicate an actual uptake of radionuclides through the roots; difference in species uptake was observed. Samples of sage from four sites, which were collected from 6 weeks to 3 1/2 years after the explosions, produce good autoradiographs in 3-12 months exposure time; Grayia and Hymenoclea from the same sites produce faint shadows; and Chrysothamnus, Purshia and Atriplex produce none. Oak and juniper at two sites showed a definite increase in radioactivity with time.

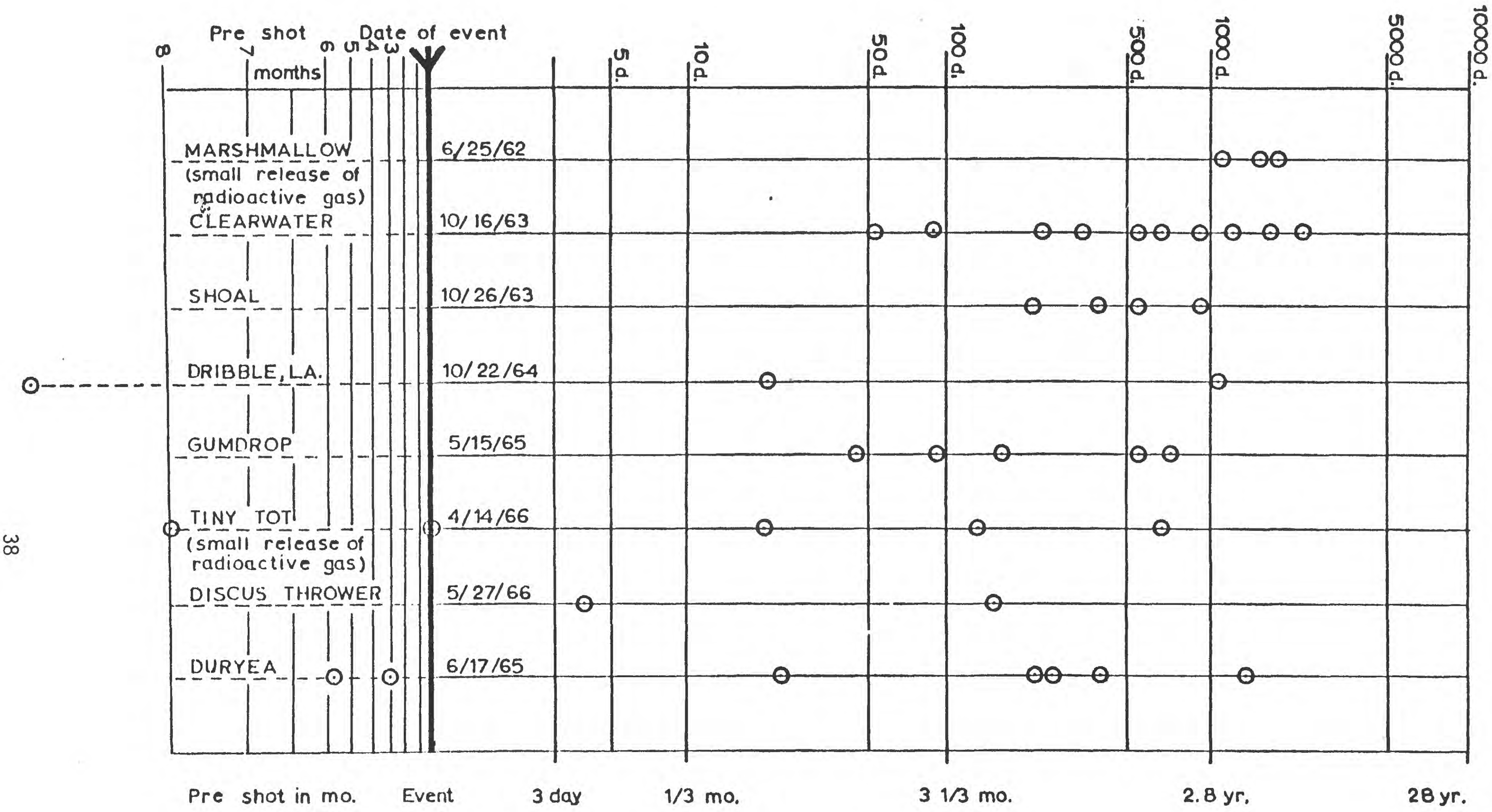


Fig. 13 INTERVALS OF STUDY OF CONTAINED EXPLOSIONS

In general, the maximum radionuclide contents measured in vegetation near explosions that were reported to be completely contained at the time of detonation were not significantly above background and consisted mainly of the long ranging contaminants ^{144}Ce, ^{137}Cs, and ^{90}Sr. Near the three detonations that were reported to have small atmospheric releases of radioactivity, ^{60}Co, ^{65}Zn, $^{95}ZrNb$ and ^{125}Sb, which generally travel only a short distance, were found in the vegetation. Moreover a juniper at Duryea, soil at Marshmallow, and Coleogyne and Ephedra at Tiny Tot, collected in the direct path of the atmospheric release, contained large amounts of $^{140}BaLa$. These analytical data, plus autoradiographs, support the contention that vegetation in these areas has absorbed radionuclides and that radiation is responsible for the gradual death of the coniferous trees at ever-increasing distances from ground zero. Similar increases in radionuclide content and increased brightness of autoradiographs in tree samples at Clearwater and Shoal suggest gradual leakage of radioactivity with time along fractures caused by the explosions. Detailed information regarding contained or relatively contained explosions is included under descriptions of specific explosions.

Nuclear explosions accompanied by release of radioactivity

Studies of Nevada Test Site events that were accompanied by a large-scale release of radioactivity included seven atmospheric explosions detonated from towers, two tunnel detonations that exploded out through the tunnel entrance, one partially contained detonation in alluvium, and three throwout craters. These sites were revisited from 1963-1970 at intervals shown on figure 14. A total of 86 site inspections were made and isotopic analyses by gamma-ray spectrometry were made of plant and soil samples from 37 inspections.

An atmosphere release of radioactivity, either planned or unplanned, may accompany nuclear explosions. The effects on vegetation are noticeable, long lasting, and may be evident for several miles. The long-term effects of radiation are particularly devastating to coniferous species; deciduous shrubs are often thrown into a resting period of suspended growth followed by gradual recovery. On the other hand, several adventive herbs and grasses are not only tolerant of large amounts of radiation but also germinate prolifically in the disturbed ground. The radiation insult to the vegetation originates in a combination of extremely high levels for a short period of time followed by much lower levels over a long period of time. Radiation induced by a hydrogen bomb, for instance, is decreased by four orders of magnitude in the first week. In the years that follow, trees and shrubs absorb certain radionuclides preferentially depending upon the plants requirements for certain elements.

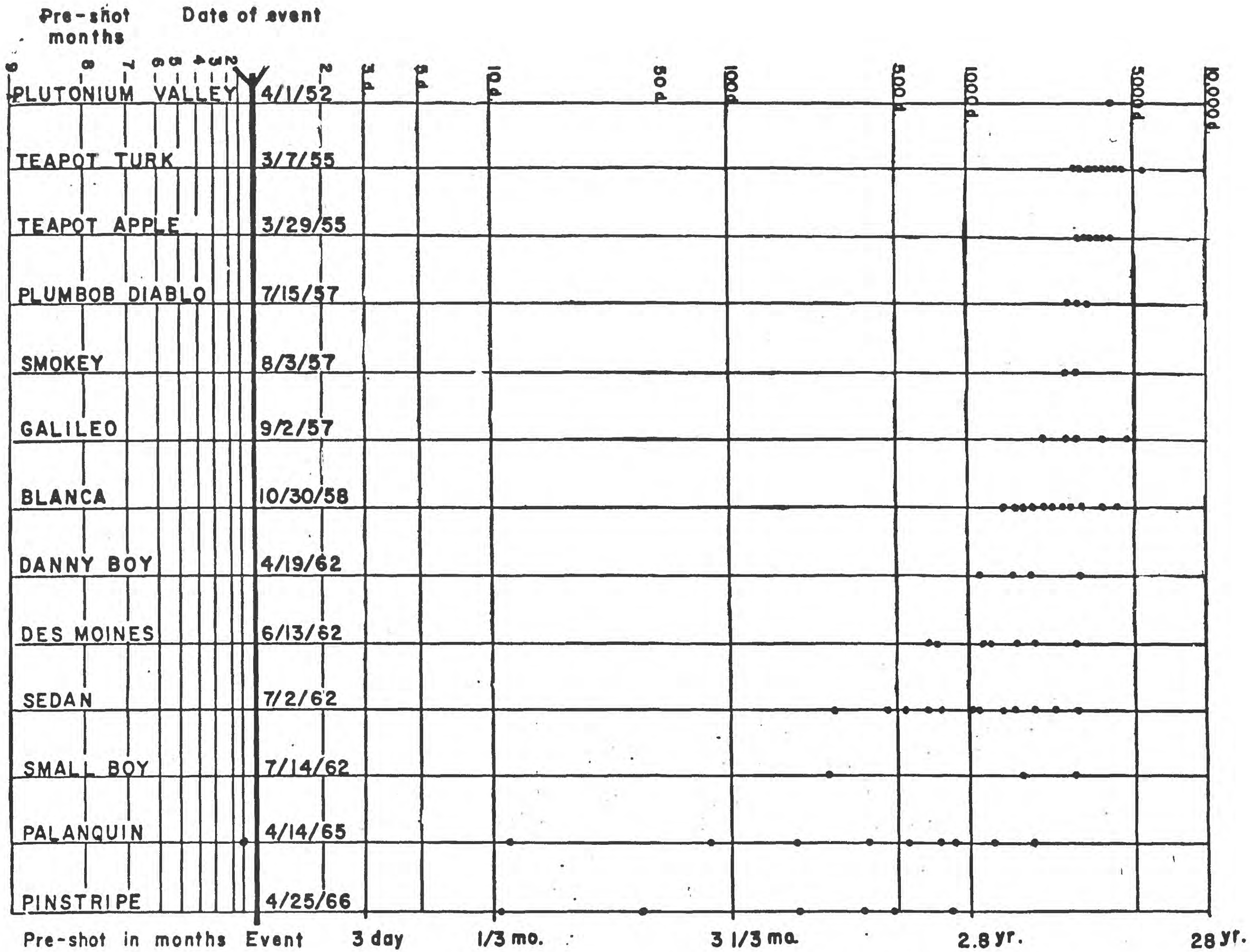


Figure 14.--Graph showing intervals of study of nuclear explosions that released radioactivity to atmosphere.

The radionuclides that are released from a 1-megaton bomb that has been detonated in basalt, their quantity, and half-life are given in table 7. The calculations were made by Miskel (1964) on the basis of two orders of magnitude neutron shielding. Collections were actually made of plants and soils 12 days after one event where the ground readings of 7 R/hr were measured, but the samples were too radioactive to be taken into the laboratory and were eventually buried by radiation safety personnel. Maximum contents of radionuclides in the first collections that were made around detonation points, shown in table 6, include thousands of picocuries per gram of ^{144}Ce, ^{95}ZrNb, and ^{106}RuRb at some of the sites. Adventive annuals had absorbed several thousand picocuries per gram of ^{95}ZrNb from the soil around the old sites of atmospheric explosions released from towers 7 or 8 years previously. Calculated to date of event, soil samples contained 7 mci/g of ^{144}Ce and ^{95}ZrNb around several of the towers, and similarly from several of the cratering explosions. Calculating disintegration rates to date of event for annuals that are living at present is not possible, but trees and shrubs that are believed to have been alive at the time of the event, calculate to very large concentrations. More than 50 mci/g of ^{95}ZrNb was calculated for trees and shrubs alive and dead, that were probably still contaminated with radioactive dust from the Blanca event. In many instances, however, values calculated to the date of the event increase with time in shrubs collected over a period of years. This demonstrates continued absorption of radionuclides because the amounts at the time of event should not change if the radiation is due to radioactive dust contamination only.

Effects of chemical (dynamite) explosions on vegetation

The separation of purely physical from radiation effects on vegetation growing near nuclear explosions is difficult at the time of the explosion. The vegetation may be exposed to heat, ground shock waves, dust, and high levels of radiation, simultaneously. In order to avoid radiation effects, the purely physical effects of conventional underground explosions on surface vegetation were studied over a period of several years at eight localities in Arizona at which dynamite had been exploded for geophysical observations related to the Mantle Project. The project afforded an opportunity to observe the effects of ground disturbance and dust from dynamite explosions of different tonnages detonated at different depth on native vegetation. The location of the study areas, the size of the explosives, the depth of emplacement, and the observed effects are shown in Table 8.

Table 7.--Release of radionuclides from 1 megaton device of 1 percent fission and 99 percent fusion (Miskel, 1964)

[Leaders, ---, indicate not calculated at to.]

	Half-life	Curies at t_o
Activation products:		
^{24}Na----------------------------	15 hr	1.9×10^4
^{31}Si----------------------------	2.6 hr	7×10^7
^{32}P (beta)----------------------	14.3 d	1.8×10^5
^{42}K-----------------------------	12.4 hr	2.8×10^6
^{45}Ca-(beta)---------------------	165 d	4.3×10^4
^{55}Fe----------------------------	2.7 y	7.5×10^5
^{56}Mn----------------------------	2.6 hr	8.4×10^8
^{59}Fe----------------------------	45 d	3.8×10^4
^{60}Co (beta + gamma)-------------	5.2 y	1×10^4
^{65}Zn (beta + gamma)-------------	245 d	---
Fission products:		
^{90}Sr (beta)---------------------	28 y	1.8×10^3
^{95}Zr (beta + gamma)-------------	63 d	---
^{99}Te----------------------------	2.1×10^5 y	6.7×10^6
^{131}I (beta + gamma)--------------	8 d	1.28×10^6
^{137}Cs (beta + gamma)-------------	33 y	1.6×10^3
^{140}Ba----------------------------	12.8 d	---
^{144}Ce (alpha, beta, gamma)-------	290 d	---
^{147}Nd----------------------------	11 d	7.5×10^5

Table 8.--Effects of dynamite exploded at depth by geophysical project on vegetation in Arizona

[Observations by H. L. Cannon]

	Location	Depth of emplacement (meters)	Amount of of charge (kilograms)	Relation to water table	Formation	Description of physical effects	Effects on vegetation
A.	Blue Mtn. east of Peach Springs, Coconino Co.	45 90 90	925 3048 3293	Above water table	Redwall Ls. under 16 m gravel	White lime throwout and cracks around 1 site	Vegetation dust covered but growth not affected
B.	Cottonwood, Yavapai Co.	45 60 90	1360 1824 2720	Moist	Limestone and shale	Only .3 m in diameter of ground disturbed	Grass and alfilaria undisturbed around shotpoint
C.	Strawberry, east of Pine, Gila Co.	46	1360	Above water table	Redwall Limestone and Naco Fm.	4)	Juniper sawed off, rapid growth to .9 m in 3 years
		38	1134	do		5)	No effects noted
		46	2720			6)	No effects noted
		43	2720			7) Scraped area, cracks noted, caved area 3 m deep	Manzanita killed where oil poured on ground
		45	1360			8) Small collapse noted after 1 yr.	Juniper sawed off is dead
		50	1805			9)	No damage
		43	910			10) Cercocarpos unaffected,	Manzanita drooped but revived
		30	245			11) Small caved area	Euphorbia growing in crater after 40 days Snakeweed and yucca in crater 1 yr. later
D.	Kohl's Ranch, 24 km E. of Payson, Gila Co.	14	245	Seepage	14 m limestone, then Troy Quartzite	Explosion crater 3 m across fracture pattern. Rocks and dirt thrown out by blast. Possible release of gases	Several inches of throwout covered annuals on road bank but annuals grew through cover. Plants around crater unaffected.
E.	Carrizo Creek, 6.4 km from Carrizo, Gila, Co.	30 46 46 60	435 910 898 1360	Water table at 14-16 m	Supai Gp. 15 m of alluvium then shale, ss. gypsum	Small craters, no cracks.	No affect on grama grass Lycium in edge of crater unaffected
F.	Bylas, 1 km W. of bridge over Gila River, Graham Co.	150 120 150 30	4545 3647 4518 898	Water table at 14-16	Alluvium 15 m and lake deposits	Transverse and radial cracks for 15 m from largest explosion sites	Creosote killed to crown in area of upheaval and faulting in 15 m radius. Also much destruction by bulldozer. First year, grass and alfilaria covered raised area and creosote shoots came out at base 3 yrs., creosote 70 cm high.
K.	4.8 km E. of Winslow, Navajo Co.	60 30 60 90	1824 975 1796 2720	Above water table	Moenkopi Fm. .6 m loose sand over shale, ss. gypsum	No physicals effects. Shot points graveled over	Grass and snakeweed unaffected outside of graveled area
L.	6.7 km S. of Sunrise, Navajo Co.	60 150 60	3647 4545 1824	Water table at 10.6-24 m	24 m alluvium over ss. and shale	Large step faults developed across fan	At 40 days, snakeweed dead along faults

Dynamite charges of 245-4545 kg were exploded at a depth of 30-90 m over a period of 22 days in April-May 1964. Although the effects on vegetation of dynamite explosions at this magnitude cannot be compared directly with large nuclear explosions detonated at greater depth, certainly the roots of deep-rooted shrubs and trees growing close to the shot-points should be effected by charges of several thousand kg at depth of 50-150 m and the tops by coverings of dust. Botanical studies were made immediately after the explosions and, at some localities, at intervals covering a period of 4 years, by which time most of the shot-points were impossible to locate with certainty. Generally, a small caved area of about 0.3 m in diameter could be observed at the surface over charges as high as 1,360 kg of dynamite. Three detonations were not completely contained as material from the shot-hole was blown out for several meters covering vegetation and the ground surface. At Kohl's ranch, the limestone was fractured, a 3-m crater was formed, and rocks were hurled at sufficient distance as to endanger the geophysicists. The extent of gaseous escape from the explosions is not known. In general, few effects of physical damage to vegetation were noted; the heads of dandelions were blown off, a manzanita died along a fracture, snakeweed died along a series of stepfaults. At several sites, the leaves of trees or shrubs closest to the shot point were darker green than in the surrounding area, presumably owing to the increased supply of nitrogen from the dynamite.

Two series of explosions, both in sediments overlain by 15-25 meters of alluvium, were of particular interest as effects ressembled those of contained nuclear subsidence craters. At Sunrise, where three explosions of up to 4543 kg at depths of 60-150 m were set off across an alluvial fan, step faults developed at right angles to the fan, and on the fault blocks, Gutierrezia (snakeweed) died on the fault blocks and was replaced by Russian thistle (fig. 14a).

At Bylas, four charges of 898 to 4,545 kg were exploded in old lake deposits covered with alluvium at a depth of 30-150 m. The area was studied before the detonations and six times afterwards during a 4-year period. The vegetative cover consisted of creosote bush, mesquite, cholla, barrel cactus, and grasses. Thick brown mud thrown out at the time of the explosions caked the vegetation around each shot point. Above the 4,545 kg detonation, radial cracks developed outward across a 15 m area around the shot point that had mounded at the time of detonation, and transverse cracks opened up around the circumference of the raised area. In the cracks, plant roots were exposed for a depth of 40-80 cm. The creosote bushes in the previously mounded area appeared to be dying two weeks after detonation and in a month were mostly dead within a 15-m radius of the shot point.

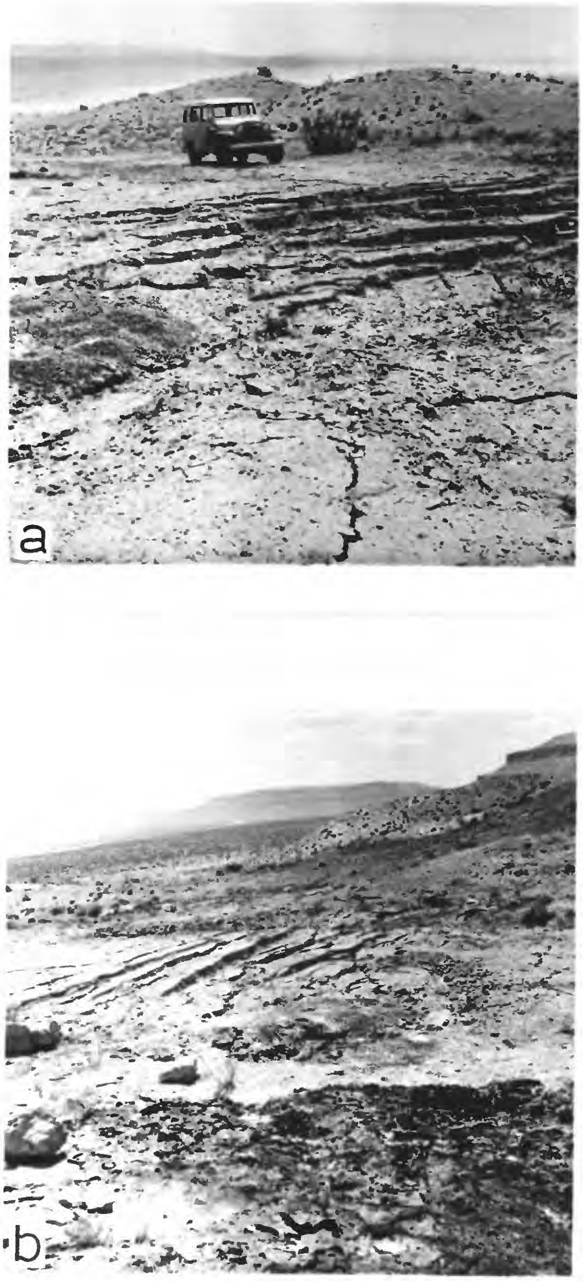


Figure 14a.--Sunrise, Arizona. Three explosions detonated across alluvial fan. a, Sunrise, step faults across alluvial fan; shot point at lower left. b, Gradual softening of breaks after 2 months; shot point in foreground.

One year after the Bylas detonations, grass, _Sphaeralcea_, and _Erodium_ sparsely covered the previously mounded area of the 4,545 kg explosion except for the crater 0.9 x 0.9 m in diameter that had been filled with gravel over the shot point. A mesquite 1-ft high had grown from the bulldozed root crown at a distance of 1.5 m from ground zero. Throwout blown by the wind had filled the radial and transverse cracks but did not appear to have encouraged plant germination. Shrubs broken off by truck activity were bushing out at the base. Although the explosions had not been completely contained, the damage to plants had been much more severe from bulldozers and trucks than from the actual detonations.

Two years after the detonations in April 1964, _Erodium_, _Eriogonum_, and grasses covered the shot points; a new _Larrea_ shoot had come up in the bulldozed area within 0.3 m of the 4,545 kg shot point. Although _Larrea_ is reported to be slow growing, the shrub was a meter high four years after the detonation and was darker green than other shrubs in the area, possibly owing to the nitrogen released by the dynamite explosion.

These conclusions might be drawn from this study. The effects of contained dynamite explosions of less than 2000 kg were undetectable. Those of partially contained explosions were negligable and shrubs cut off at the root crown by bulldozers and truck activity grew back quickly. The dust thrown up from non-contained explosions did not harm vegetative growth even when heavily caked.

Discussion

Around conventional chemical (dynamite) explosions discharged underground and around contained nuclear explosions there is more damage to vegetation from vehicular traffic, bulldozing, and the building of roads than from any other cause. Explosions detonated at the appropriate scaled depth of burst (SDOB = depth of burst-yield) to produce subsidence craters are designed to avoid release of radioactivity to the atmosphere. This type of detonation will disturb the vegetation physically little if at all, so that the subsided surface of the craters continues to be vegetated. Contained explosions of a greater scaled depth of burst, which do not crater may, if conditions are right, produce extensive fracturing and faulting. After such disruption, plant growth may be stimulated by the creation of fractures through near-surface caliche along which roots may penetrate or by providing channels through rock for a temporary upward surge of ground water to the root zone of deep-rooted trees or shrubs. On the other hand, the fractures or faults may disturb or destroy roots of plants; only the side of the tree or shrub next to the fracture may be killed or damaged. Deciduous trees or shrubs so damaged may color early in the fall so that the fracture pattern around ground zero is visible from the air and may be recorded on color air photographs.

Atmospheric nuclear tests and nuclear explosions that produce gas erosional or throwout craters effectively eradicate all vegetation for a considerable distance, and blanket the area with highly irradiated silicious glass and throwout material that will remain radioactive for decades. Such areas are soon covered with Russian thistle and the original plant population is extremely slow in coming back. Areas of atmospheric testing in Frenchmans and Yucca Flats appear from the air as green circles in early summer and as red circles in the fall, owing to the cover of Russian thistle and *Eriogonum nidularium*, dominant in the test areas for more than 10 years. These types of explosions, and also nuclear underground explosions that accidently vent through tunnel exits or along faults, may produce radiation damage to vegetation similar to that observed in controlled experiments with a radiation source. These effects have been reported by others and observed by the authors as a modification of apical meristem with reduction in growth and a stimulation of laterals in *Pinus*, *Quercus*, and other genera. Species tolerance to radiation has been shown to depend on cell nuclear volume, *Pinus* being least tolerant of any species observed. *Pinus monophylla* and *Juniperus osteosperma* are, as their tolerance limits are reached, dying back farther each year from explosions that were accompanied by a release of radioactivity. The plants, after 10 years, are absorbing largely ^{144}Ce, ^{137}Cs, and lesser amounts of ^{90}Sr. The continuous availability to plants of high levels of ^{144}Ce, which has a half-life of only 290 days, is probably caused by additions from later explosions. *Quercus* may go into dormancy at the time of the explosion and remain largely dormant for at least as long as 4 years followed by unsuccessful attempts at growth near the base. When the main branches break dormancy, curled deformed leaves are produced the first year and the terminal shoots die soon after emergence.

Pioneer plants of some species able to grow in highly radioactive soil have exhibited anomalous growth changes. Both *Chaenactis stevoides* and *Stanleya pinnata* have been observed to produce apetalous flowers with no stamens. The Stanleya produces thickened dark-green sepals and can produce a second or even a third plant asexually from the pistil. Plot experiments with Stanleya have shown that abnormal flowers can be produced by radiation. The production of large numbers of tumors has also been observed in Atriplex linearis. In conclusion, contained nuclear explosions do no lasting damage to the vegetative cover, but vented explosions may change the plant population or physiognomy by reducing or destroying the coniferous forests and encouraging grasses and adventive weeds. Deciduous trees may be defoliated, but many will eventually recover after a period of dormancy that may last many years.

Observed effects of specific nuclear explosions on vegetation

Contained nuclear explosions in Nevada and Mississippi

Gumdrop (NTS).--The emplacement was 180 m below the top of Tippapah Peak, 360 m from the tunnel entrance, and was detonated May 15, 1965. The rocks at the surface above the tunnel were highly fractured with a dominant set of fractures developed 0.9-1.5 m apart parallel to the tunnel face and extending for 60 m across the flat top of Tippapah Peak. Six site visits were made from 6 weeks to 1 1/2 years after the detonation. The plant assemblage on the mountain top included:

Artemisia tridentata, sage
Chrysothamnus viscidiflorus, rabbitbrush
Eurotia lanata, winterfat
Ephedra nevadensis, mormon tea
Oryzopsis hymenoides, rice grass
Bouteloua gracilis, gramma grass

Some shrubs were torn completely loose and dropped into the fractures; others had half their roots torn off but remained alive. At the end of 3 months, Ephedra growing along the fractures were mostly dead owing to root damage. No Ephedra remained by November, 1966. Wood of Artemisia and Ephedra growing along the fractures produced good autoradiographs in 12 months time (fig. 15); roots collected at the same time did not. Unwashed twigs were slightly more radioactive than washed, suggesting dust as a source of contamination. Small amounts of ^{54}Mn, ^{60}Co, ^{95}ZnNb, ^{125}Sb, ^{137}Cs, and ^{144}Ce were detected in sage and soil but the amounts were not sufficient to indicate a delayed escape of radiation from the explosion along the fractures.

Discus Thrower (NTS).--The emplacement was 330 m below the ground surface in northern Yucca Flat, and detonated May 27, 1966. Gamma radiation 4 days after detonation measured only 0.02 mr/hr at ground zero and 0.03 mr/hr along a fault with 1.5 m of displacement that opened up northwest of the crater (fig. 16). Grayia spinosa and Coleogyne ramossissima collected along the fault contained small amounts of ^{95}ZrNb (1.38 and 2.02 pci/g) and ^{106}Ru (0 and 6.72 pci/g) and 5 months later had died owing to physical damage, not radiation. Hymenoclea salsola, which had originally blackened and died back to the crown, put out new growth through the summer following the detonation.

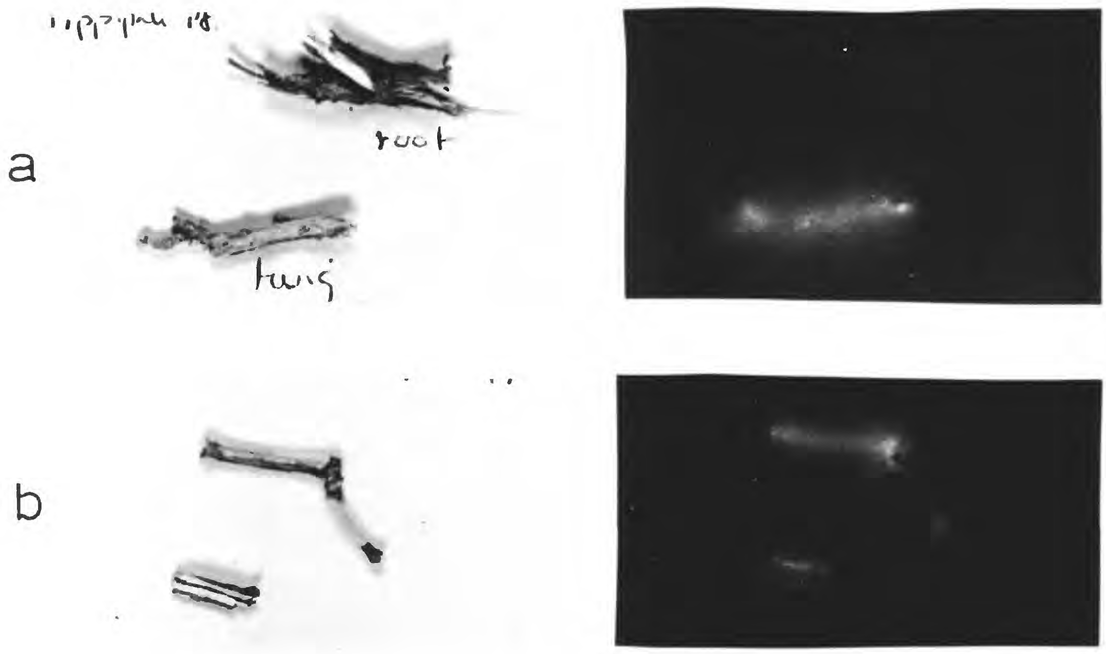


Figure 15.--Autoradiographs of Artemisia tridentata (sage) and Ephedra nevadensis (Mormon tea) collected along fracture produced by Gumdrop contained detonation, 6 months after detonation. a, Sage wood and roots. Autoradiographs after 12 months exposure time. b, Mormon tea twig. Autoradiographs after 12 months exposure time.

Figure 16.--Fault produced by Discus Thrower detonation, Nevada test site.

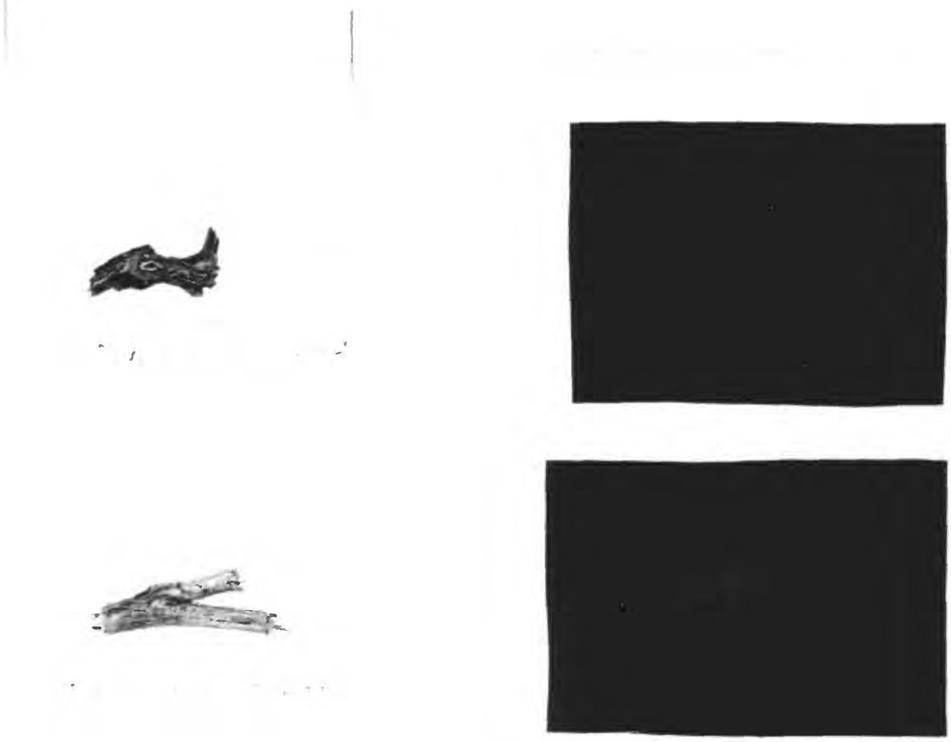


Figure 17.--Hymenoclea salsola collected 6 months after event along fault produced by Discus Thrower Nevada test site. Autoradiographs of old and new wood after 12 months exposure time.

The new twigs and leaves contained more ^{106}Ru (23.5 pci/g) than the early samples and also 2.66 pci/g ^{60}Co not detected earlier; the increase suggests contamination of the groundwater with $^{106}RuRh$ and upward movement of the water that should intercept the tuff acquifer at about 180 m (Winograd and Thordarson, 1975) along the fault. Hymenoclea is a phreatophyte. Autoradiographs were obtained on both dead and new growth (fig. 17). ^{106}Rh was also reported in sage growing along fractures more than 2 years after the Shoal event.

Dribble (Lamar County, Mississippi).--The emplacement was at a depth of 827 m in rock salt below the water table in Tatum salt dome, Louisiana, and was detonated October 22, 1964. After the detonation, the water table rose 55 m and then slowly receded. Mud balls of fine white sand appeared on the fill around ground zero and also northeast and southwest of ground zero on stream alluvium in the swamp. Pre-explosion collections of leaves and wood of four genera of trees, *Quercus falcata*, *Pinus palustris*, *Liquidambar styraciflua*, and *Nyssa sylvatica*, contained no short-lived radionuclides, but contained from 11.9-80.6 pci/g of ^{144}Ce, presumably from atmospheric fallout. Collections of the same species made 21 days after detonation showed small amounts of ^{54}Mn (1.7-5.0 pci/g) and ^{137}Cs (2.2-8.3 pci/g) not present in the earlier collections. Differences in reflectance that were measured on leaves by Itek Corp. were attributed to radiation escape; a small amount of leakage was later detected by the Atomic Energy Commission.

Marshmallow (NTS).--The emplacement was 315 m from the tunnel entrance and 182 m from ground surface on Tippipah Peak; the detonation was on May 25, 1962. A small amount of radioactivity was released through a vent 100 m or more above the tunnel. No plans were made to study this explosion until it was noticed on October 31, 1965, 3 1/2 years after the event that the pinyon (*Pinus monophylla*) above the vent were dying. Samples of damaged pinyon showed small amounts of ^{54}Mn, ^{106}Ru-Rh, ^{125}Sb, ^{137}Cs, and ^{144}Ce (table 9). The surface soil also contained $^{95}ZrNb$ and ^{140}Ba-La. One year later, the area of dead trees had spread considerably (fig. 18). The growing tips of the damaged pinyon produced an autoradiograph of bright intensity (fig. 19), whereas the older portions of the twig produced only a shadow, which indicates continued uptake of radionuclides.

Table 9.--Gamma radionuclides measured in pinyon and soil after Marshmallow event

[Analysts: C. A. Bush and C. M. Bunker; all values in pci/g; measured in dry plant; leaders, --, indicate not detected]

	^{54}Mn	$^{95}ZrNb$	$^{106}Ru\text{-}Rh$	^{125}Sb	^{137}Cs	$^{140}BaLa$	^{144}Ce
Pinyon 3 1/2 years after event--------	0.26	--	6.3	15.9	2.7	--	21.3
Pinyon 4 1/2 years after event--------	--	0.83	5.1	--	1.5	--	--
Soil 3 1/2 years after event--------	--	31.0	22.7	--	--	97.6	29.3

Figure 18.--Dead pinyon in path of Marshmallow atmospheric release 5 years after detonation.

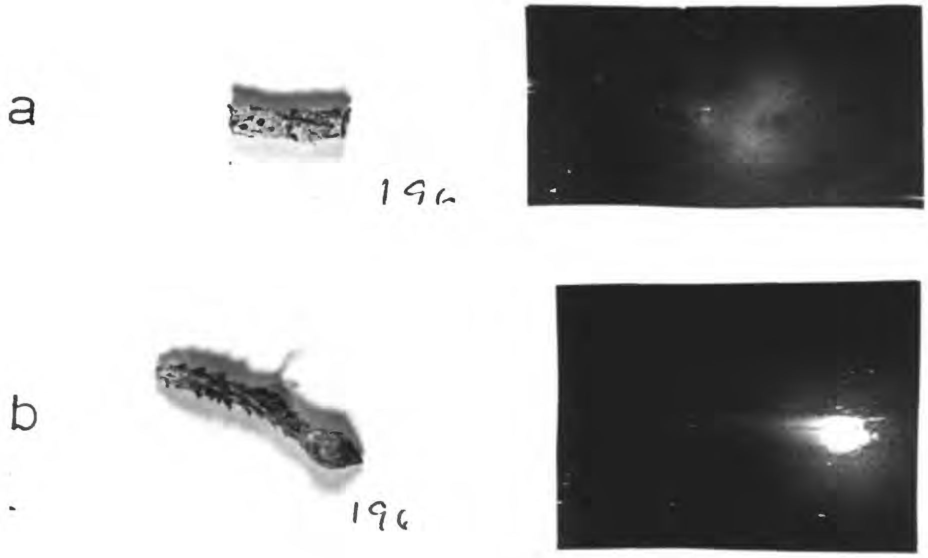


Figure 19.--Autoradiographs of *Pinus monophylla* in area of atmospheric escape of radioactivity above Marshmallow tunnel. a, 1962 portion of twig. b, 1965 terminal growing tip (12 months after exposure).

Tiny Tot (NTS).--Detonated on June 17, 1965 at the north end of Yucca Flat, at depth of 109 m in a large granite chamber, and was reported to vent slightly through the drift and up the access shaft. Four site visits were made to this area. The nearest vegetation that had not been removed during site preparation was growing 150 m east of ground zero. Pre-explosion samples show contamination from ^{54}Mn, ^{137}Cs, and ^{144}Ce in all plants and soils that were collected and ^{106}Ru in Coleogyne ramossissima. Wood sections of Purshia glandulosa show damage in mid 1957 presumably from the nearby Smokey explosion detonatd in Aug. 1957 in northern Yucca Flat (fig. 20). Plant samples collected 5 months after the explosion contained relatively low levels of the above radionuclides, $^{95}ZrNb$, and 72.6 pci/g of ^{140}La in Coleogyne and 108.5 in Ephedra nevadensis. Apparently the shrubs that were rooted along fractures absorbed relatively low levels of radionuclides. Analytical data are given for Purshia and Coleogyne in table 10. Autoradiographs were obtained of all three species (fig. 21); autoradiographs of Purshia were made through a 2-year period as shown in figure 22. Pre-explosion exposures showed the effects of an earlier atmospheric explosion.

Clearwater (NTS).--The emplacement was at a depth of 600 m and the device was detonated October 16, 1963 on Rainer Mesa. The explosion was reported to be completely contained in volcanic tuff. Five site visits were made to this area. A large amount of fracturing and faulting accompanied this event. Quercus gambeli (scrub oak) 52 m west of ground zero was covered with several inches of drilling mud and dust at the time of the explosion but the trees were not adversely affected. On the contrary, several trees were greatly stimulated in growth and put out 20-cm shoots (see fig. 3) in the first spring, possibly in response to increased water availability (figs. 23 and 24). Trees growing along radial and transverse faults were adversely affected by the physical movement, and many oak, pinyon and sage died where roots were greatly disturbed. Wood sections show development of traumatic canals in sage (fig. 25). This event produced a classical example of physical effects of shock to roots of vegetation. Roots of trees within 4.5 m of the major fault 300 m southeast of ground zero were affected. After 8 months, unhealthy

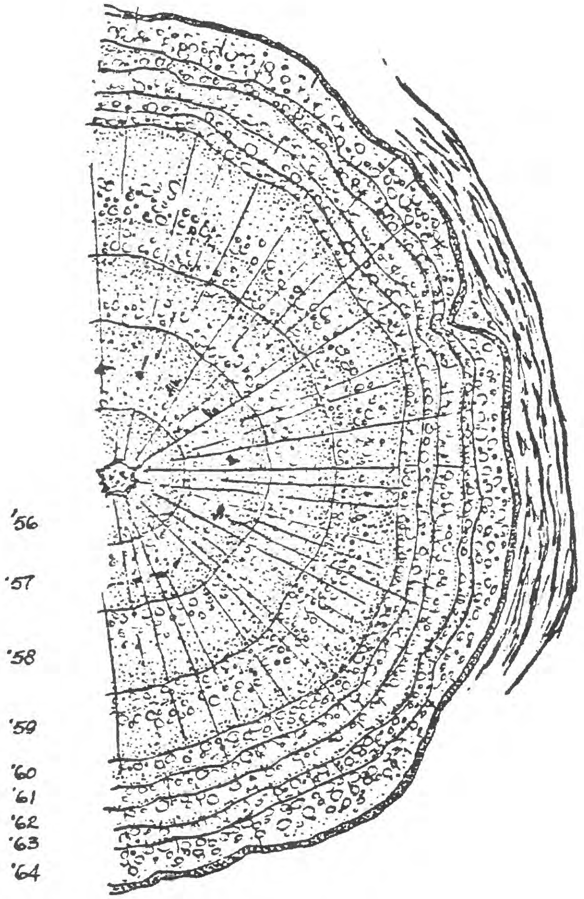


Figure 20.--Purshia wood section from area of Tiny Tot event showing effect from atmospheric explosions in 1957.

Table 10.--Radionuclides in picocuries per gram in two shrubs collected near Tiny Tot Ground zero

[Analysts: C. A. Bush and C. M. Bunker; measured in dry plant; leaders, --, indicate not detected]

	^{54}Mn	^{60}Co	$^{95}ZrNb$	^{106}Ru-Rh	^{137}Cs	^{144}Ce	^{140}La
Purshia glandulosa							
Pre-explosion-------	5.40	--	--	--	12.51	18.8	--
5 months------------	--	.32	4.98	16.8	6.43	30	--
1 year--------------	--	--	2.84	7.32	5.54	--	--
Coleogyne ramossissima							
Pre-explosion------	5.85	--	--	155	25.0	43.4	--
5 months-----------	.80	--	--	85	4.02	4.5	72.6
1 year-------------	--	--	6.82	10.8	6.54	--	--

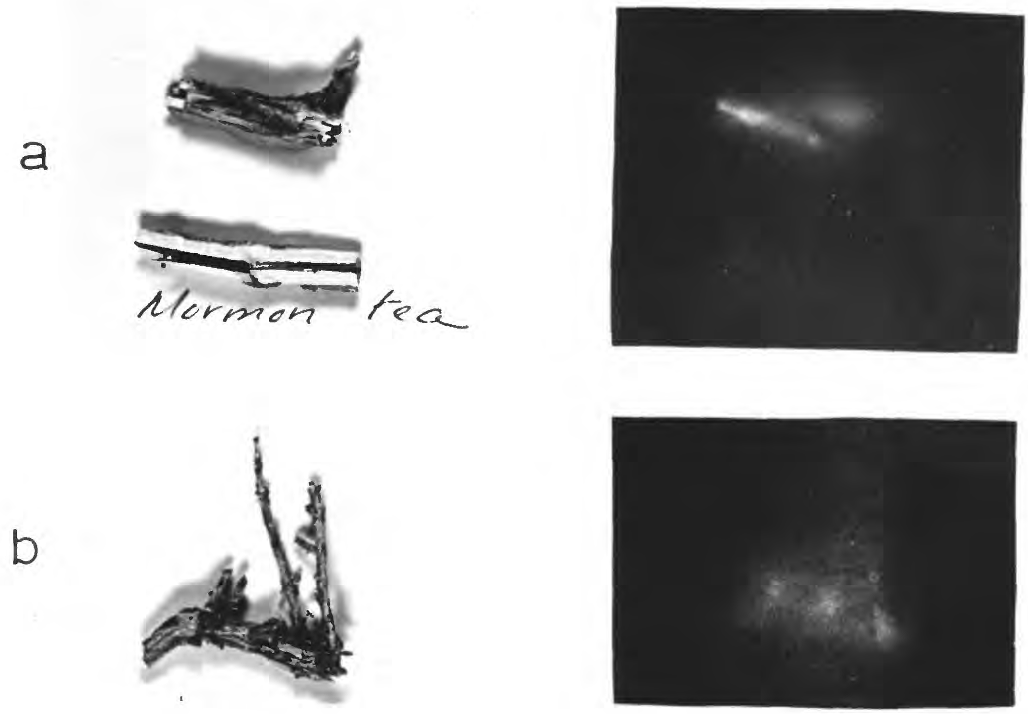


Figure 21.--Ephedra nevadensis (mormon tea) and Coleogyne ramossissima (blackbrush) collected 150 m east of Tiny Tot ground zero. a, Mormon tea collected 5 months after event. Autoradiograph after 6 months exposure time. b, Blackbrush collected 12 months after event. Autoradiograph after 4 months exposure time.

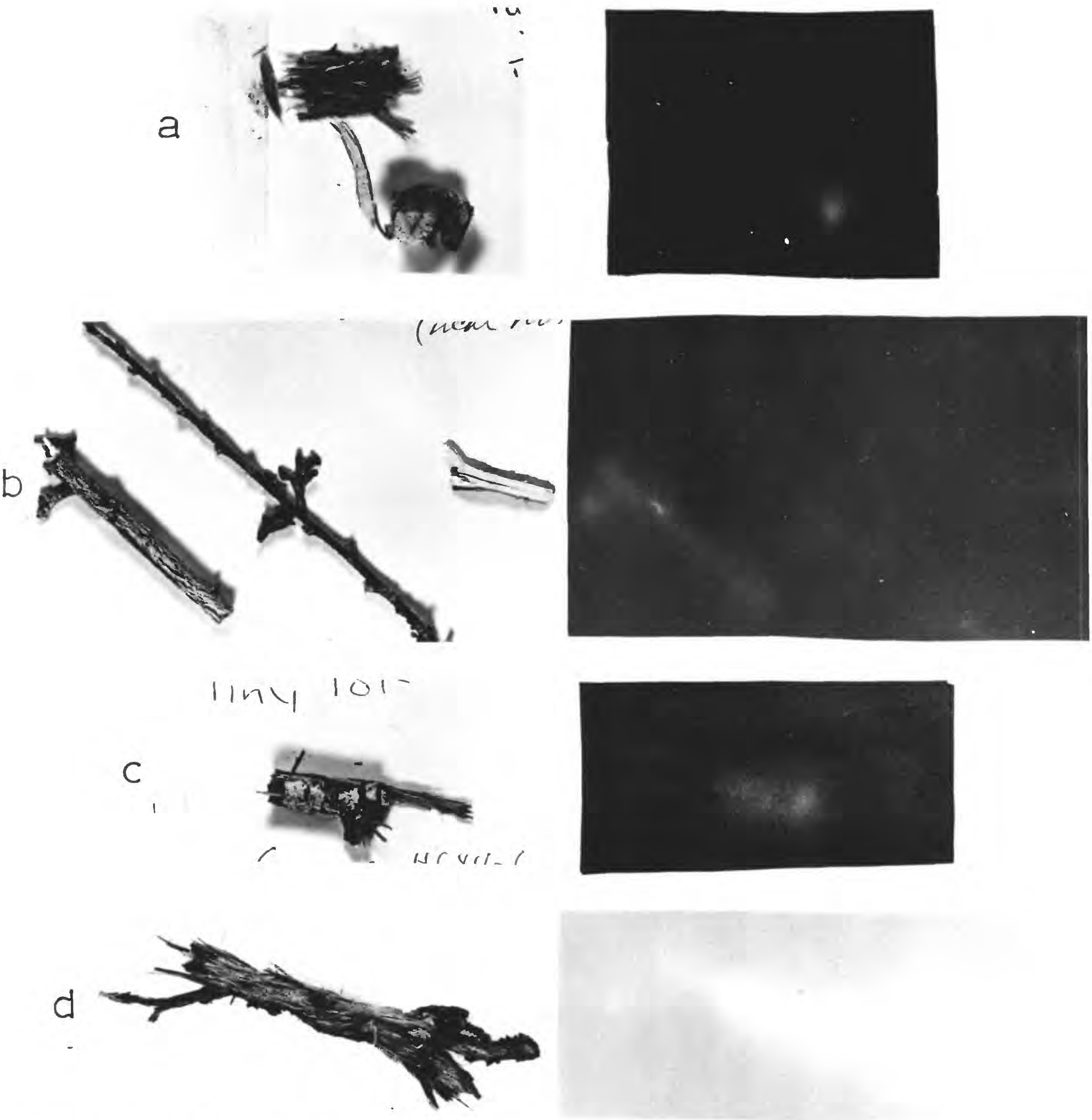


Figure 22.--Autoradiographs of <u>Purshia glandulosa</u> (antelope brush) collected before and after the Tiny Tot event. a, Antelope brush collected before the event. Autoradiograph after 3 months exposure time showing contamination from earlier atmospheric explosion. b, Antelope brush collected 5 months after event 150 m east of ground zero. Autoradiograph after 6 months exposure. c, Antelope brush collected after 12 months event. Autoradiograph after 4 months exposure time. d, Antelope brush collected 2 years after event. Autoradiograph after 13 months exposure time.

Figure 23.--Stimulated lateral buds of Quercus, 52 m west of Clearwater ground zero, 1964.

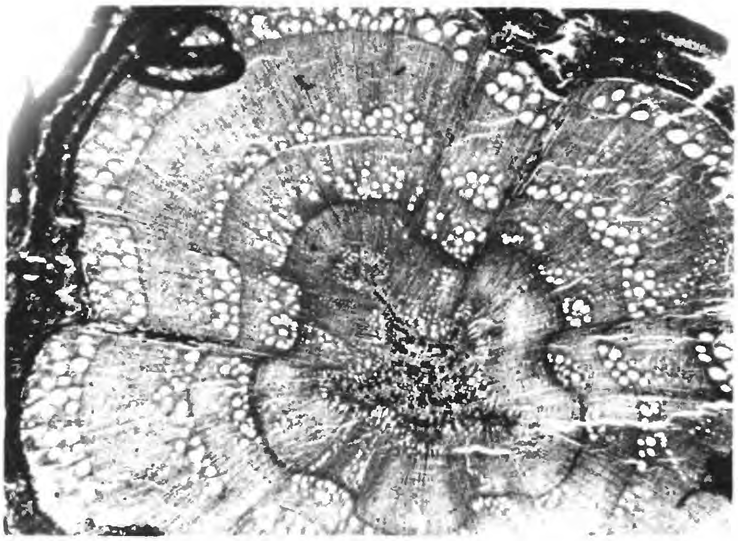


Figure 24.--Wood section of stimulated oak shoot collected in 1966, west of Clearwater ground zero.

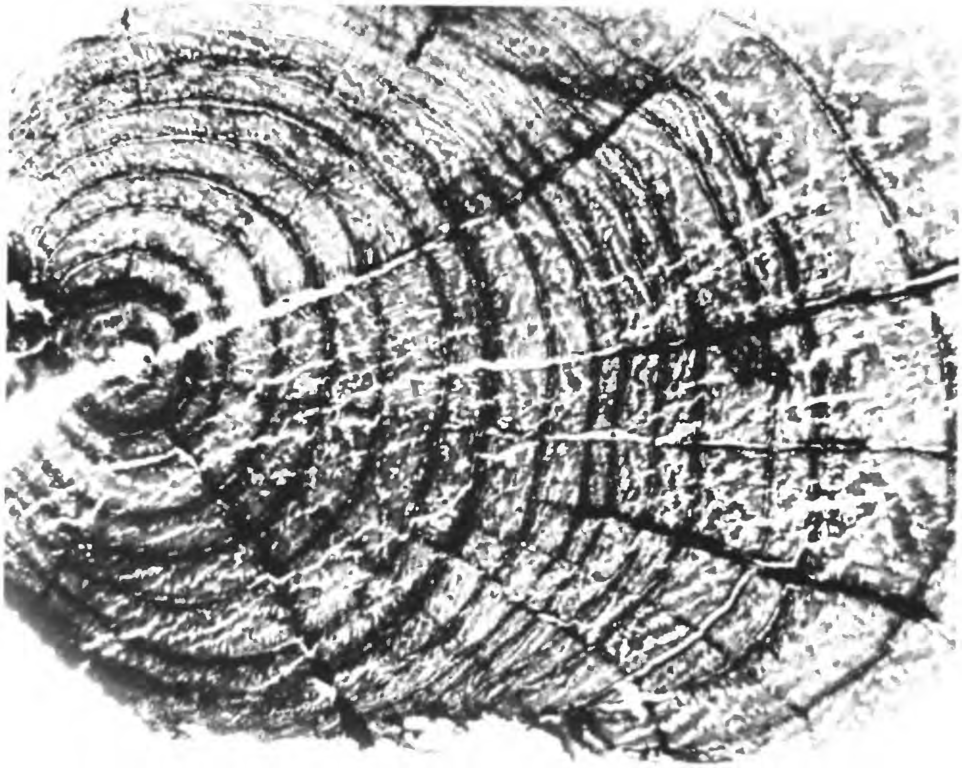


Figure 25.--Sage collection in 1966 shows traumatic canals in dying shrub.

pinyon and oaks with small leaves that colored early were observed. After 2 years and 8 months many oak and the conifers, pinyon, and mormon tea had died. Similar but less-extensive damage occurred in the vicinity of lesser fractures. Oaks growing in longitudinal areas along fractures were characterized by abnormally red leaf coloration and turned color in advance of other oaks during the first fall (figs. 26 and 27). The pattern of colored patches was concentric and extended the same distance out from ground zero as the fracture pattern.

By 3 1/2 years after the event, all *Purshia*, and *Artemisia* were in an excellent state of recovery, but areas of pinyon were still unhealthy. Five years after the event, damaged pinyon and all species that had not been killed outright had completely recovered.

No radionuclides were reported in samples collected at the end of 3 months, except for a small of amount of ^{144}Ce from fallout. After 8 to 11 months, however, ^{54}Mn, ^{60}Ce, ^{125}Sb, and ^{137}Cs occurred in leaves and in growing tips of oak growing along the fractures, but not in measureable amounts in oak away from the Clearwater site. The same trees contained no detectible levels of radioelements after 2 years and 8 months (fig. 28). Autoradiographs also show shadows in oak collected at 8 to 11 months, and sage wood produces a faint image. These data suggest some leakage along the fractures at Clearwater, but disappearing completely after 3 years. By far the greatest damage to trees at this site is believed to be physical.

Duryea (NTS).--The emplacement was at a depth of 542 m on Pahute Mesa; detonation occured on April 14, 1966. The explosion was contained except for a small dust cloud that settled in a stand of trees 165 m from ground zero. Sections show the effect in the annual rings (fig. 29). A reading of 0.03 mr/hr gamma was taken within a few feet of ground zero, 23 days after the event. Polygonal cracking was observed in the soil but no rock fractures or faults (fig. 30). At a distance of 74 m from ground zero and 23 days after detonation, the vegetation was still dust covered but healthy. The assemblage consisted of grasses, *Astragalus lentiginosus*, *Chrysothamnus* sp., *Artemisia tridentata*, and *Atriplex canescens*. The latter (a phreatophyte) was dusty, but stimulated in growth by a rise in the water table; the bush was very lush and wet to the touch. The radioactive dust cloud apparently was too high to affect the vegetation nearest to ground zero but settled in the trees 165 m from ground zero and then moved across to the southwest. The trees and *Artemisia* in the path of the cloud yellowed and *Cowania* died.

Pre-explosion plant collections (but after the Palanquin explosions had vented 8 km to the west) contain $^{95}ZrNb$, ^{106}Ru, ^{137}Cs, and ^{144}Ce from atmospheric contamination but autoradiographs show no evidence of actual absorption. Juniper collected in the path of the Duryea dust cloud 23 days after the detonation, contained in addition to the above-mentioned radionuclides, 70 pci/g ^{140}Ba-La, and also some ^{54}Mn, ^{60}Co, ^{66}Zn, and ^{125}Sb. Two years and 7 months after the explosion, the concentrations of these

Figure 26.--Colored oak, Quercus gambeli, along fracture.

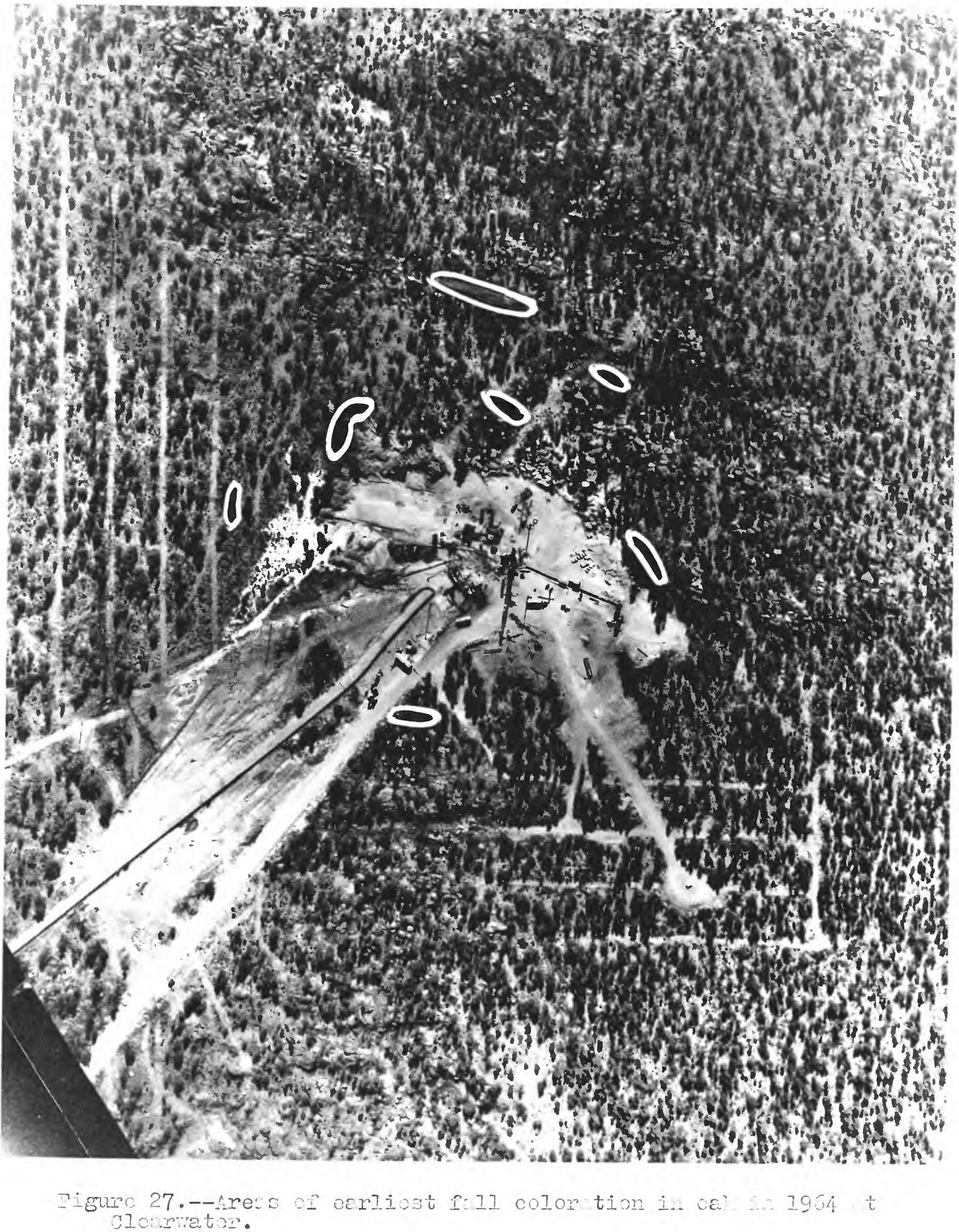
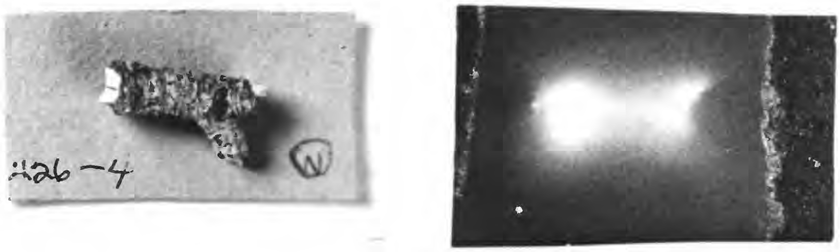


Figure 27.--Areas of earliest fall coloration in oak in 1964 at Clearwater.

a



b

Figure 28.--Autoradiographs from trees growing over contained Clearwater explosion. a, Pinyon collected 2 months after detonation 160 m from ground zero (10 months exposure) (Autoradiograph reversed in printing.) b, Oak collected 1 year after detonation 60 m from ground zero (4 months exposure) showing uptake of radionuclides by new growth.

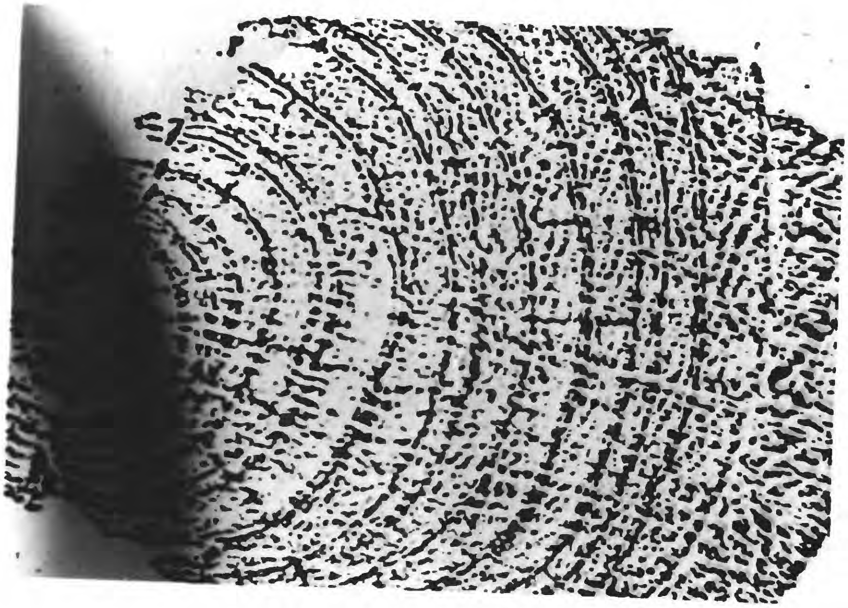


Figure 29.--Sage collected 2 months after the Duryea event shows no shock effects.

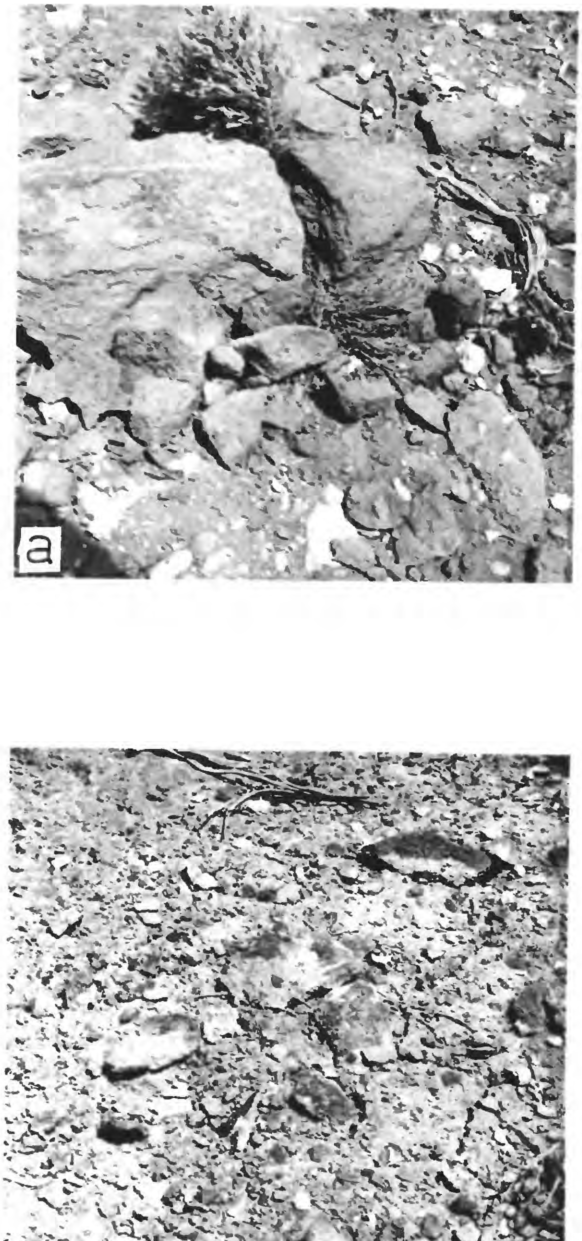


Figure 30.--Physical effects of Duryea event. a, Broken boulder; b, Cracks in soil.

nuclides had either lessened or could not be detected in the trees. The phreatophyte, Atriplex canescens (saltbush), which became wet to the touch close to ground zero, contained only fallout contaminants after 23 days but after 7 months contained ^{66}Co, ^{95}ZrNb, and ^{106}Ru-Rh, which are believed to have been absorbed from ground water. In the following year, after the ground water table had receded, the leaves were small and dry in contrast to their previous lush and wet condition. Autoradiographs of sage collected 75 m west of ground zero 23 days and also 7 months after the explosion showed only a faint shadow. Autoradiographs of sage, saltbush, and juniper collected a year after the event are shown in figure 31.

Shoal.--Churchill County, Nevada. The Shoal event was a contained nuclear explosion detonated on October 26, 1963 at a depth of 360 m in granite of the Sand Springs Range. Four inspections were made of this site, which is 320 km northwest of the Nevada Test Site. A considerable amount of fracturing resulted from this explosion; several long fractures extended west from ground zero for more than 270 m and prominent cross fractures were observed 90 m from ground zero. The fracturing seriously affected the shrub cover, -Grayia spinosa and Ephedra nevadensis more so than Artemisia tridentata. After 1 1/2 years, most Grayia and Ephedra plants in the area of cross fracturing were dead and the side of many shrubs nearest the fracture was dead along the length of two major fractures. This effect on the shrubs was largely physical and can be attributed to root brittleness. Growth differences in sage can be seen in the wood sections (fig. 32). Growth stimulation may have been caused by a rise in water table. The settling of fine dust over the area was favorable for the germination of Bromus tectorum (cheat grass) and Artemisia, which were much in evidence 1 1/2 years after the event. In an area east of ground zero near the equipment for exhausting the air from the shaft through a series of filters and finally through a stack, the shrubs had been killed to the crown in 13 months.

The best evidence of leakage along fractures from otherwise contained explosions was obtained in the shrubs at intersecting fractures just west of ground zero (table 11). Early collections at 7 and 13 months after the explosion contained far-ranging ^{144}Ce, ^{137}Cs, and also some ^{54}Mn and ^{125}Sb, which were no longer detected in samples collected after 2 1/2 years. ^{95}Nb was detected at four stations from 82 m to 290 m from ground zero, ^{60}Co was detected at one station and ^{106}Ru appeared in sage after 2 1/2 years in 2 samples. The contents reported are greater than background levels in Yucca Flat. Unfortunately, the 1965 samples were not analyzed, although good autoradiographs of wood were obtained. Analyses show an increase in radionuclides with time and also a consistently greater uptake by Artemisia (sage) than by Grayia (hopsage), which may explain in part the greater tolerance for radiation observed in Grayia by Wallace and Romney (1972). Higher concentrations of radionuclides were found in the shrubs that were growing 60-90 m from ground zero than at a greater distance. Autoradiographs of sage were brighter than of hopsage growing at the same sample station and were clearest in shrubs rooted in the intersecting fractures 90 m west of ground zero. The autoradiographs show a definite increase in radioactivity with time (fig. 33); sage collected 2 1/2 years after the explosion produced a brilliant autoradiograph of the growing twig tip. This evidence substantiates the premise that leakage has occurred, particularly at the intersection of fractures 60-90 m west of ground zero.

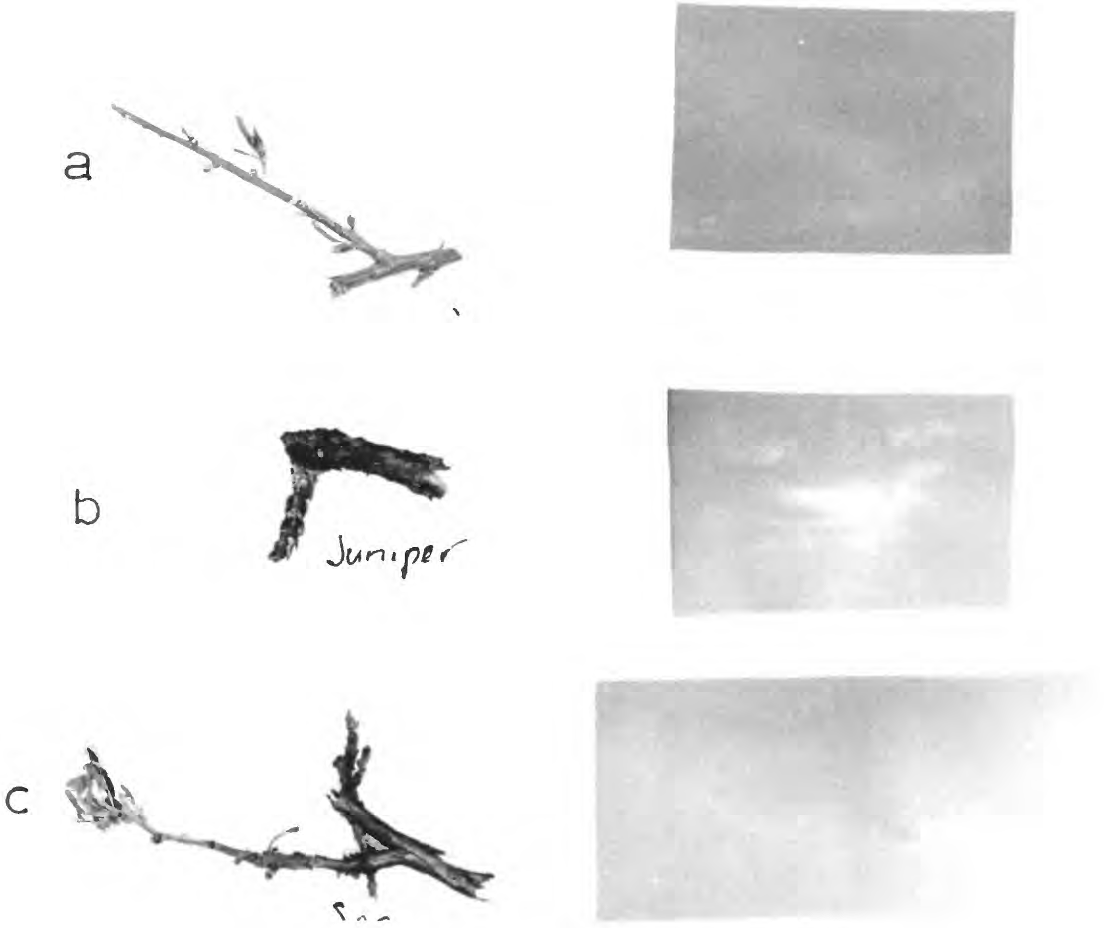


Figure 31.--Autoradiographs of *Atriplex canescens* (saltbush), *Juniperus osteosperma* (juniper), and *Artemisia tridentata* (sage) collected 1 year after Duryea event. a, Salt bush 75 m west of ground zero. Autoradiograph after 6 months exposure time. b, Juniper 165 m west of ground zero in path of radioactive cloud. Autoradiograph after 6 months exposure time. c, Sage at same station. Autoradiograph after 6 months exposure time.

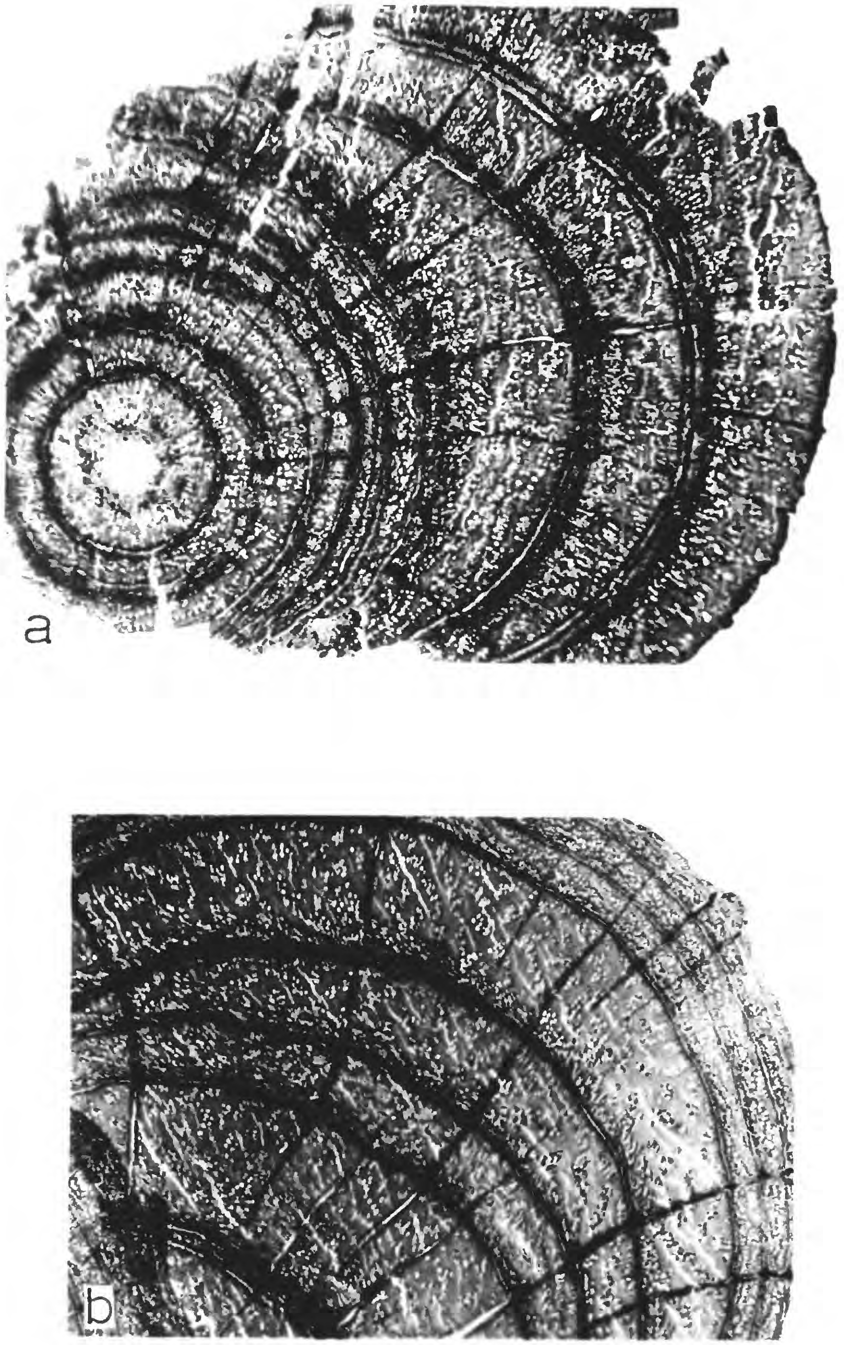


Figure 32.--Artemisia tridentata collected 90 m east of Shoal ground zero. a, Stem; growth actually stimulated on side of shrub toward fracture produced by explosion. Sample collected in 1966. b, Root; note traumatic eragastic fillings along rays. Sample collected in 1964.

Table 11.--Total gamma radiation in vegetation at Shoal site exclusive of natural isotopes and cerium

[Analysts: C. A. Bush and C. M. Bunker. Leaders (---) indicate not detected.]

Station (12)	Meters from ground zero	Plant	7 mo. incl. ^{54}Mn, ^{125}Sb, ^{137}Cs, ^{106}Ru-Rh		13 mo., same radionuclides as 7 months		2 yrs. 8 mo., $^{95}ZrNb$, ^{106}Ru-Rh, ^{60}Co only	
			Artemisia	Grayia	Artemisia	Grayia	Artemisia	Grayia
9 W	60	Sage---	---	---	20.88	---	---	---
10 W	82	Hopsage	---	---	---	1.97	---	---
	82	Sage---	---	---	---	---	14.64	---
	in exhaust							
8 E	90	--do---	---	---	12.34	---	---	---
	on hill							
13 E	90	--do---	---	---	---	---	25.40	---
6 W	90	--do---	16.73	---	---	---	---	---
		Hopsage	---	9.26	---	10.27	---	---
11 W	97	Sage---	---	---	---	---	14.58	---
5 W	160	Hopsage	---	14.81	---	---	---	---
4 W	190	--do---	---	246.85 (incl. 240. ^{106}Ru-Rh)	---	---	---	---
3 W	250	--do---	---	9.65	---	---	---	---
2 W	258	--do---	---	9.86	---	---	---	---
1 W	280	--do---	---	6.31	---	---	---	---
15 W	290	--do---	---	---	---	---	---	2.86
7 W	800	Sage---	---	---	13.48	---	---	---
		Hopsage	---	7.11	---	---	---	---
	Average		16.76	9.12 (+240 ^{106}Ru-Rh in one sample)	17.6	6.12	18.20	2.86

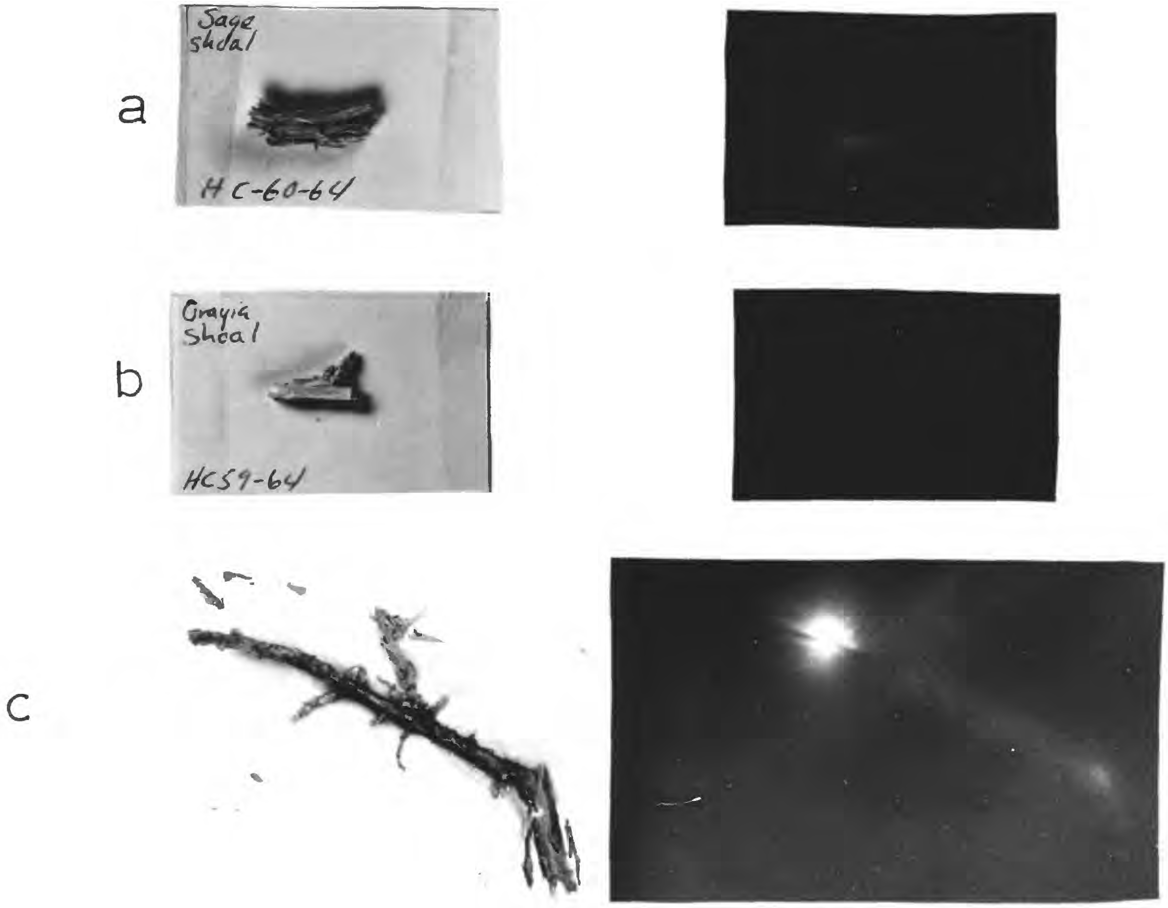


Figure 33.--Autoradiographs of Artemisia tridentata (sage) and Grayia spinosa (hopsage) collected 90 m west of Shoal ground zero at intersection of fractures in granite. a, Sage collected 7 months after detonation. Autoradiograph after 6 months exposure time. b, Hopsage collected at same time. Bright area of autoradiograph appears to be fork in twig. 6 months exposure time. c, Sage collected 2 1/2 years after event. Autoradiograph after 8 months exposure time shows bright area on growing tip.

Nuclear explosions accompaned by release of radioactivity

Partially contained explosions

The two tunnel explosions that were studied at NTS, had exploded out through the tunnel and a radioactive cloud had then blown back up over the forested mesa in which the tunnel had been excavated. Both emplacements were in tuff beds of Rainer Mesa. Physical effects on vegetation were confined to the areas of explosion and rock breakage at the tunnel entrances where roots of shrubs were physically damaged were and affected by the heat of the vented blast. The heat charred the bark of the trees and those that were not actually killed put out adventive proliferations along the branches as shown in figure 40 (in section discussing Blanca). By far the greatest damage to vegetation has been caused by radiation as described as follows.

Des Moines.--Series of charges were detonated in tunnels in volcanic tuff, in the side of Rainer Mesa in June, 1962. Two of the three explosions vented through the tunnel entrance; in one, the metal door was hurled against the hill on the south side of the valley, then the dust cloud turned with a change in wind direction and rolled back over the mesa above the tunnel.

The area was not studied for 2 years until an area of dead trees was observed in the path of the released cloud (fig. 34).

The foliated trees and shrubs closest to the rim in May, 1964, and also in August, 1965 were as follows:

	Distance from rim	
	May 1964	August 1965
Cowania stansburiana (cliffrose)---	9 m	3 m
Juniperus osteosperma (juniper)----	60 m	300 m
Pinus monophylla (pinyon)----------	90 m	450 m

The soil near the *Cowania* observed in 1964 measured 0.005 gamma and 0.015 beta radiation in milliroentgens per hour. Juniper, pinyon, and Mormon tea continued to die back farther from the rim each year, but shrubs and scrub oak gradually recovered near the edge of the mesa. *Cowania stansburiana* had been exposed to considerable contamination from ^{144}Ce, ^{106}Ru-Rh, and ^{95}Nb. When the ^{95}Nb contents in *Cowania* collected 4 1/2 years after the event are computed back from the date of analysis to the date of the explosion, a value of more than 8 M pci/g is obtained.

Several unusual growth phenomena were observed at this site. These include increased growth of laterals in oak, dead terminal tips in pine, clubby growth in *Eurotia lanata*, and shortened plumules in *Cowania stansburiana*. Wood sections of *Cowania* do not show a marked disturbance in growth rings (figs. 35 and 36).

Figure 34.--a, Clubby growth in *Eurotia lanata*. b, Dead trees in path of radioactive gas cloud vented from Des Moines explosion.

Figure 35.--Wood section of *Cowania stansburiana* over Des Moines tunnel. *Cowania stansburiana*, +9 m from rim, suffered considerable exposure (see fig. 36) but has flourished in area of dead trees. Note lack of resin canals.

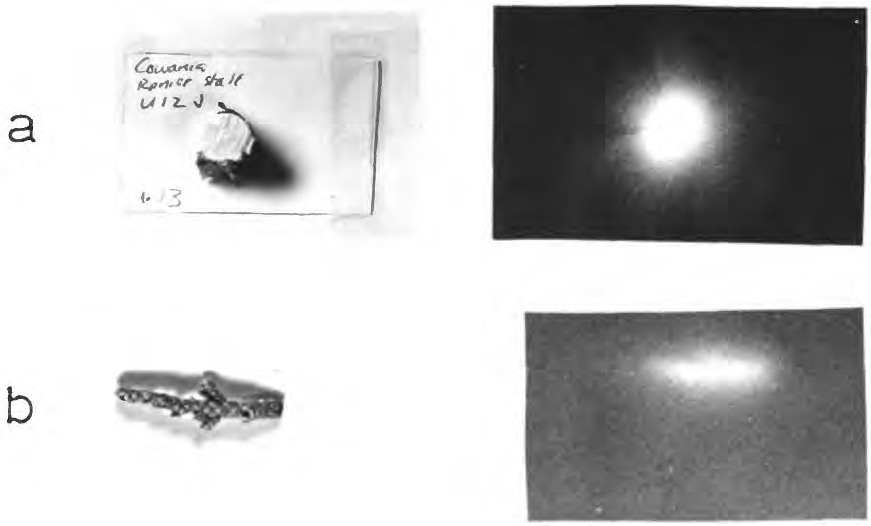


Figure 36.--Autoradiographs of *Cowania stansburiana* (cliffrose) collected 60 m from rim above Des Moines tunnel explosion. a, Cliffrose collected 2 years after the event. Autoradiograph of wood section after 10 months exposure time. b, Same cliffrose collected 4 years after event. Autoradiographs of twig after 4 months exposure time shows continued absorption of radionclides.

Autoradiographs (fig. 36) of Cowania 60 m from the mesa rim show continued absorption of radionuclides with 4 1/2 years post-explosion twigs producing as bright autoradiographs as 2 years post explosion wood. The shrub was still producing morphologically deformed fruits (fig. 37) in 1970. Juniper also shows increasingly bright autoradiographs with time (figs. 37 and 38).

Blanca.--A 19-23 kt nuclear bomb was emplaced in a tunnel 335 m beneath the surface of Rainer Mesa in volcanic tuff; it was detonated on October 30, 1958. There was an initital heaving, 450 m in diameter, of a portion of the mesa, and 15 seconds later a crater was formed by collapse of the chamber and a radioactive dust cloud hung east of the tunnel entrance briefly, then rolled back up over the mesa. The present edge of the crater at the top of the mesa is estimated to be 180 m from the original tunnel entrance. Neptune, a similar tunnel explosion that was detonated nearby on October 14, 1958, also vented and is responsible for a part of the damage to vegetation along the edge of the mesa.

Early observations at the Blanca site were described by Shields and Rickard (1959, 1960). Shield's and Rickard's report of 1959 to the U.S. Atomic Energy Commision states that at D+1 the 1R/hr (gamma) contour upwind was only 760 m from the Blanca tunnel, but that downwind the 9 R/hr contour extended 5-8 km in a pattern 1.2 km wide. At D+2, radiation at the crater was reduced to 2,100 mr/hr and by the end of November, 1958, was only 15-25 mr/hr. There was a gradual appearance of tree damage not accounted for by rock slide and by September, young juniper and pinyon were dead 150-225 m down-slope from the crater. Only the terminal shoots of most of the older pinyon and Ephedra in this area were dead but Ephedra was completely dead 45 m south of the crater. Above-ground portions of Coleogyne, Quercus, and Ribes were dead, but new shoots were appearing from the root crown. In May, Mentzelia albicaulis, Cryptantha pterocarya, Phacelia vallismortae, Mentzelia congesta, Gilia sinuata and Eriogonum trichopes were growing around the crater in the 15-25 mr/hr zone. By November of 1959, pinyon and juniper were dead for 0.8 km to the east and north of the crater ringed by a band of trees with dead branch tips and arrested apical growth.

Damage to conifers and shrubs, which Shields and Rickard attributed to root shock, had continued to appear over an expanding radius for a period of 2 years. Peripheral trees that had only damaged tips in 1958 were dead in 1959. The area of dead trees (pinyon and juniper) was first mapped by V. R. Wilmarth of the U.S. Geological Survey in 1959. At that time, the area of damage was largely confined to the east side of the mesa, as shown in figure 39, but has subsequently extended far to the west.

The senior author first visited the site in April 1962, 4 1/2 years after the device was detonated. The bark of pinyon and juniper trees growing along the edge of the crater was burned by the heat of the blast, and the trees have since put out adventitious proliferations along the branches. This effect has been noted in other burned areas (figs. 40 and 41). The oaks went into a resting stage, so that no leaves or growth were evident for 5 years after the explosion. The first leaves to emerge were twisted and deformed but were normal the following year. A similar phenomenon was described by Platt 1962 as occurring in oak near an unshielded reactor. Deciduous growth has since recovered in the path of the radioactive cloud but the coniferous pinyons, junipers, and Mormon tea have died back farther each year, and an area of partially dead trees now extends down the west side of the mesa.

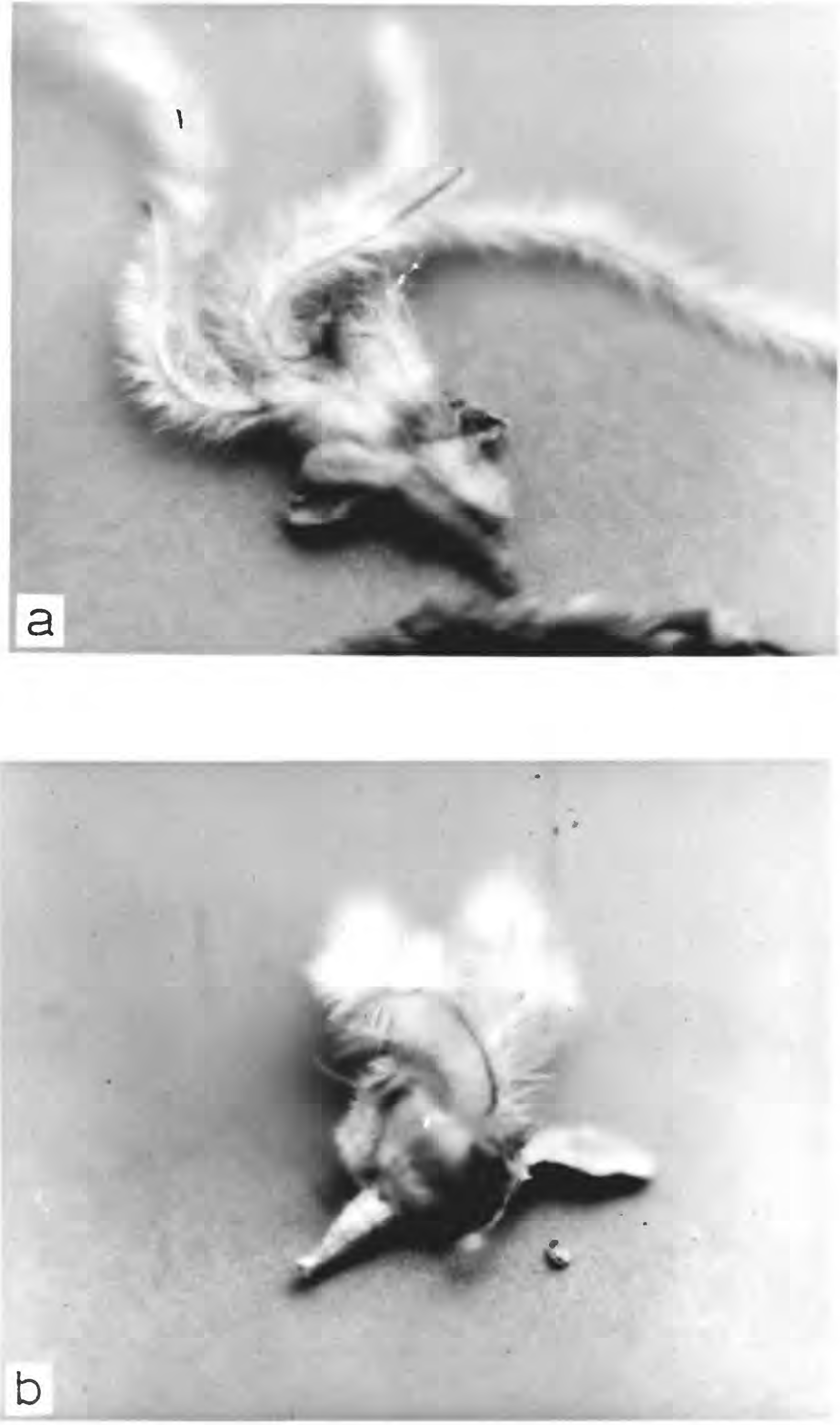


Figure 37.--Photograph of normal (a) and deformed (b) fruits of *Cowania stansburiana*.

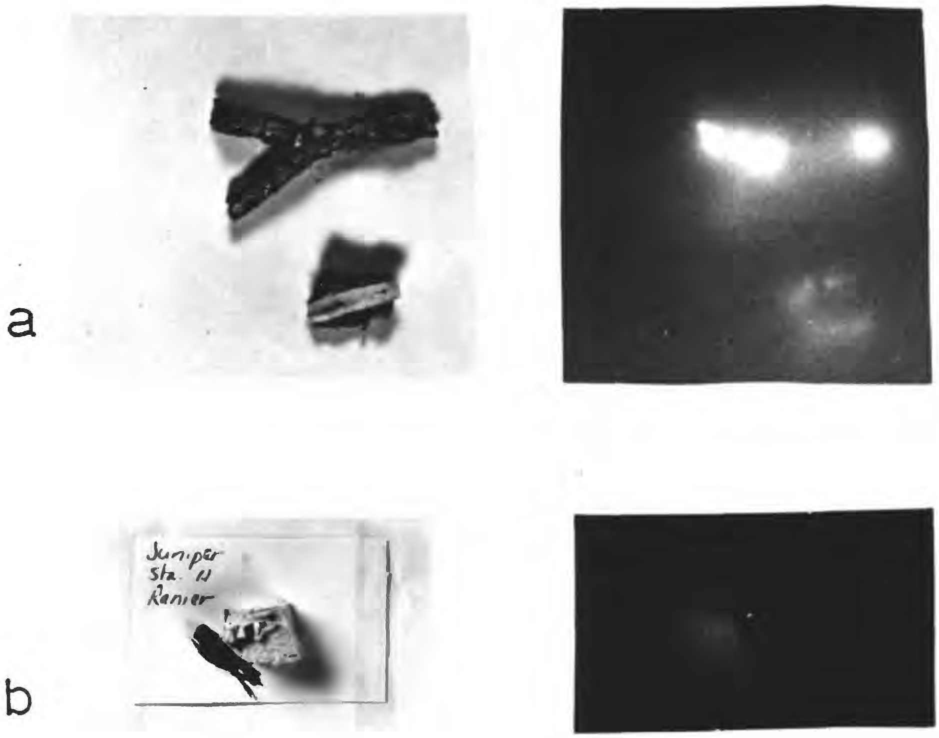


Figure 38.--Autoradiographs of Juniperus osteosperma (juniper) collected 84 m from rim above Des Moines tunnel explosion. a, Juniper collected 2 years after the event. b, Juniper collected 4 years after event. Autoradiograph of leaf scales shows absorption of radionuclides.

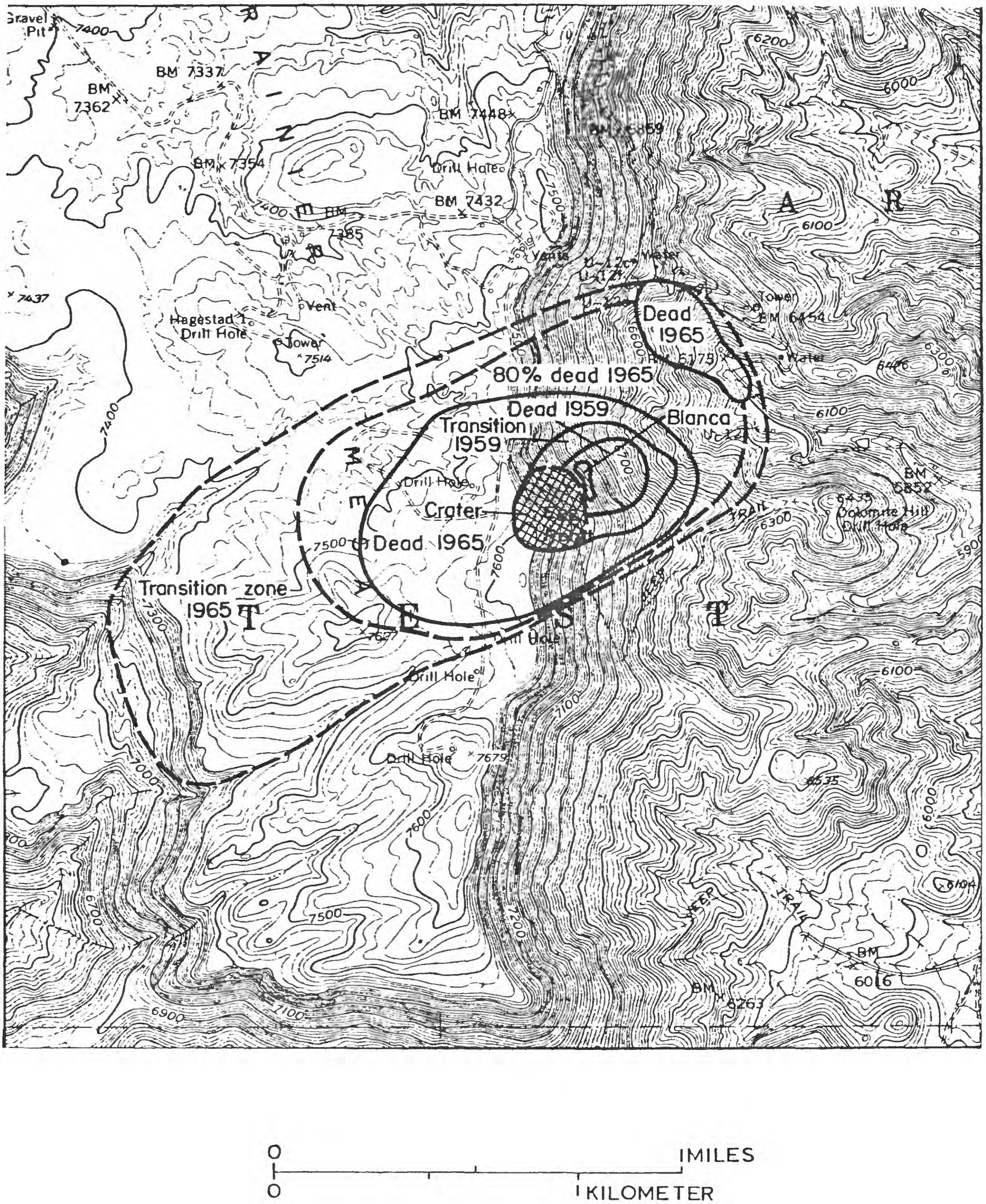


Figure 39.--Progressive conifer kill with time as related to Blanca explosion.

Figure 40.--Adventitious roots along juniper limbs due to heat from Blanca explosion.

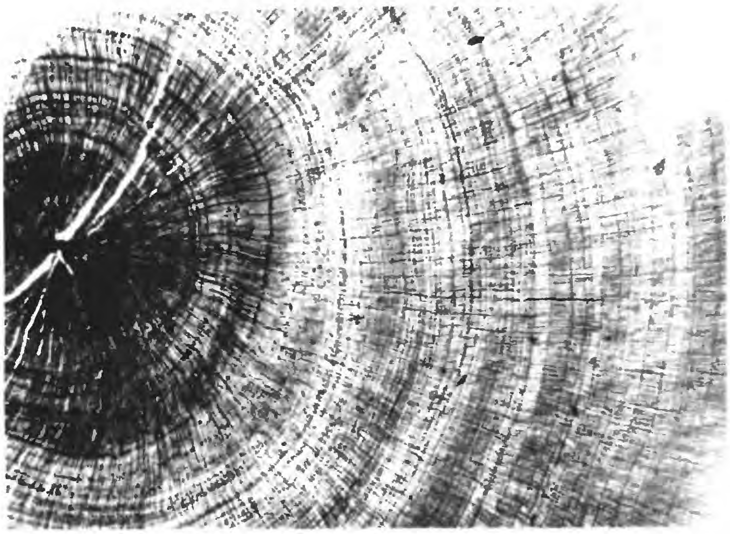


Figure 41.--Cross section of adventitious root, shown in figure 40.

Reduction in length of the terminal growth and stimulation of the laterals gives a curious dichotomous pattern of growth to _Quercus gambeli_, _Pinus monophylla_ and other trees. Wood sections show a stimulation in growth immediately following the detonation followed by a reduction in growth for the next several years. This effect was seen in sections of trees for at least a mile west of the crater.

Gamma-ray analyses by the U.S. Geological Survey of the surface _soils_ collected in 1963 from the east rim to to the west rim of the mesa show small amounts of $^{144}CePr$, ^{125}Sb, ^{60}Co, and ^{54}Mn. The greatest concentration reported is 34 pci/g of ^{125}Sb at the cratered east rim. Live _plants_ that were growing near the east rim in 1963, however, contained as much as 540 pci/g of $^{95}ZrNb$, 40 pci/g of ^{144}Ce and 750 pci/g ^{137}Cs, and lesser amounts of ^{125}Sb, and ^{54}Mn. ^{137}Cs and ^{144}Ce values remained high for a mile across the mesa and have remained high throughout the period of study. As the half-life for ^{137}Cs is 30 years and for ^{144}Ce only 290 days, the concentrations of ^{144}Ce in the vegetation were not expected. Seven years after the detonation, the plants actually contained more ^{144}Ce than any other gamma radionuclide. The absorption of ^{144}Ce through the roots and translocation to the leaves is illustrated by the following data:

Station 1, at cratered east rim of mesa.
Recorded September, 1964 as pci/g of ash.

	^{137}Cs	$^{144}CePr$
Chrysothamnus, new growth	130	270
Chrysothamnus, wood killed in blast	390	96
Chrysothamnus, roots	not detected	170

Both elements are concentrated in leaves and needles as compared to twigs.

Shields and Rickard's early analyses (1959) of plant material from the Blanca site showed uptake of ^{144}Ce, ^{106}Ru, and to a lesser degree ^{95}Zr. Fourteen months after collection, the samples still registered beta activity, which was believed to be surface contamination because both Phacelia and Abronia with hairy leaves registered the most activity. Chenopodium album and Gilia sinuata showed low gamma but high beta activity. Gamma radionuclides in vegetation were reported as follows:

	Blanca site	Nonirradiated site
^{144}Ce	146-2,360 pci/g	8 - 50 pci/g
$^{106}Ru/Rh$	305-2,900 pci/g	not detected
^{95}Zr	28- 530 pci/g	.5 - 7.9 pci/g
^{95}Nb	55-1,060 pci/g	.9 -15.9 pci/g

They concluded that evidence of radiation damage at Blanca was definite. Bromus rubens grown in soil that was collected by Mills and Shields (1961) from the Blanca crater 1 year after the detonation that measured 20-30 mr/hr, absorbed the following amounts of radionuclides (dry weight):

	In soil pci/g x 10^4	In leaf stem pci/g x 10^4	Absorption coefficient
Lanthanide rare earths (mostly $^{144}CePr$)------	2.85	0.05	1.75
$^{106}Ru/Rh$---------------	2.23	.146	6.54
$^{95}Zr/Nb$----------------	.49	.003	.61
$^{90}Sr/Y$ (beta)----------	.46	.134	29.13

Because the changes in the vegetation are correlative with distance from the crater at the east rim of the mesa, and have been studied over a considerable period of time, they will be discussed in greater detail by area.

Cratered edge of mesa 305-360 m above tunnel entrance

Trees and shrubs at the edge of the mesa were probably killed by heat at the time of the blast for the pine pitch is completely charred. Adventitious proliterations were common on trees that were not killed as described previously. By 1963, deciduous shrubs of many species had sprouted from the old root crowns, but weak stems and a loss of apical dominance resulted in procumbant growth (fig. 42). The grass and herbs appeared to be normal. On the other hand, Ephedra nevadensis that was recorded at this station in 1962 had died.

Figure 42.--Dead trees but live perennial growth at edge of Blanca crater. a, Collapsed perennials among dead pinyon, 1964. b, Growth habits of <u>Chrysothamnus</u>, 4 years after explosion.

Considerable throwout still clings to the bark and old wood of the dead trees near the edge of the crater at the rim of the mesa. Juniper bark collected 4 1/2 years after the explosion contained 65 pci/g ^{144}Ce, 100 pci/g ^{137}Cs, 17-18 pci/g ^{125}Sb and ^{60}Co, and more than 3,000 pci/g of ^{95}ZrNb. When the values are computed back to the date of the event, the trees received several thousand pci/g of ^{144}Ce and >100 M pci/g ^{95}ZrNb. As these trees were killed at the time of the blast, absorption cannot be considered to have altered the values.

The oak trees 360 m from the rim remained largely defoliated and dormant for 4 years after the Blanca event, but each spring from 1963 through 1965 about 125 cm of new growth was observed to sprout at the base and then die (fig. 43). In June 1966, curled deformed leaves emerged on the old branches. In 1967, the leaves were normal. Wood sections show the effects on the annual increment (fig. 44). Absorption of radionuclides from the soil is evident in the young twigs of oak and in pine, juniper, and shrubs as the contents of ^{60}Co, ^{65}Zn, and ^{137}Cs, and ^{144}Ce are much higher than those of the soil, collected 4 1/2 years after the event. Collections of the shrubs that have put out new growth since the explosion show some interesting differences, as shown in table 12. The old dead wood of Chrysothamnus contains ^{54}Mn, ^{60}Co, and ^{65}Zn, and of Quercus, ^{54}Mn, and ^{60}Co. Neither ^{60}Co nor ^{65}Zn is detectable in the new growth of these species. On the other hand, increased amounts of ^{95}Nb, ^{125}Sb, ^{137}Cs, ^{144}Ce, and an unidentifiable nuclide reported as eRa-U was absorbed by the roots and translocated to new growth of Chrysothamnus near the edge of the crater 4 years after the event, and ^{144}Ce and the unidentifiable radionuclide by Quercus 5 years after event. This absorption of nuclides shows clearly in the autoradiographs (fig. 45). These first oak leaves were curled, misshapen and rapidly died. Concentrations of 48 pci/g ^{60}Co, 43 pci/g ^{125}Sb, 115 pci/g ^{137}Cs and ^{90}Sr in the humus composed of leaves that were killed at the time of the explosion shows retention of these radionuclides in the organic layer during the 6-year period. Eight years after the event, little radiation was detectable in the new growth and no autoradiograph was obtained.

Figure 43.--Oak 360 m west of rim above Blanca detonation. (a) Tree virtually dormant, 1962. (b) New growth has sprouted at the base each year since 1963 but tips die back after a few weeks.

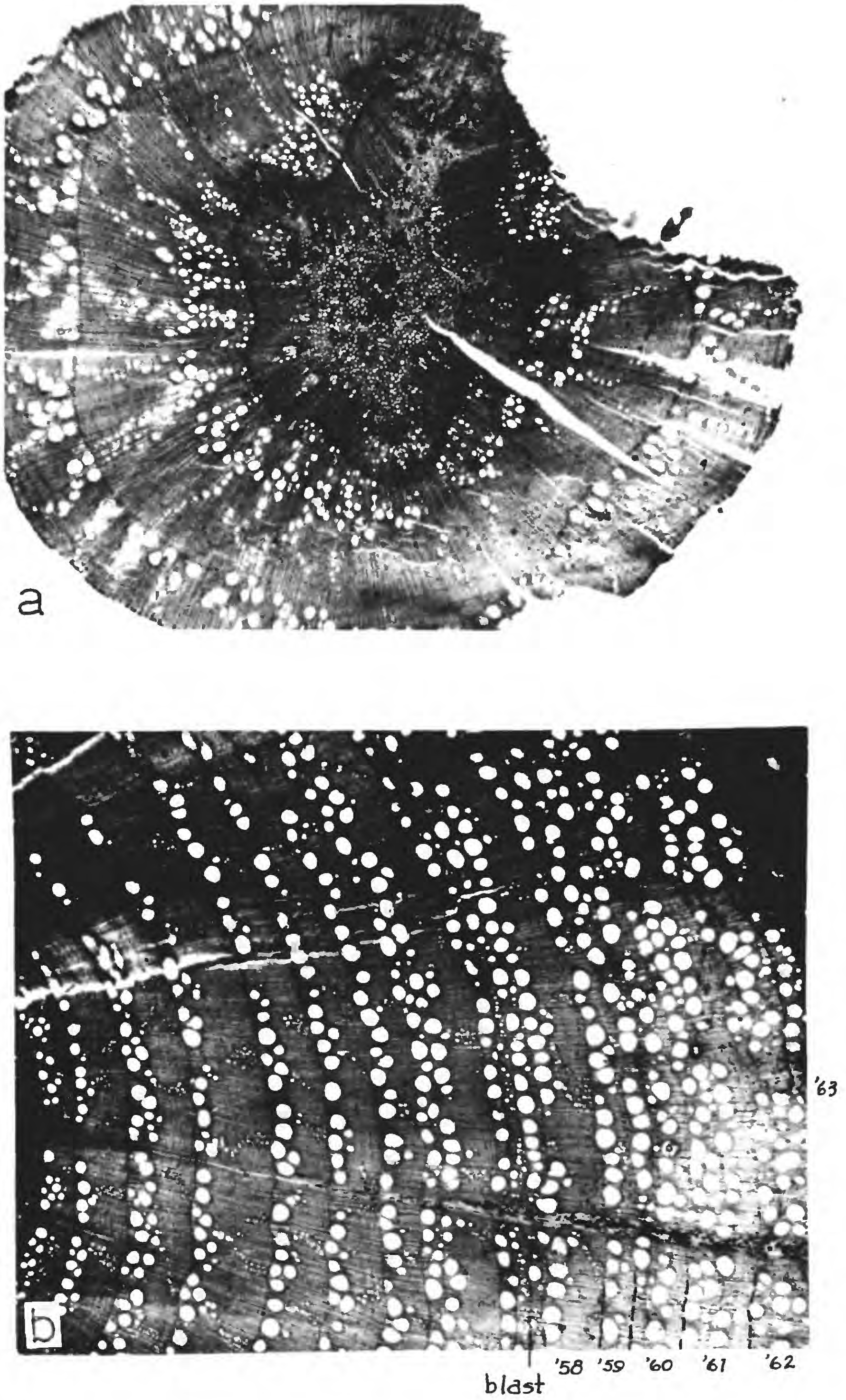


Figure 44.--Quercus gambeli, nearest foliated oak 360 m from Blanca crater. (a) Young oak shoots at base after 4 years. (b) Old oak wood showing slow growth during period of virtual defoliation; also ergastic deposits in rays.

Table 12.--Contents of radionuclides in old and new wood collected after the Blanca event

[Shown in pci/g of dried plant material; n.d., not determined]
Analysts i.e., A. Bush and C. M. Bunker, U.S. Geological Survey

	Plant part	Autoradiograph data	^{54}Mn	^{60}Co	^{65}Zn	^{90}Sr	^{95}Nb	^{125}Sb	^{137}Cs	^{144}Cs	eRa-U (ppm)
Chrysothamnus (rabbitbrush) at crater edge killed to ground by blast but growing 4 years after event.	Dead wood-----	-----------------	9.51	6.61	93.6	n.d.	----	----	27.6	21.0	21.0
	New green branches----	-----------------	----	----	----	n.d.	543	4.03	754	35.6	31.9
	Roots---------	-----------------	----	4.35	----	n.d.	261	3.59	----	41.0	54.5
Quercus gambeli (oak) 400 feet (122 m) from crater edge, leafed out 5 years after event.	Dead wood-----	Slight shadow----	2.77	0.91	----	23.90	----	3.90	14.6	15.4	1.70
	Green leaves--	-----------------	2.09	----	----	1.25	----	1.95	1.88	15.5	6.4
	Young twigs---	Very bright------	18.5	----	----	n.d.	----	10.9	----	128.0	86.0
	Humus---------	-----------------	----	48.1	----	53.0	----	42.2	115	----	-----
8 years after event.	Leaves and twigs.	Blank------------	----	----	----	1.33	----	----	----	----	6.80

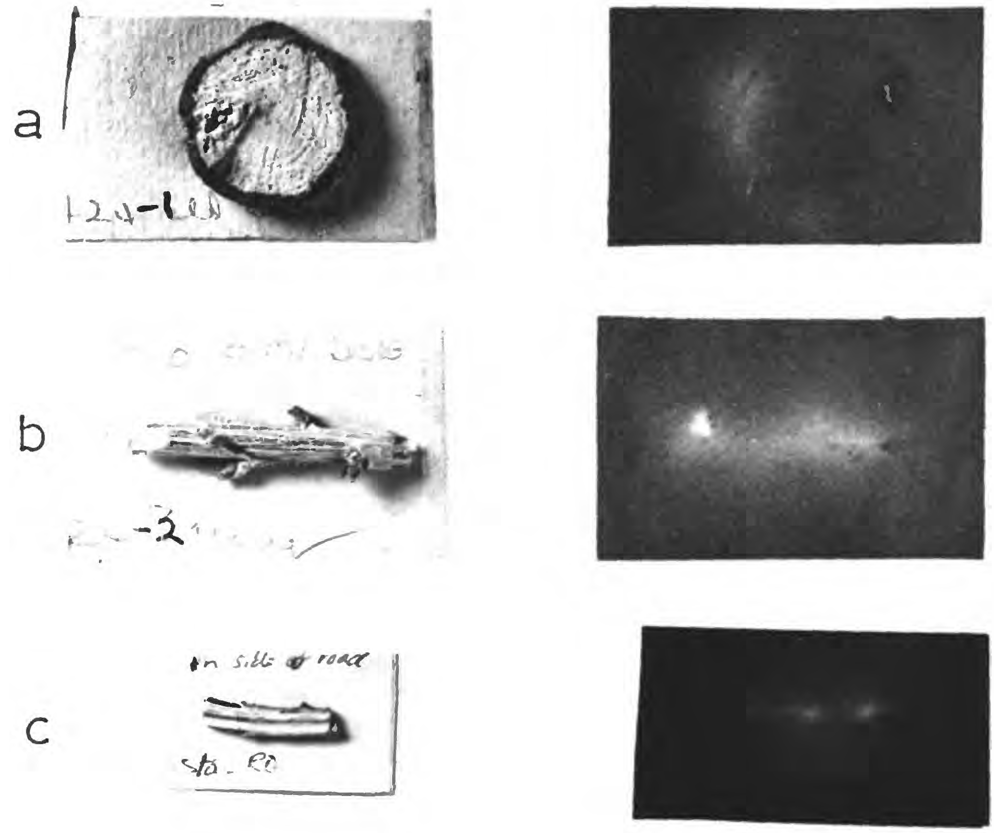


Figure 45.--Autoradiographs of Quercus gambelii (oak), that sprouted from base of tree 360 m west of Blanca crater 4 years after event. a, Old wood, collected 5 years after event, showing faint autoradiograph on side of tree toward explosion after 6 months exposure time. b, New wood collected 5 years after event showing autoradiograph to be brightest at cut end. (Seven months exposure time.) c, Split twig of same oak collected 6 years after event.

427-486 m from east rim

This area was severely affected and, in 1963, 4 1/2 years after the event, all pinyon and juniper were dead and *Ephedra nevadensis* (mormon tea), which is also a conifer, was dying. *Cowania stansburiana*, (cliffrose) and *Artemisia* (sage), remained dormant. There was, however, a good grass cover. The *Ephedra* was developing a witch's broom growth pattern that continued until death of the shrub (fig. 46).

Wood sections of the nearest live oak to the crater in 1962 showed clearly the date of the blast and subsequent reduction in summer vessels (fig. 47). This tree first leafed out in 1962 with curled deformed leaves but, in later years the leaves were observed to be normal. By 1965 the *Cowania* and *Artemisia* were again leafing out and growing normally.

730-1,100 m from east rim

In 1963, the nearest foliated sage was 730 m from the crater. Wood sections showed extreme disturbance to cellular growth at the time of the blast and the development of traumatic canals (fig. 48). This sage has since recovered.

The nearest live pinyon in 1962 was entirely dead in 1965. The autoradiographs showed the presence of radionuclides (figs. 49, 50, 51).

At 1,100 m, the coniferous trees showed considerable evidence of damage in 1962 and 90 percent of the trees were dead in 1965. Die-back of the terminal growing points on pinyon is shown in figure 52.

1,610-3,220 m) from east rim

At the extreme west edge of Rainier Mesa, 1,610 m from ground zero but still in the path of the radioactive cloud from the Blanca event, effects of the Blanca detonation (fig. 53) show in the wood sections as:

1. stimulation of growth during the year of the explosion
2. reduction in growth for several years following the year of the explosion, and
3. development of traumatic deposits of ergastic material in both *Ephedra* and *Juniper*.

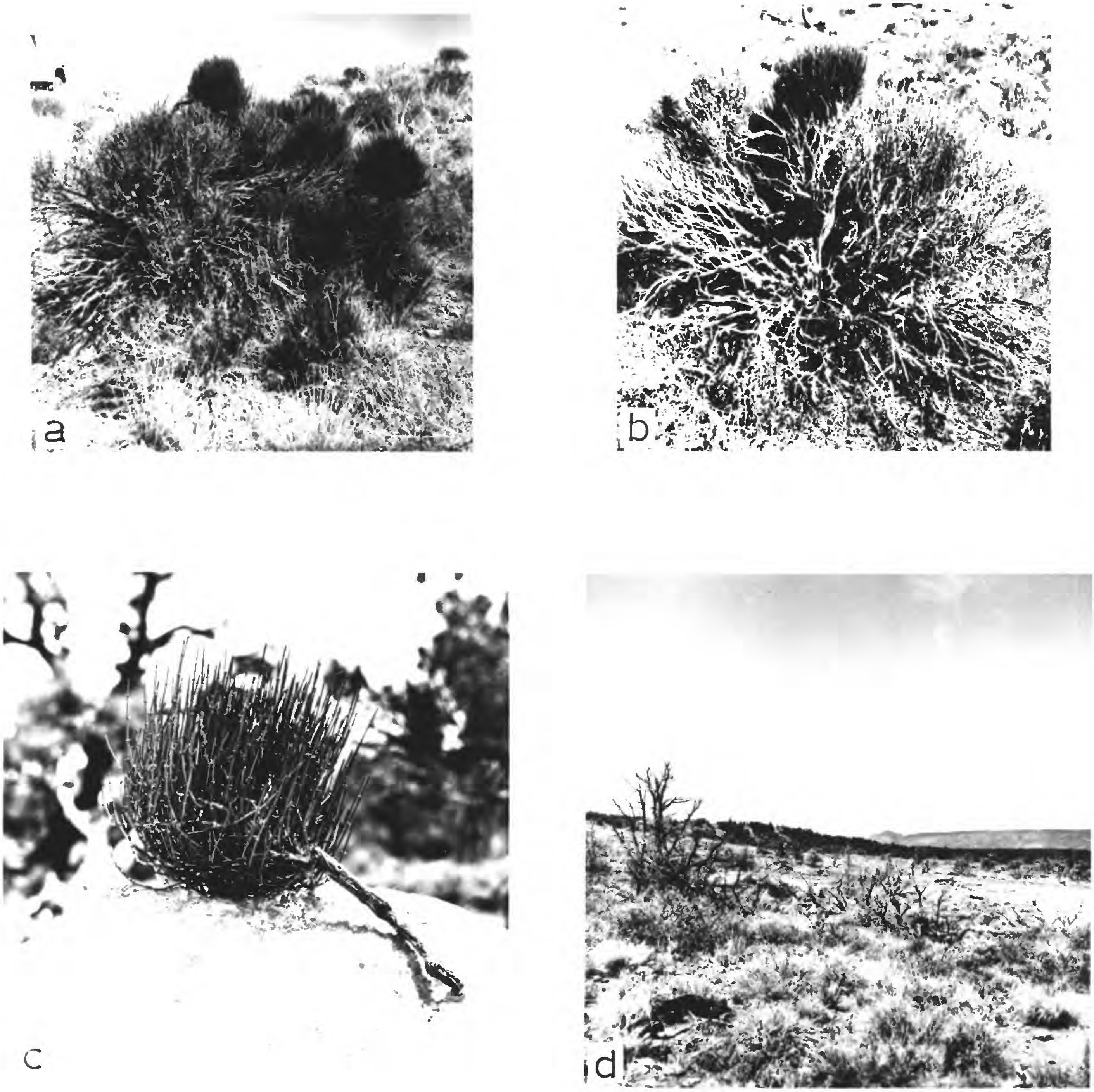


Figure 46.--Witch's Broom development and progressive death of Ephedra nevadensis, 428 m west of Blanca crater. a, 1964; b, 1965; c, Closeup of witch's broom; d, view toward northwest from this station showing extent of forest loss.

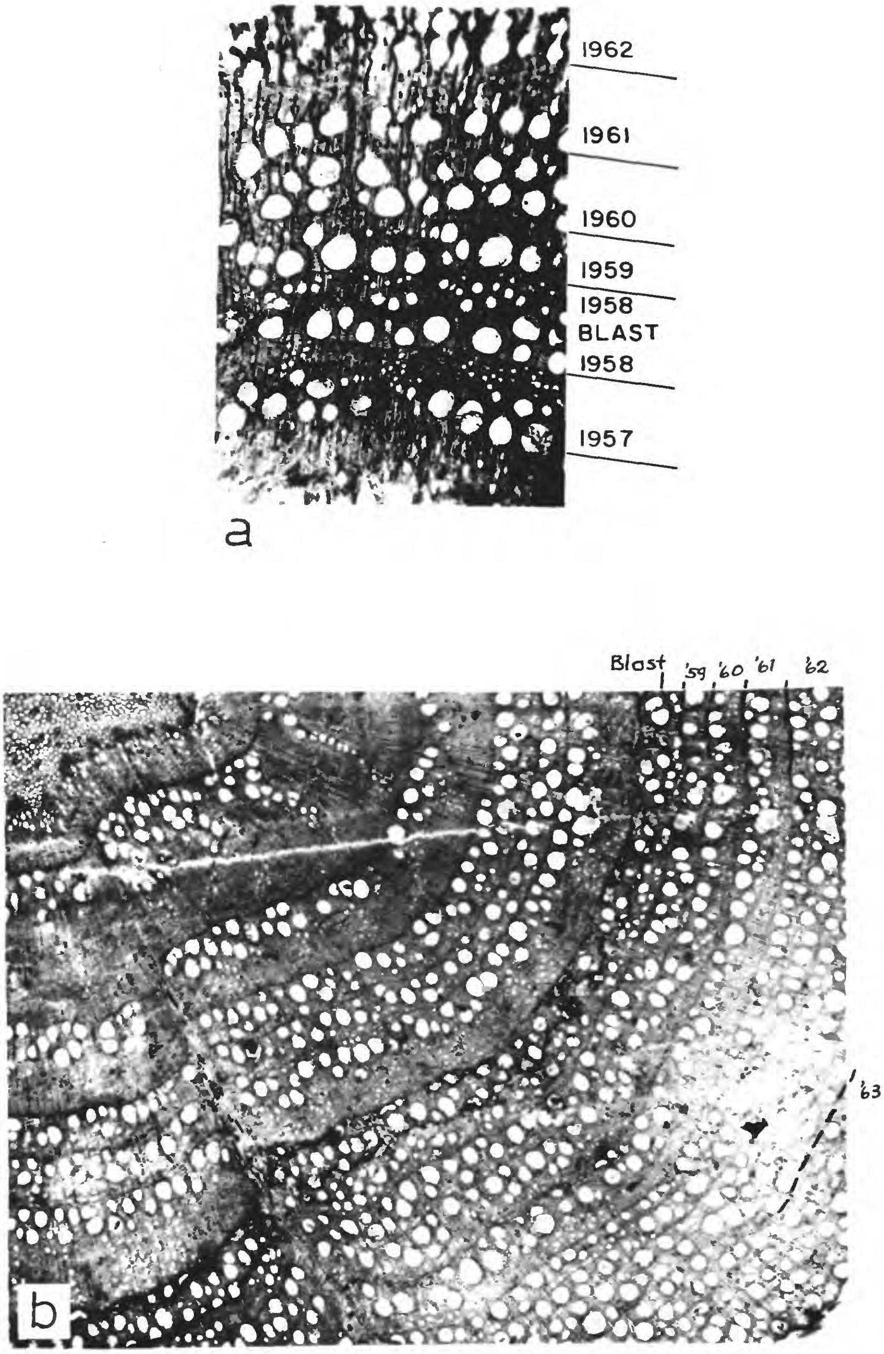


Figure 47. Wood sections of Quercus gambelii (nearest foliated oak in 1962) 450 m from Blanca ground zero. a, Wood collected in 1962 shows dark line at time of blast and reduction in summer vessels for several years. b, Wood from same tree in late 1963 shows improvement in growth.

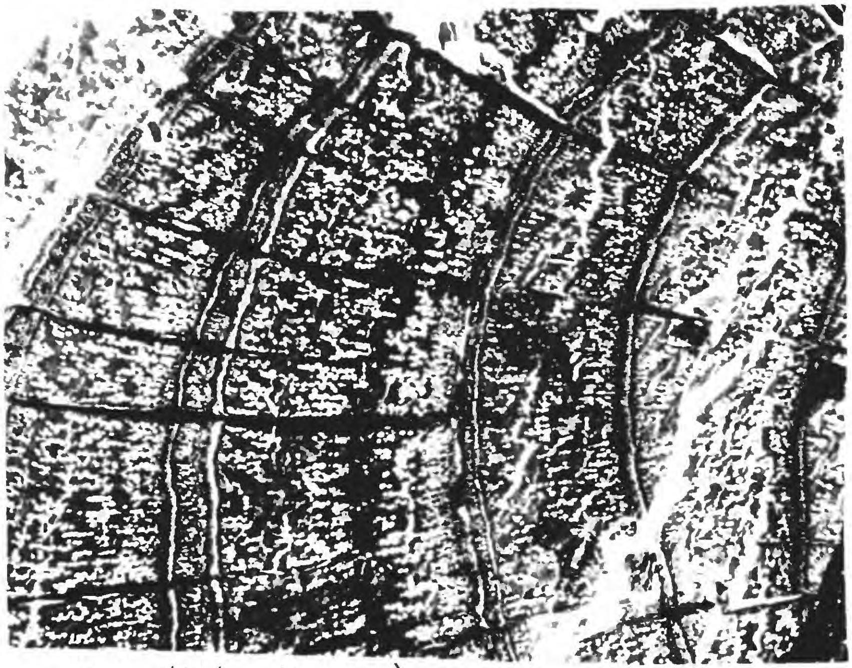


Figure 48.--Artemisia tridentata, nearest foliated sage 730 m from Blanca crater in 1963. Wood shows breakage and shock at time of blast and ergastic ray fillings.

Figure 49.--Autoradiograph of nearest live pinyon 730 m west of ground zero collected 4 years after Blanca vented explosion. Autoradiograph after 1 year exposure.

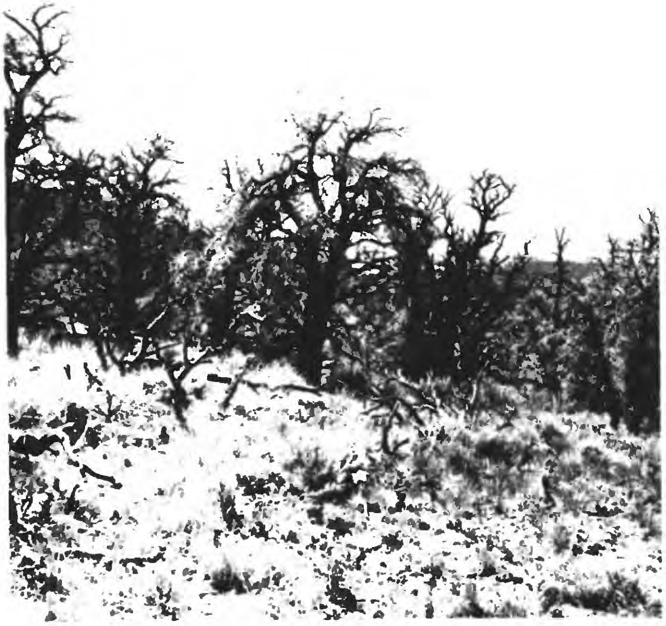
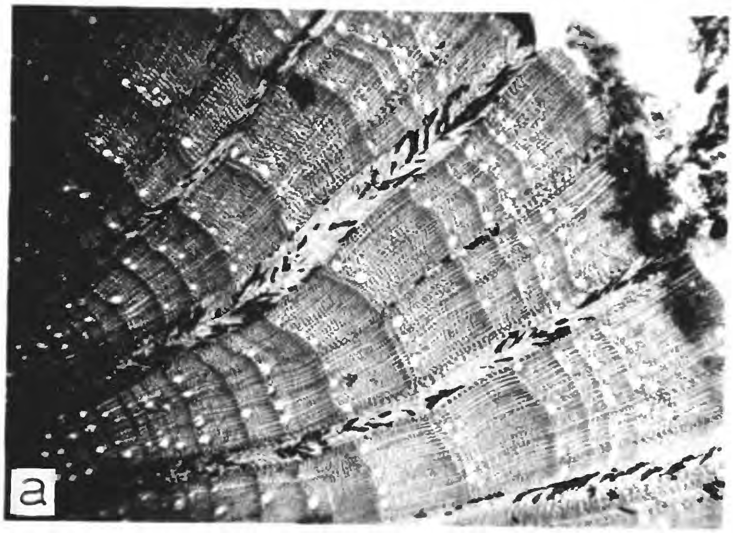


Figure 50.--Pinyon (autoradiograph figure 49) entirely alive in 1962; entirely dead in 1965.

Figure 51.--*Pinus monophylla* 1,100 m west of Blanca crater. Tip die-back in pine, 1964.

Figure 52.--Late stage in death of juniper and pinyon at same station. Ninety percent of trees alive in 1962; 90 percent of trees dead in 1965.



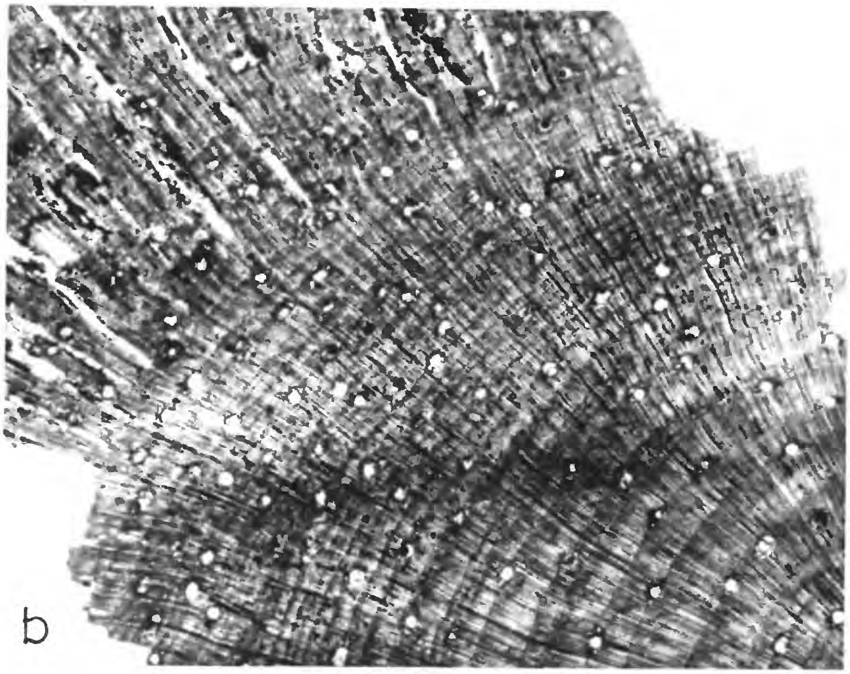


Figure 53.--Wood sections of Ephedra nevadensis (mormon tea) and Juniperus osteosperma collected from west edge of Rainier Mesa, 1.6 km from Blanca crater. a, Mormon tea showing stimulation in 1958, reduced growth in 1959, 1960, 1961, and recovery in 1962. Deposits in rays. b, Juniper showing change in growth patterns and development of resin along traumatic canals after blast.

Data from the first collections that were made 4 1/2 years after the Blanca explosion show a decrease in several radionuclides in juniper and pine with distance (table 13). Most of the trees are now dead for about 1,220 m. Unfortunately, the total radiation received in the past 15 years cannot be calculated as continued absorption upsets any attempts at half-life calculations back to the time of the event and the beta radiation is not known. Coniferous trees appear to die upon reaching their limit of tolerance as discussed earlier. By 1970, dead trees along the path of the original radioactive cloud extended nearly to the valley bottom west of the mesa, 3.2 km or more from the explosion and well beyond the area of physical shock from the detonation.

Pinstripe NTS.--Pinstripe was detonated on April 25, 1966 and was visited within 11 days after the explosion but the vegetation, was studied in a northeast direction from ground zero because of misinformation. Later studies were made directly north of ground zero in the true direction of the cloud path where, according to radiation safety personnel, ground readings of as much as 200 mr/hr had been recorded. Most of the samples of *Larrea divaricata* and soils that were collected for 6.4 km along the northeast traverse 11 days after the event showed considerable amounts of ^{140}Ba-La (1320 pci/g to 70 pci/g) and only 25-.04 pci/g of ^{144}Ce, ^{137}Ce, and ^{54}Mn. Calculated to the day of the event, the ^{140}Ba-La contents of the top 1.2 cm of soil were as much as 13,220 pci/g. Samples in the direct path of the cloud, which were not collected until 6 months after the event, show no ^{140}Ba-La but 8-100 pci/g of ^{95}Nb-Zr. A similar loss in ^{140}Ba-La was found in all *Larrea* samples collected 1 month after the detonation at the same stations from which early collections had been made. ^{95}Nb-Zr and ^{106}Ru are reported for later samples and not in earlier samples, both of which were collected no more than 1.6 km from ground zero, but these nuclides may have been masked by the large amount of ^{140}Ba-La in earlier samples. Most if not all the radionuclides recorded for *Larrea* were from dust adhering to the sticky leaf surface even though the samples were washed. However, the contents in the plants were less than in the top 1.3 cm of soil except for ^{137}Cs which was always higher in the plants. The autoradiographs show an interesting change from dust contamination to actual absorption at the stations directly north of ground zero. *Ephedra* that was killed at the time of the explosion produced an extremely bright autoradiograph even though the samples were washed. New growth of *Ambrosia dumosa* in an area that had been scraped but the roots not killed, also

Table 13. Change in radionuclide concentrations in trees with distance from Blanca tunnel entrance shown in picocuries per gram of dry plant material

[Analyses: C. A. Bush and C. M. Bunker; leaders, ---, indicate not detected]

	Distance in meters	^{54}Mn	^{60}Co	^{95}Nb	^{137}Cs	^{144}Ce
Pinus tips (dead)	180	1.08	5.48	680	17.8	25.3
live	760	---	---	---	9.05	10.6
live	1,150	---	---	---	4.41	16.2
live	1,580	.94	1.24	---	1.72	15.1
Juniperus tips (dead)	180	1.86	17.0	3,020	103.0	65.8
	760	---	.15	---	6.33	---
	1,580	---	---	---	4.67	1.57

produced bright autoradiographs (fig. 54). Washed Larrea collected 6 months after the event produced a bright picture on old and blackened wood in 9 days exposure time and the new, green wood a bright picture in 5 months time (fig. 55). Plants from the same area that were collected alive 1 year after the explosion, but that were dying at the last visit show good autoradiographs of both old and new growth in 4 months exposure time. The autoradiographs of new growth demonstrate the actual absorption of radionuclides.

Atmospheric nuclear explosions (NTS)

Plumbob series.--Atmospheric explosions were detonated in August and September 1957 on towers in Yucca Flat. Some of the resulting fire balls (Areas 1, 2, and 4) were on earlier explosion sites that were already bare except for a pure stand of the annual Salsola iberica (Russian thistle). One of the series, Smokey, was located at a new site in Area 2a in a mixed stand of Coleogyne ramossissima (blackbrush) and Grayia spinosa (hopsage). The blast effects and subsequent revegetation of the areas were studied in detail by Shields and Rickard (1960), Rickard and Shields (1963), Shields, Wells, and Rickard (1963), and Shields and Wells (1962). A fission bomb releases 50 percent of its energy as shock, 35 percent as heat and 15 percent as forms of radiation. Radiation levels of 1000 mr/hr were measured at 0.1/6 km and 100 mr/hr at 10-24 km from ground zero at D+3. A 40-kiloton bomb released at 150 m above the ground surface denudes the ground of vegetation for 1 to 1.6 km and removes a layer of soil for a radius of 0.16 to 0.5 km. At a distance of 0.8-1 km the reports state that the seared crowns of grasses were still alive and that the shrubs had unilateral blast damage with leaves hanging on through the season, but next spring no foliage appeared on the shrubs. In the following year, nearly pure stands of the annual Mentzelia albicaulis germinated from 0.3 to 0.5 km from ground zero, and from 0.6 to 1.3 km the flora also included Chaenactis spp., Gilia latifolia, Amsinckia tessellata, and Cryptantha spp.

Figure 54.--Autoradiograph of Ambrosia dumosa collected 6 months after the Pinstripe explosion. Entire shrub had grown from root crown since detonation. Exposure time 5 months.

Figure 55.--Autoradiographs of Larrea divaricata (creosote bush) collected 6 months after the Pinstripe explosion. a, Old and blackened wood (washed) after 9 days exposure time. b, New green shoot after 5 months exposure time.

After the spring annuals died in June, the summer annual, Salsola kali, grew sparsely in the denuded area from ground zero to 0.16-0.5 km. In the second year, it provided a 7-20 percent ground cover for 0.16 km around ground zero and replaced Mentzelia, at a distance of 0.5 to 1.0 km from ground zero. In 1959, Mentzelia, Amsinckia, Delphinium, and Chaenactis were able to grow 0.5 km from ground zero and seedlings of Bromus rubens and Rafinesquia neomexicana appeared. The Salsola stand increased in radius. In 1960, Chaenactis and Cryptantha were replaced by Mentzelia, and Bromus was growing as near as 0.16 km to ground zero.

The immediate stimulated growth of Mentzelia in areas of undisturbed but highly radioactive soils is particularly interesting. This species has been observed also in areas of high natural radioactivity (Cannon, 1957). More recent observations show the areas denuded by the Plumbob series of tests to be still radioactive (5 mr/hr 8 years after event) largely owing to surface contamination from radioactive glass created from the silica sand added to the fireball. Analyses in U.S. Geological Survey laboratories from 1963-1970 showed herbs from three of the <20 kiloton atmospheric tower explosions to contain ^{54}Mn, ^{125}Sb, ^{137}Cs, ^{144}Ce, and ^{60}Co in amounts of <20 pci/g, and the nearest shrubs to contain as much as 3,482 pci/g ^{95}ZrNb 450 m from ground zero and 997 pci/g at a greater distance than 914 m 8 years after the event. Herbs, 8-11 years after a 43-kt atmospheric explosion contained <20 pci/g of ^{54}Mn, ^{60}Co, and ^{125}Sb but 30 pci/g ^{137}Cs and 3,260 pci/g ^{95}Zr-Nb. A shrub 969 m from ground zero contained 558 pci/g ^{95}Zr-Nb. Probably ^{144}Ce concentrations that appear to be too high in samples collected at Smokey and Galileo after June 30, 1965 have been increased by contamination from a later explosion in north Yucca Flat.

The annual Eriogonum nidularium, at Galileo, is absorbing ^{144}Ce in amounts equal to that in the 15-cm soil sample collected through the root zone. Oryzopsis hymenoides, perennial rice grass, contained 36 times more ^{144}Ce at Teapot Apple than the 15-cm soil sample. Salsola, Russian thistle, may be able to grow in highly radioactive soil because of an ability to restrict the absorption of radionuclides, as the plants collected at Smokey and Plumbob Diablo have contained considerably less of all radionuclides than the concentrations in the 15-cm soil zone.

Cratering nuclear explosions (NTS)

Several nuclear detonations were designed to produce explosive throwout craters with attendant release of radioactive gasses. Two of these have been studied, Danny Boy on Buckboard Mesa and Sedan in northern Yucca Flat. In addition, we have studied Palanquin, which was designed to produce an upheaval mound (retarc) but owing to casing failure produced a throwout crater with a release of considerable radioactivity. Sedan and Palanquin have been studied in detail because of the extensive damage to vegetation.

Danny Boy.--Detonated on April 19, 1962, produced a throwout crater; a close-in ground survey showed the 1000 R H+1 hour isodose contour extending 250 m to the north asymetrically and the 1 R H+1 hour isodose contour for 5 km to the northwest from ground zero. We did not visit the area until 3 years after the event and only a few samples have been taken. Artemisia was killed for about 0.4 km from ground zero. The soil 225 m from ground zero contained ^{54}Mn, ^{60}Co, ^{125}Sb, ^{137}Cs, and 85 pci/g ^{106}Ru-Rh and 400 pci/g ^{144}Ce. Chrysothamnus nauseosus and Atriplex canescens were killed to the ground but have since come up from the old root crowns. The gamma radionuclides in the new growth of the nearest live Atriplex 225 m from ground zero were mostly ^{144}Ce and only a slight shadow was visible on the autoradiograph. A year later, no ^{144}Ce was reported but the plant had begun to absorb ^{106}Ru-Rh from the ground water and also contained 4 pci/g ^{95}Nb.

Three years after the event, the nearest live Artemisia was growing 330 m from ground zero. The plant bore only a few sprigs of live growth and the entire shrub was dead the following year (fig. 56). Samples of the old wood made a bright autoradiograph but the new growth made only a slight shadow (fig. 57). Wood from Artemisia collected at a station 760 m from ground zero (10 R H+1 hour) 5 years after the nuclear explosion also produced bright autoradiographs but the Chrysothanmus nauseosus collected at the same station produced only a shadow.

Sedan.--Detonated on July 2, 1962, and was a 100-kt thermonuclear explosion that formed a crater 360 m in diameter and 193 m deep in the alluvium and tuff of upper Yucca Flat, with a release of large amounts of radioactivity. According to Jorgensen, Allred, and Beck (1962) there were two plant zones present before the explosion: an area reduced by previous explosions to Salsola kali, Sitanion hansenii, Oryzopsis hymenoides, and Mentzelia albicaulis: and an undisturbed area of shrub cover including Coleogyne ramossissima, Grayia spinosa, and Lycium andersoni. After the blast, three distinct vegetative zones could be seen:

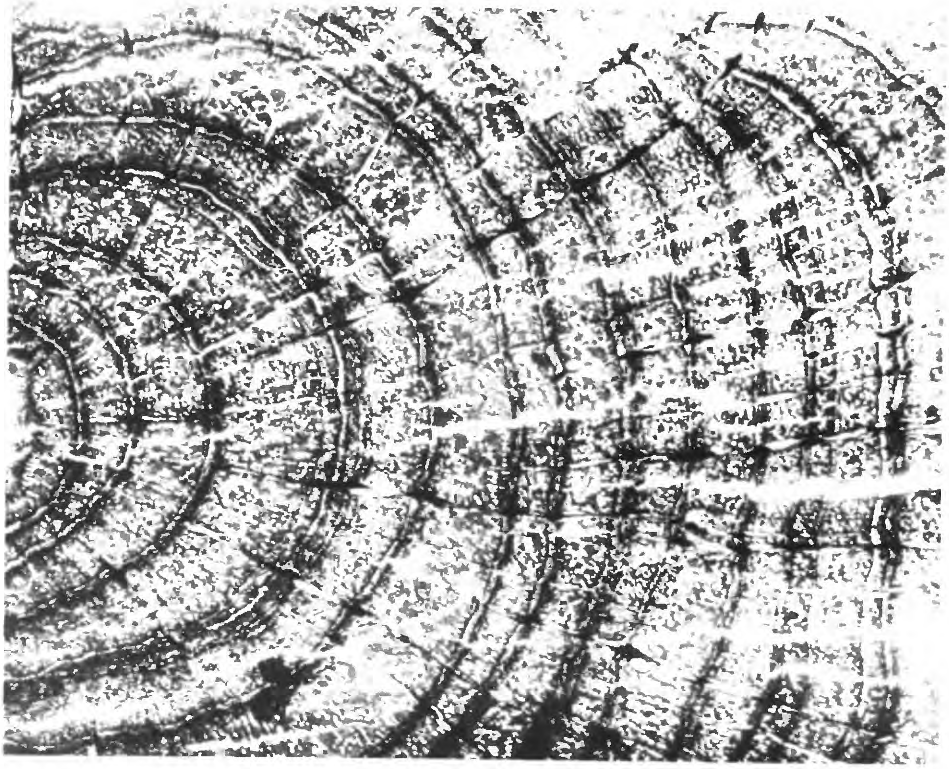


Figure 56.--Nearest live Artemisia branch on defoliated shrub 330 m from Danny Boy ground zero.

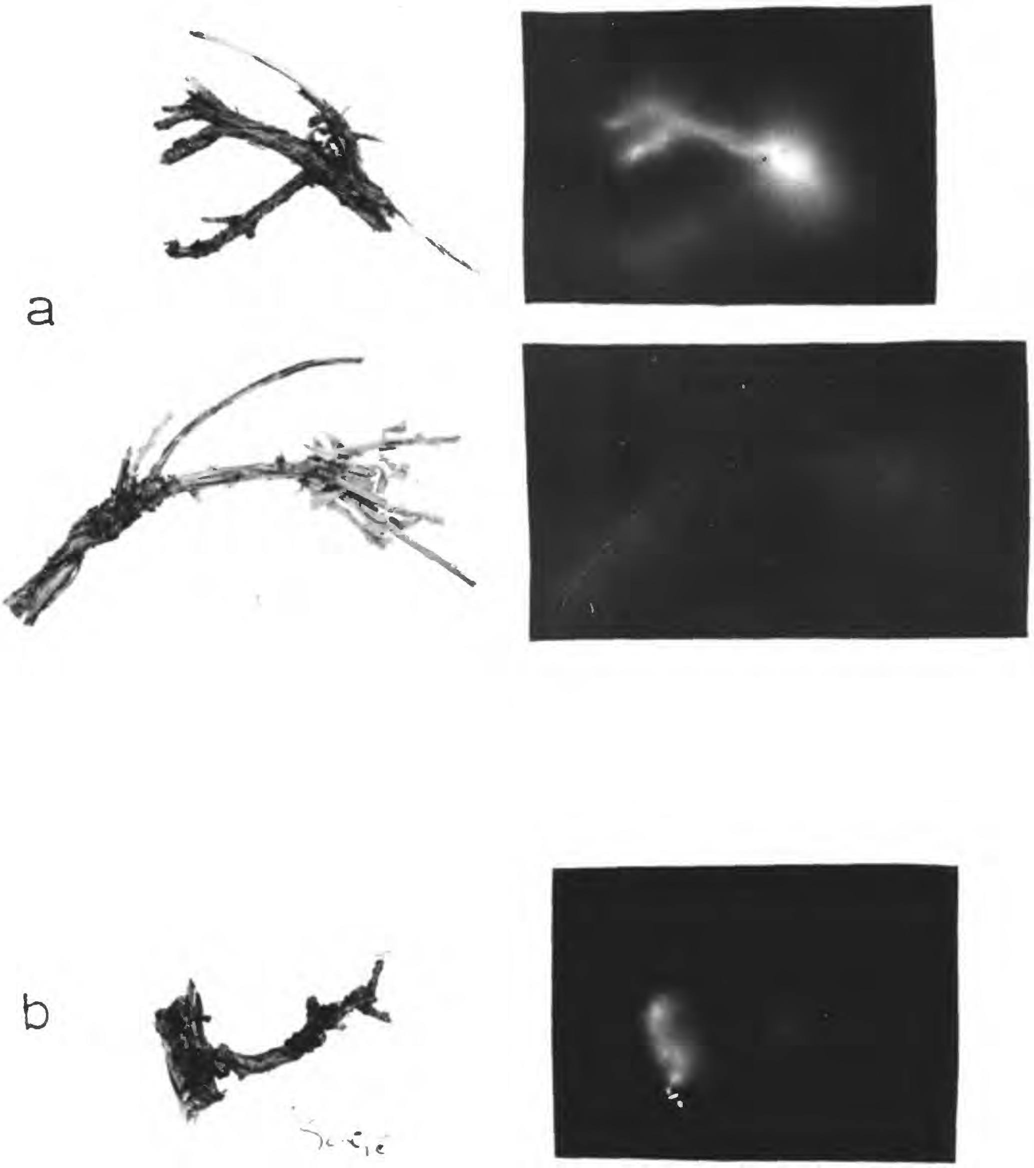


Figure 57.--Autoradiographs of Artemisia tridentata (sage) collected near Danny Boy crater. a, Nearest live sage collected 330 m from ground zero 3 years after the event. Autoradiograph of old and new wood after 8 months exposure time. b, Sage collected 760 m from ground zero 5 years after event. Autoradiograph of old wood after 8 months exposure time.

1. Ground zero to 915 m--vegetation completely destroyed and covered with >0.3 m of throwout.

2. 915-1,525 m--vegetation flattened and defoliated by flying missles and physical force.

3. 1,524+ m--a distinct layer of dust but no visible damage to plants.

Twenty-four hours after the event, an aerial radiometric survey (corrected to 0.9 m above the ground surface) registered 40 R/hr at ground zero, 1 R/hr at a distance of 4 km (fig. 58), 100 mr/hr at 51 km, and 1 mr/hr at 160 km. Martin and Turner (1965) made a broad study of radiostrontium in the food chain of the fallout area by collecting plants and rabbits before and for 60 days after the detonation at stations that registered 75 to 1.5 mr/hr 5 days after the event and covered a distance of 160 km. They found that ^{89}Sr on D+5 (5 days after the detonation) was 100 times higher than ^{90}Sr in plants and that ^{90}Sr was not significantly higher than in pre-explosion samples at 12 of these 20 stations. Therefore, they studied ^{89}Sr and found that twigs and foliage of shrubs (largely _Artemisia tridentata_ and _Atriplex confertifolia_) ranged from 6487 pci $^{89}Sr/g$ in the dried sample where readings of 75 mr/hr were obtained on D+5 to 228 pci/g at 1.5 mr/hr, and by D+60, ^{89}Sr contents had reduced to a range of 1719 to 40 pci/g. The wide range in values is attributed to the roughness of the leaf and paths of wind turbulance. Experiments have shown a half-life loss due to rain and wind to be about 14 days. Correcting for this environmental half-life, Martin and Turner calculated that the effective half-life of ^{89}Sr from D+5 to D+30 was 18 days and of ^{90}Sr 28 days, and from D+30 to D+60 the effective half-life of ^{89}Sr was 38 days and of ^{90}Sr more than 100 days.

A close-in study of soils and vegetation was made by U.S. Geological Survey personnel and is reported here. A line of stations 3.6 km north from the edge of the crater was studied on 12 site visits from 1963 through 1970. Briefly, throwout could be detected on the surface of the ground for about 2,400 m from ground zero and Russian thistle germinated the next year throughout the entire area of throwout. Shrubs were buried or killed to the ground for 1,830 m from the crater but by 1970 (8 years later), _Atriplex canescens_ was growing within 12 m of the crater rim or 165 m from ground zero. Records have been kept of the plants at each station and samples have been collected at intervals for analysis.

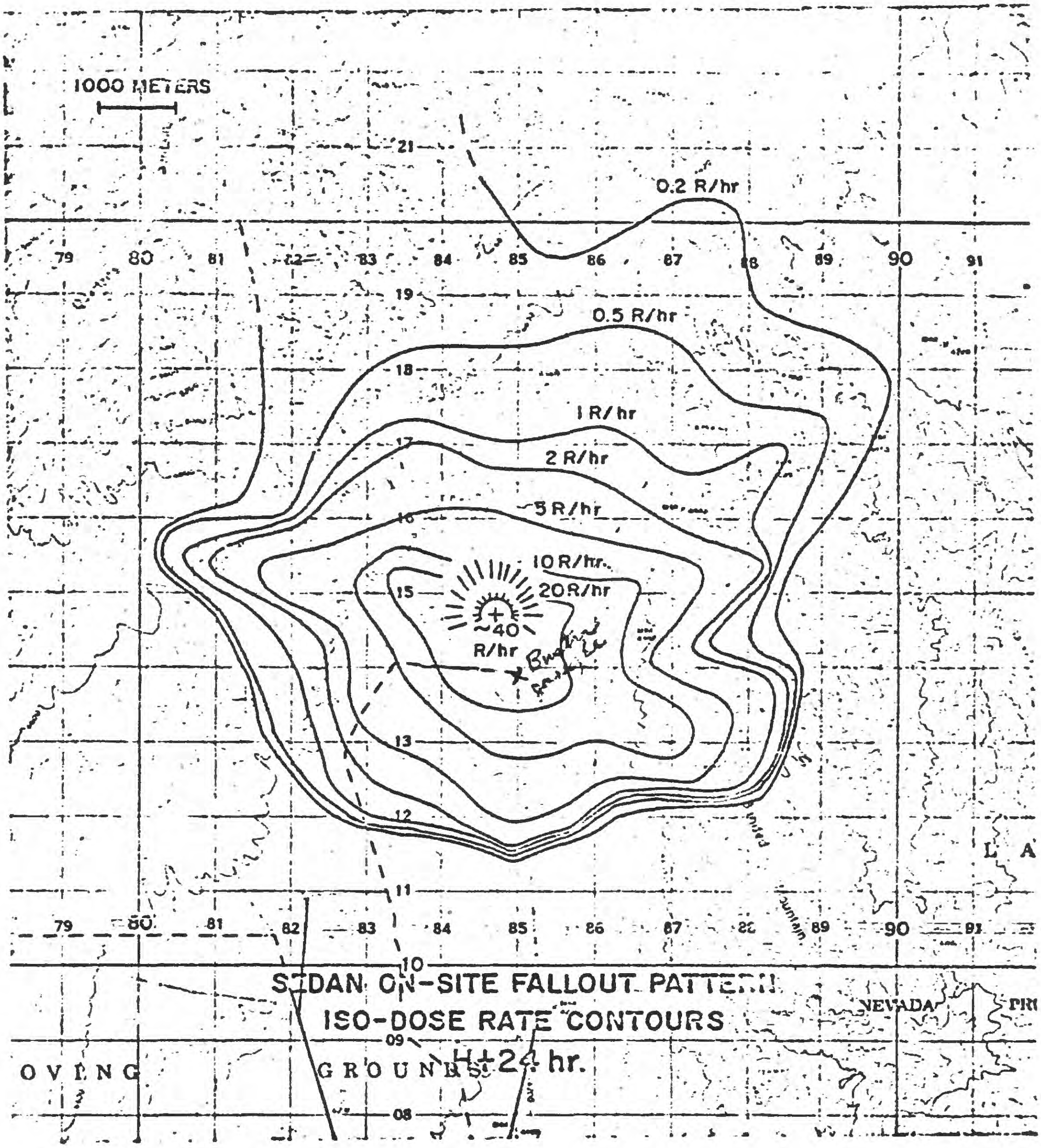


Figure 58.--Sedan close-in fallout pattern.

Surface soils sampled at different distances 1 1/2 years, 2 years, 3 years, and 8 years after the Sedan event (table 14) show a logical decrease in radionuclide concentration with distance and with time except for unusual ^{144}Ce at 3,390 m which may be an error in analysis or from fallout produced by another explosion. When the values are calculated by computer to the day of the event according to individual isotopic half-lives, the values at any given distance should be approximately the same regardless of the date of collection. However there is considerable variation owing to unusual decreases in radionuclides caused by wind turbulence and unusual increases due to increments from other nearby explosions.

Collections were made through two soil profiles north of the Sedan crater (table 15); one, in an area of Russian thistle and throwout, and one beyond throwout in a shrub-covered area. Russian thistle germinated over the entire area of throwout but became scarcer as the throwout thinned to 1 cm or less. In both profiles, ^{54}Mn and ^{144}Ce decreases regularly from the surface downward, but ^{137}Cs and ^{60}Co are more irregular. The isotopes measured as equivalent radium-uranium cannot be identified but have obviously been produced by the bomb. The values of all radionuclides are much higher in the protected location under the _Hymenoclea salsola_ shrub than in the exposed area between shrubs. This phenomenon is not believed to be caused by absorption and concentration by the shrub but by preservation from the strong vertical winds that blow constantly in the denuded dusty area surrounding the crater.

Initially all vegetation was destroyed and covered with throwout for a distance of 1,840 m from the crater. At 1,840 m the shrubs were flattened and defoliated but the dead tops remained as shown in figure 59. By the spring of 1963, _Sphaeralcea ambigua_ and _Salsola iberica_ were growing 1,220 m from the crater in soil reading 5.5 mr/hr and a few plants of _Oryzopsis hymenoides_ were growing 1,520 m from the crater in soil reading 3 mr/hr. These three species have germinated closer to the crater each year as the levels of radiation diminished. The shrubs have recovered and grown from the old root crown where the depth of burial was not too great. The return of shrubs, grasses and _Salsola_ is shown in figure 60.

Table 14.--Radionuclides in top centimeter of soil collected north of Sedan event

[Values in pci/g. Tr, trace. Values of ^{54}Mn, ^{60}Co, ^{144}Ce, and also ^{140}La show influence from nearby explosion. Leaders (---) indicate not detected.]

Distance from ground zero feet (meters)	Collection time after no. of event (years)	^{54}Mn at collection	^{54}Mn at event	^{60}Co at collection	^{60}Co at event	^{106}Ru-Rh at collection	^{106}Ru-Rh at event	^{137}Cs at collection	^{137}Cs at event	^{144}Ce at collection	^{144}Ce at event	eRa-U at collection	^{65}Zn at collection	^{65}Zn at event
11,300 (3,390)	1 1/2	385	1,390	11.7	14.2	2,640	7,150	67.2	69.7	414,000	1,418,000	---	---	---
8,500 (2,550)	1 1/2	425	1,540	10.8	13,0	4,310	11,650	89.4	92.7	1,400	4,800	---	---	---
6,500 (1,980)	1 1/2	300	1,100	12.0	14.6	4,660	12,600	96.0	99.6	2,620	9,000	60.0	---	---
5,000 (1,525)	1 1/2	2,600	9,370	119	144	37,800	102,320	780	810	12,300	42,000	378.0	---	---
7,000 (2,135)	2	240	1,720	35.7	47.8	Tr	Tr	.61	.65	1,530	10,000	110	---	---
4,000 (1,220)	2	1,060	7,540	14.8	19.8	Tr	Tr	185	190	6,170	40,400	340.0	---	---
6,500 (2,000)	3	200	3,020	47.6	70	452	3,600	100	119	14,600	190,400	---	---	---
5,500 (1,675)	3	200	2,910	81.7	127	452	3,600	120	130	16,700	218,750	---	---	---
5,000 (1,525)	3	570	8,300	250	370	1,570	12,540	370	400	50,700	661,600	---	---	---
3,500 (1,065)	3	1,730	25,220	630	935	4,930	39,350	100	1,080	144,000	1,876,000	---	---	---
5,000 (1,525)	8	---	---	200	580	---	---	145	170	---	---	---	840	172,000
4,000 (1,220)	8	---	---	90	250	---	---	70	90	22	17,600	---	390	79,000
3,500 (1,065)	8	---	---	215	600	---	---	150	180	64	50,400	---	835	170,000
500 (150)	8	---	---	45	130	---	---	45	50	6.1	4,875	---	240	500,000

Table 15. Distribution of gamma radionuclides through soil profiles in Sedan area of fallout, collected 2 years after event

[Analysts: C. A. Bush and C. M. Bunker, U.S. Geological Survey; leaders, --, indicate not detected]

	^{54}Mn (pci/g)	^{60}Co (pci/g)	^{137}Cs (pci/g)	^{144}Ce (pci/g)	eRa-U (ppm)
Station Y 19d 1,220 m from ground zero					
0- 1 cm throwout----------	1,060	14.8	185	6,170	340
1- 3 cm throwout----------	990	136	170	--	400
3- 8 cm throwout----------	850	11.8	330	3,840	300
8-15 cm original clay-----	450	65.4	91.7	2,390	230
Station Y 17a 2,135 m from ground zero					
0- 1 cm under shrub-------	1,100	148	208	1,740	440
0- 1 cm between shrubs----	240	35.7	.61	1,530	110
1- 3 cm sandy gravel------	140	21.0	37.5	355	65
3- 8 cm sand--------------	3.4	--	2.5	22.2	4.7
8-15 cm clay and caliche--	--	--	--	--	3.1
Hymenoclea salsola--------	95.5	12.4	21.9	207	43.0

Because plants were destroyed for a considerable distance, plant samples for the first 4 years after the event could be collected only from 1,000-3,600 m from ground zero. ^{65}Zn and ^{95}Nb were reported in plants collected 9 months after the event but not in later samples. The plants contained ^{54} Mn, ^{60}Co, ^{137}Cs, ^{144}Ce, and commonly ^{106}Ru-Rh. An unidentified radionuclide in *Chrysothamnus* was reported as eRa-U in quantities as great as 123 ppm.

Figure 59.--Photograph taken in 1963, of shrubs knocked over and killed to ground by blast of Sedan detonation; shrubs later sprouted from root crown in 1964.

Surface soils sampled at different distances 1 1/2 years, 2 years, 3 years, and 8 years after the Sedan event (table 14) show a logical decrease in radionuclide concentration with distance and with time except for unusual ^{144}Ce at 3,390 m which may be an error in analysis or from fallout produced by another explosion. When the values are calculated by computer to the day of the event according to individual isotopic half-lives, the values at any given distance should be approximately the same regardless of the date of collection. However, there is considerable variation owing to unusual decreases in radionuclides caused by wind turbulence and unusual increases due to increments from other nearby explosions.

Collections were made through two soil profiles north of the Sedan crater (table 15); one, in an area of Russian thistle and throwout, and one beyond throwout in a shrub-covered area. Russian thistle germinated over the entire area of throwout but became scarcer as the throwout thinned to 1 cm or less. In both profiles, ^{54}Mn and ^{144}Ce decreases regularly from the surface downward, but ^{137}Cs and ^{60}Co are more irregular. The isotopes measured as equivalent radium-uranium cannot be identified but have obviously been produced by the bomb. The values of all radionuclides are much higher in the protected location under the Hymenoclea salsola shrub than in the exposed area between shrubs. This phenomenon is not believed to be caused by absorption and concentration by the shrub but by preservation from the strong vertical winds that blow constantly in the denuded dusty area surrounding the crater.

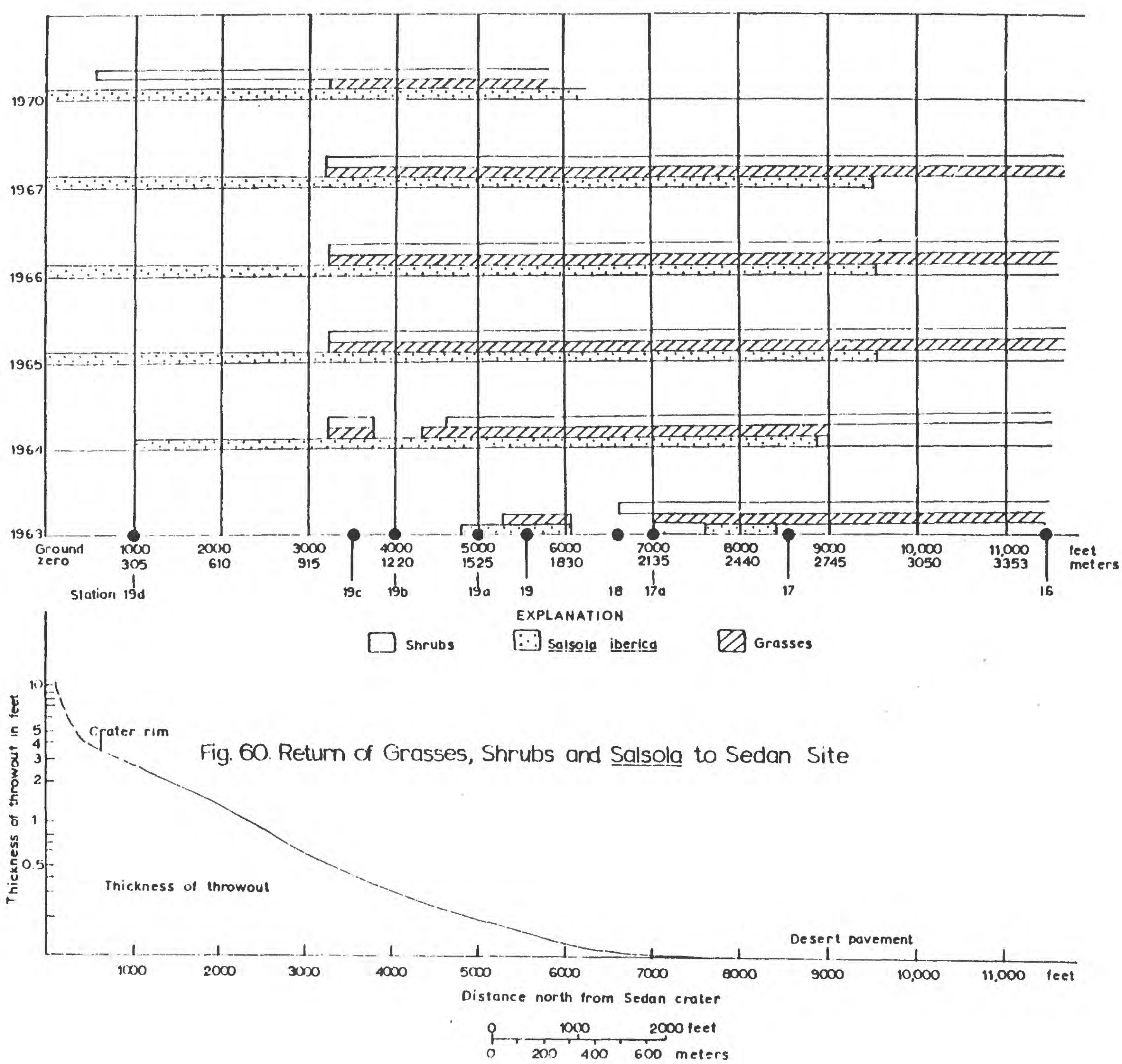


Fig. 60. Return of Grasses, Shrubs and *Salsola* to Sedan Site

Janice Beatley (1966), who had ecologic plots in the area, found that Chaenactis seedlings of the first post-Sedan populations, which appeared following September 1963 rains, were the largest and most vigorous populations observed anywhere on the Nevada Test Site. The plants were two to three times the size (diameter of leaf rosettes) of those on all of her other Yucca Flat plots; the leaves were larger, thicker, and darker green. Among the abnormally gigantic annuals (1.2 percent), were conspicuously abnormal plants of Chaenactis stevioides with greatly reduced internodes resulting in dwarfism, bushiness in plants, and failure of corolla and other flower parts to develop. She attributed the gigantism to ionizing radiation and the aberrations to chromosomal and (or) gene mutations induced in the seed by radiation.

The absorption of radionuclides differs more sharply between species of shrubs than occurs in trees of the pinyon-juniper zone. Larrea divaricata appeared to absorb all radionuclides in greater quantity than any of the five shrubs that have been analyzed, and contained more ^{144}Ce at a distance of 3,150 m from the crater than other shrubs at 1,525 m. However, the plant is sticky and the concentrations may represent in part dust that was not removed in washing. Rice grass growing within 1,670 m of ground zero 4 years after the event, absorbed only ^{137}Cs and ^{144}Ce from the soil. Good autoradiographs from both stem and root were obtained of young Russian thistle growing 1,670 m from ground zero 14 months after the event and at 1,065 m 22 months after the event (fig. 61) indicating absorption by the plant of radionuclides. As the radioactivity in the soil lessened with time, other species of plants were able to germinate and to grow closer to the crater each year. This progression is shown in table 16. The unusual number of species 1,065 m from the crater grew in a small draw.

The Atriplex linearis that was observed at the edge of the crater in 1970 in throwout reading 1 mr/hr was covered with tumors and had misshapen leaves. Throwout with a thickness of 1.7 m near the crater buried and killed all perennial shrubs; Atriplex presumably has germinated and grown from seed in this material at the crater rim.

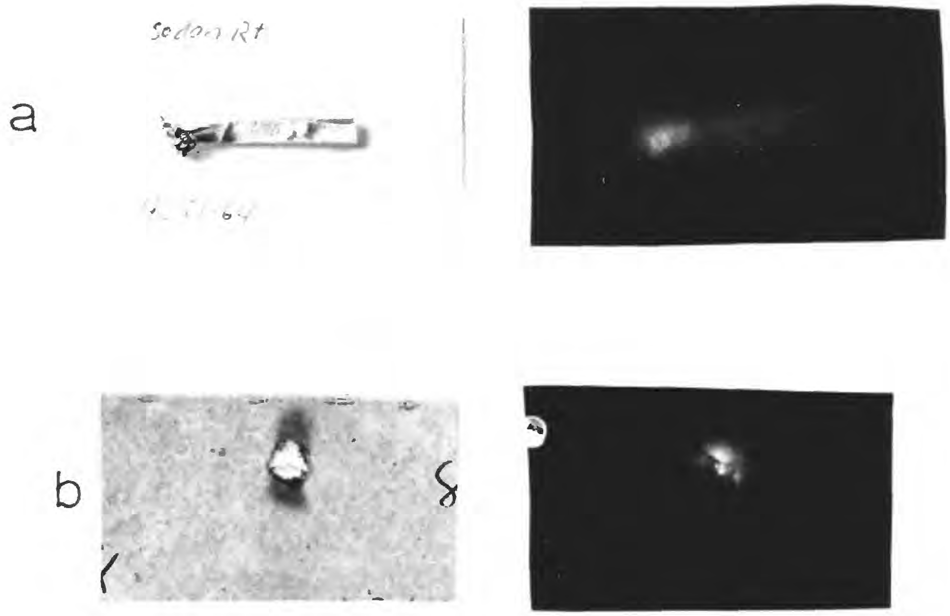


Figure 61.--Autoradiographs of stem and root of Salsola iberica (annual Russian thistle) collected 22 months after the event from throwout reading 6 mr/hr 1,065 m from Sedan crater. a, Autoradiograph of Russian thistle stem after 1 year exposure time. b, Sectioned root of Salsola iberica. Autoradiograph after 1 year exposure time.

Table 16.--Plants recorded at stations along a north traverse from Sedan crater and date of first observation at each station after detonation on July 2, 1962

Plant	Sta. 19c (crater rim)	Sta. 19b 3,500 ft. (1,065 m)	Sta. 19d 4,000 ft. (1,229 m)	Sta. 19a 5,000 ft. (1,525 m)	Sta. 19 5,500 ft. (1,650 m)	Sta. 18 6,500 ft. (1,980 m)	Sta. 17a 7,000 ft. (2,135 m)	Sta. 17 8,500 ft. (2,590 m)	Sta. 16 11,500 ft. (3,500 m)
Forbs									
Salsola iberica	5/26/64	5/11/64	9/11/64	12/09/63	9/30/63	9/11/64	9/11/64	7/01/65	
Sphaeralcea ambigua		5/11/64			4/08/63				7/01/65
Calycoseris wrighti			5/08/66		5/08/66				
Oenothera avita		5/11/64							
Cymopteris ripleyi		5/11/64							
Astragalus lentiginosus	2/15/70			5/11/64				5/26/64	
Eriogonum nidularium				5/11/64	5/08/66			5/08/66	5/26/64
Eriogonum wrighti					5/08/66				
Chaenactis steviodes				5/11/64	5/08/66	5/26/64		5/26/64	5/26/64
Malocothrix glabrata				5/11/64					
Euphorbia sp.		5/11/64							
Phlox stansburyi									5/26/64
Lepidium fremontii	4/15/70		4/15/70					5/26/64	
Eriogonum maculatum									7/01/65
Mentzelia nitans			7/01/65						
Stephanomeria parryi			7/01/65						
Machaeranthera tortifolia								5.08/66	
Mentzelia gracilenta					5/08/66				
Mentzelia veatchiana				5/08/66					
Cryptantha nevadensis			5/08/66						
Eriogonum deflexum	4/15/70								
Baileya pleniradiata		5/11/64		5/11/64					
Grasses									
Oryzopsis hymenoides		5/11/64	7/01/65	5/11/64	9/30/63	5/26/64		5/26/64	7/01/65
Sitanion hystrix		5/11/64		5/11/64		5/26/64		7/01/65	
Stipa speciosa			5/08/66	5/08/66	5/08/66			7/01/65	7/01/65
Shrubs									
Chrysothamnus paniculatus		5/11/64						9/30/63	7/01/65
Coleogyne ramossissima				5/11/64	5/26/64	5/08/66		4/08/63	4/08/63
Larrea divaricata									4/08/63
Hymenoclea salsola		11/01/66	10/28/68	12/09/63	9/30/63	9/30/63	9/11/64	5/26/64	12/09/63
Grayia spinosa			4/15/70	5/11/64	5/26/64	4/08/63		5/08/66	4/22/65
Yucca brevifolia							4/08/63		
Lycium andersoni		4/22/65	5/08/66	5/08/66		9/30/63			7/01/65
Ephedra nevadensis			4/15/70			9/30/63		5/08/66	7/01/65
Atriplex canescens	4/15/70	5/11/64	7/01/65						
Ambrosia dumosa		5/11/64	10/28/68						
Opuntia basilaris						5/26/64			

Palanquin.--Detonated on April 14, 1965 on Pahute Mesa with a shallow emplacement at 85 m; was designed to produce an upheaval mound or retarc but vented because of faulty casing, producing a throwout crater with a ground zero reading of 7 R/hr. The radioactive cloud of dust formed a whirlwind, the vortex of which moved north across the sage-covered mesa. The senior author made pre-explosion studies around the site and studied plants at 18 stations from 180 m south of ground zero to 6,250 m north on 10 different occasions for 5 years after the event. Of these, selected samples have been analyzed by gamma spectrometer from four collections only. Unfortunately, neither the pre-explosion samples nor those collected 12 days after the event were analyzed, because the pre-explosion samples had too low a total gamma count to make analysis feasible and the later samples were too radioactive to bring into the laboratory. Autoradiographs have been made on material from five collections.

The condition of shrubs along the north traverse, that were observed at nine intervals from 12 to 1,800 days after the event, is shown graphically in figure 62 and the first appearance of herbaceous plants is shown in table 17. The area for 350 m north of ground zero was restricted from access and was studied only four times, in the company of radiation safety personnel. The shrubs in this area yellowed and wilted within 12 days and presumably died shortly thereafter; the shrubs and ground were covered with a thick coating of throwout. No signs of live plants were observed 75 days after the event for a distance of 655 m to the north of ground zero; ground at this distance registered 100 mr/hr 3 feet above ground. In a westerly direction 150 m to 184 m from ground zero where a reading of 12 mr/hr was taken and throwout was observed, *Juniperus* (juniper) and *Artemisia arbuscula* (sage) were dead and *Ephedra nevadensis* was yellowed, *Chrysothamnus nauseosus* was dead or defoliated, and *Cowania mexicana* was dying. However, a small lupine, *Lupinus flavoculatus*, and *Phacelia fremonti* had germinated. Shrub growth did not appear to be seriously affected farther to the west and not at all south of the crater where *Astragalus purshii* was in bloom. Continuing north from the main road, *Artemisia*, *Ephedra nevadensis*, and *Grayia spinosa*, the dominant shrubs, were yellowed and wilting for 6,000 m, although a few green shoots were unaffected on the side of the shrubs away from the explosion. Isolated specimens of *Astragalus lentiginosus*, *Oryzopsis hymenoides* and *Sitanion hystrix* were observed. Juniper growing about 1,500 m north of ground zero appeared at this stage to be unaffected but was observed to be yellowing at D+405 days and dead at the next observation 750 days after the event. Some fracturing or ground disturbance was observed for 1,500 m north of the crater (fig. 63), and beyond this distance plants were clearly affected only in in the direct path of the radioactive cloud. Because of the waywardness of the cloud, only the overall appearance of the largest percentage of a given species can be graphed. Occasional plants were not touched at all, and, in many instances, single live shoots on the far side of otherwise dead bushes were observed. Here, as at Shoal and elsewhere, young sage germinated after several years, and the area after 6 or more years is once again shrub-covered. The disappearance of juniper is probably permanent. *Atriplex canescens*, as observed elsewhere, was not damaged below ground and grew rapidly from the old crown to produce a healthy shrub after a few months in soil reading as high as 60 mr/hr beta plus gamma. *Atriplex confertifolia* also recovered quickly at station K6. The general devastation of the dominant

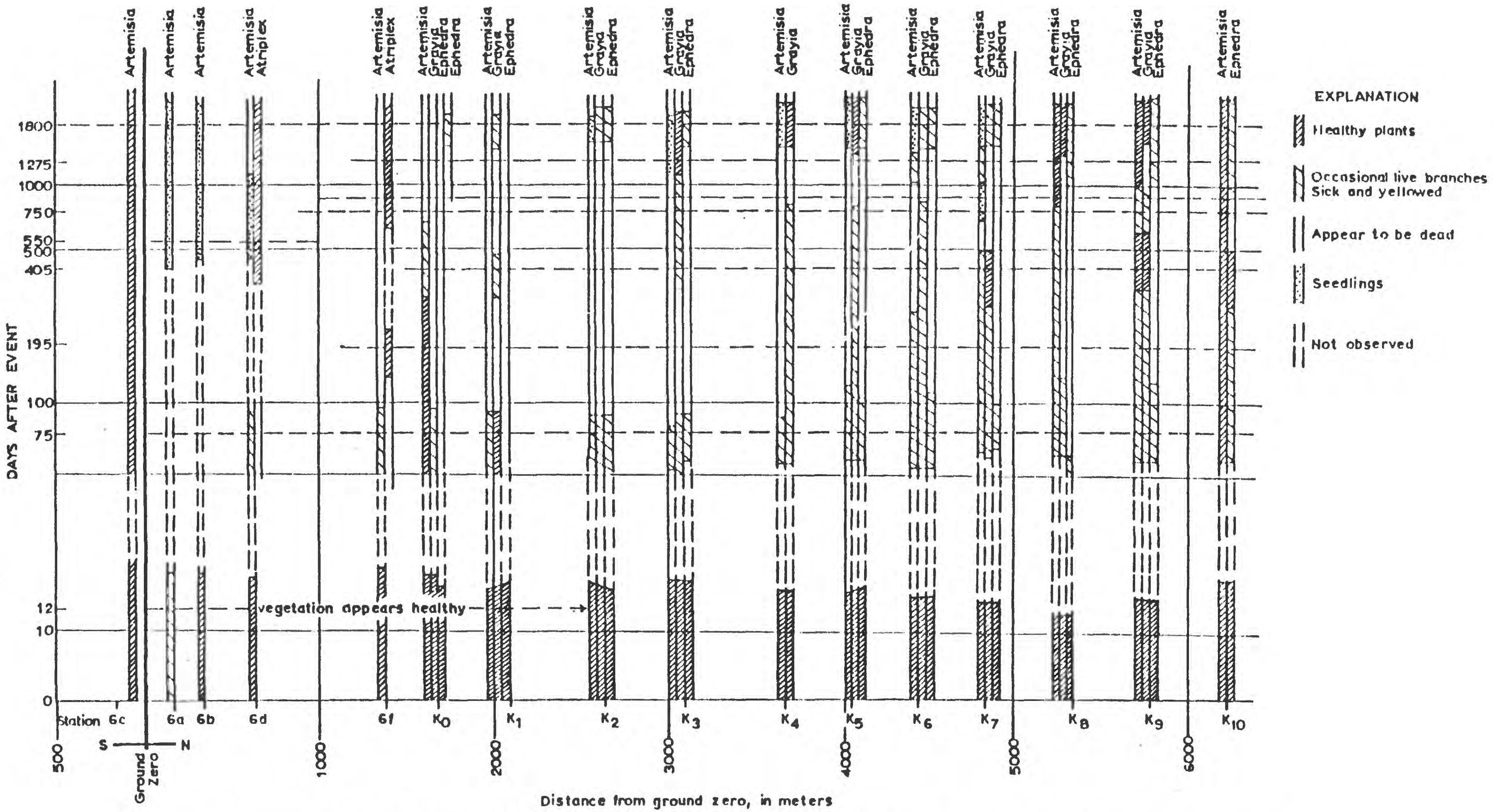


Fig 62 DIAGRAM OF EFFECTS ON VEGETATION ALONG A NORTH-SOUTH TRAVERSE -- PALANQUIN

Table 17.--First observed appearance of herbaceous plants at various distances and times relative to Palanquin event

[Number of days after the event and radiation levels in mr/hr are given for each species and locality. Where Where beta (B) and gamma (Y) were measured separately, they are so indicated; other mr values are gamma only]

Plant species	Distance north from ground zero															
	180 m	330 m	650 m	750 m	1350 m	1675 m	2130 m	2590 m	3050 m	3500 m	3960 m	4420 m	4880 m	5330 m	5790 m	6250 m
Grasses																
Oryzopsis hymenoides (Rice grass)	555 days 105B 50Y	1800 days 5Y 3B	405 days 2.5B 2.0Y	877 days 2mr			75 days 5mr	405 days 1.2mr	405 days 1.0mr	195 days 2.0Y 1.0B	750 days 28mr	195 days .9Y 1.6B	750 days .17mr	877 days	195 days .4Y .3B	195 days .4mr
Sitanion hystrix (Squirrel tail)	1800 days 50mr	555 days 50B 30Y					75 days 5mr						1800 days .1Y .1B			
Poa sanbergii (Blue grass)	1800 days 50mr									1800 days .1B .1						
Stipa speciosa (Desert needle grass)	555 days 105B 50Y	555 days 50B 30Y	750 days 3mr		750 days	877 days 0.8mr		405 days 1.2mr	405 days 1.0mr	405 days .7mr	877 days .24mr		877 days .2mr	750 days .1mr	877 days .12mr	1275 days .03 Y .01B
Forbs																
Astragalus lentiginosus (Speckled milkvetch)			750 days 3mr			75 days 10mr		405 days 12mr	405 days 1.0mr	877 days .35mr			877 days .2mr	877 days	405 days .21mr	195 days .6mr
Astragalus purshii var. tinctus (Pursh milkvetch)	555 days 40B 30Y										405 days .7mr	405 days .6mr				
Castilleja sp. (Paint brush)																750 days .07Y
Chaenactis stevioides (False yarrow)															405 days .21mr (reduced)	
Cymopterus purpurescens (Chimaya)											750 days .16mr					
Crypthantha sp. (Cryptanthe)	555 days 60B 40Y			750 days												
Eriogonum nidularium (Eriogonum)	555 days 105B 50Y	555 days 50B 30 Y		750 days		dominant 1275 days .7Y .2B			877 days .4mr	877 days .35mr		877 days	1275 days .08mr		1275 days .04 Y .01B	195 days .6mr
Eriogonum leptophyllum (Eriogonum)												877 days				1275 days .03 Y .01B
Eriogonum deflexum (Skeleton weed)						877 days 0.5mr						877 days				877 days
Eriogonum ovalifolium v. ovalifolium (Cushion eriogonum)							405 days 1.2mr									750 days .07 Y
Lepidium lasciocarpum (Pepperweed)	555 days 105B 50 Y															
Lupinus flavoculatus (Lupine)	75 days 12mr								405 days 1.0mr						877 days .12mr	877 days
Linum lewisii (Perennial flax)																
Machaeranthera canescens (Desert aster)	555 days 105B 50Y	555 days 50B 30Y						877 days 0.4mr	877 days .4mr	877 days .35mr			877 days .2mr	877 days	877 days .12mr	877 days
Mentzelia gracilliana							405 days 1.2mr									
Penstemon palmeri (Beard tongue)						1275 days .5Y .2B										
Phacelia fremontii (Yellow throat)	75 days 12mr		750 days 3mr				405 days 1.2mr									750 days .07mr
Phlox stansburyi (Phlox)			405 days 2.5B 2.0Y													
Salsola iberica (Russian thistle)		dominant 1800 days 3B 5Y		dominant 877 days 2mr		1275 days .7Y .2B		877 days 0.4mr	877 days (every 5') .4mr	877 days .35mr						
Sphaeralcea variabilis (Globe mallow)	555 days 105B 50Y	555 days 50B 30Y		877 days 2mr		877 days 0.5mr			1275 days .3Y .1B	1275 days .1Y .1B	877 days .24mr	877 days		750 days .1mr	405 days .21mr	877 days

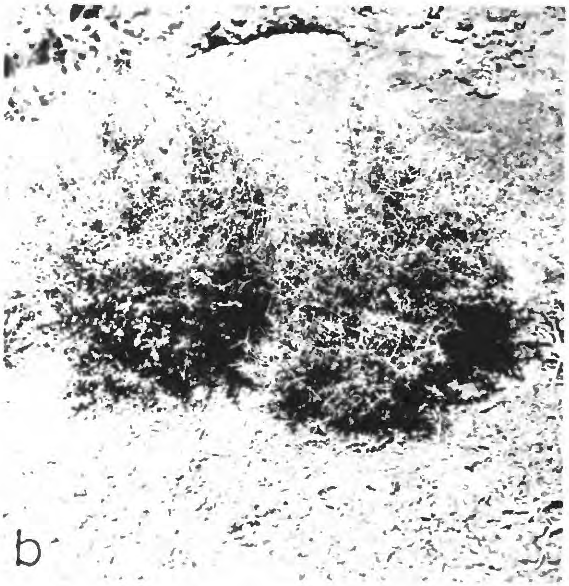


Figure 63.--Physical effects noted north of Palanquin crater. a, Faulted ground surface observed 1,500 m north of ground zero. Photograph taken in 1967. b, Coleogyne ramossissima split by ground fracture. Photograph taken in 1967.

shrubs in the path of the radioactive cloud across the mesa was probably the most intense during the second year; there was a noticeable improvement in the shrubs in the fifth year. Oryzopsis hymenoides and Stipa speciosa were, during the interim, dominant plants in the area. The adventive Eriogonum nidularium also came in early. By the end of the study, a large number of flowering plants had returned to the area, but competition had developed with Russian thistle. The thistle first came in along the roads 2 years after the event but had become dominant in the area of greatest dust cover south of the road by the end of the study. Machaeranthera canescens (Pursh) A. Gray was observed growing 150 m north of ground zero in soil reading 200 mr/hr (110 beta, 90 gamma) only 1 1/2 years after the detonation, and at many stations after the second year.

Unusual growth effects that were observed during the study included shortened plumose styles on Cowania (as was also observed at the Des Moines vented explosion), a clubby appearance of Eurotia owing to affected terminal buds, small leaves and unusually spiny Atriplex confertifolia, and the lack of seed production in Oryzopsis and Artemisia during the season following the explosion.

The curves shown in figure 64 show a lessening in radiation levels with time and distance but are approximate as there were variations between instruments and in readings by different personnel. The radiation level dropped from 7 R/hr at the time of the event to about 3 mr/hr 5 1/2 years later. Although the beta radiation was probably twice that of gamma near ground zero and for 5,000 m for D+195 days, the beta levels were lower than gamma at D+3 1/2 years, except near the crater. ^{45}Ca with a half-life of 165 days and ^{35}P with a half-life of 14 days may account for the early high levels, and ^{90}Sr for the longer-lived beta radiation. Rhoads and Platt (1971) concluded that beta damage was greater than gamma and pointed out that each species has its own characteristic developmental stages and that the most sensitive stages may be out of phase with neighboring species. Meristem coverings such as bud scales that would protect from beta radiation vary with species. Also species with large chromosome volume such as Juniperus and Artemisia are more sensitive than Grayia with smaller chromosome volume. We also found Grayia to be much more resistant to radiation than Juniperus and a little more resistant than Artemisia.

Radionuclide levels measured by gamma-ray spectrometer of the soils at Palanquin differ in several ways (table 18). There was considerably less contamination to the south than to the north. No throwout was visible on the southern vegetation that continued to grow even though the area was severely fractured at the time of the explosion (fig. 65). The samples of throwout from the north side of the crater collected 12 days after the explosion, consisted mostly of glass and were too radioactive to be brought into the

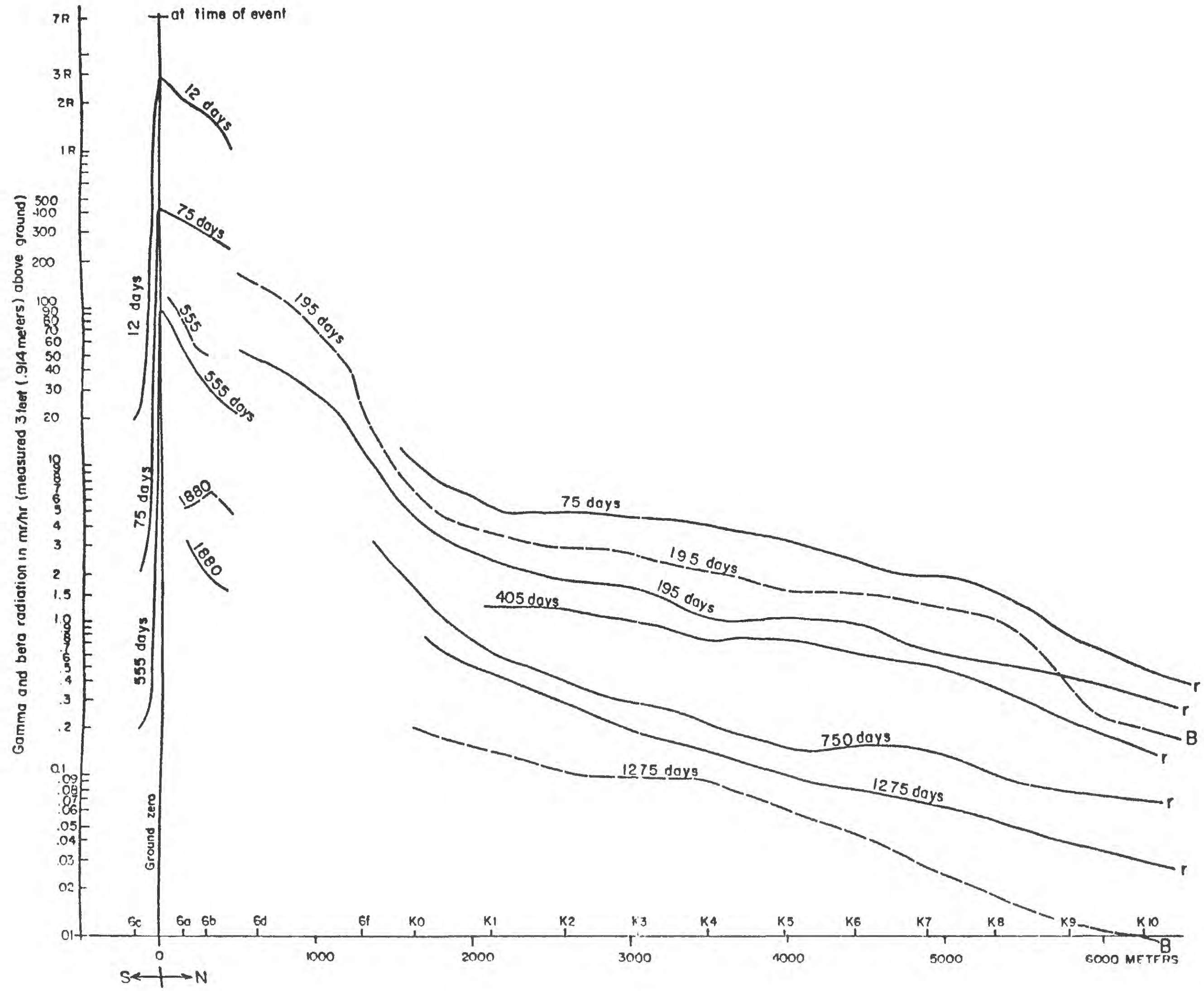


Figure 64.--Diagram of radiation levels along North-South traverse from Palanquin shot, plotted with time.

Table 18.--Gamma radionuclides calculated to date of collection and date of event in soils collected at Palanquin site (pci/g, pico curies per gram)

mr/hr above ground surface gamma	beta	Distance from ground zero (feet) (meters)	Collection time after event	^{54}Mn At collection	^{54}Mn At event	^{60}Co At collection	^{60}Co At event	^{88}Y At collection	^{88}Y At event	$^{95}ZrNb$ At collection	$^{95}ZrNb$ At event	^{106}Ru At collection	^{106}Ru At event	^{137}Ru At collection	^{137}Ru At event	$^{140}LaBa$ At collection	$^{140}LaBa$ At event	^{144}Ce At collection	^{144}Ce At event
2.5		500 S (150)	2 3/4 months	---	---	41.9	43.18	---	---	678.	1,670.	135.	160.	---	---	64.	5,750.	7,780.	9,460.
12.		600 W (180)	----do------	---	---	1,650.	1,700.	---	---	20,900.	51,420.	17,600.	20,610.	---	---	1,160.	105,270.	227,000.	275,720.
12.		1,000 W (300)	----do------	---	---	2,140.	2,200.	---	---	30,000.	74,550.	2,680.	3,130.	---	---	---	---	295,000.	358,930.
100.		2,150 N (655)	----do------	---	---	3,310.	3,410.	---	---	103,000.	253,870.	---	---	---	---	3,410.	308,400	746,000.	906,650.
		500 S (150)	6 months	8.94	14.48	2.55	2.74	---	---	47.6	400.	---	---	2.71	2.75	130.	5,581,740.	36.5	57.90
20	30	5,500 N (1,675)	----do------	---	---	3,720.	3,990	600.	2,127	157,000.	1,325,000.	---	---	---	---	---	---	107,000.	169,940.
2	1	11,500 N (3,500)	----do------	---	---	28.6	30.7	10.	36.	860.	7,270.	---	---	17.6	17.72	214.	9,080,800.	560.	900.
.4	0	20,500 N (6,245)	----do------	---	---	9.74	10.50	---	---	300.	140.	---	---	7.34	7.44	---	---	220.	350.
.1	.2	500 S (150)	18 months	0.66	2.65	3.88	4.77	---	---	---	---	---	---	---	---	---	---	---	---

Figure 65.--*Artemisia arbuscula* 150 m south of Palanquin ground zero in fractured zone. Shrubs here continued to leaf out and to fruit, unaffected by the event.

laboratory. The area was restricted from access and no attempt was made to recollect glass in this area where no vegetation grew. The soil sample collected 1,650 m north 18 months after the event was a surface soil sample, as was the sample collected 150 m to the south; the remaining samples represent a composite of 0-7.6 cm. Collections on different sides of the crater appear to differ in radio nuclide composition. No ^{106}Ru-Rh was reported in the early collections from the north side nor in any later collections. Soil on the south side of the crater where there was no throwout was much lower in all other radionculides but was higher in ^{140}Ba-La than soil on the north side. As would be expected, the levels of all radionuclides decrease with both distance and time.

As the concentrations of the most abundant but short-lived radionuclides decreased, other radionuclides that had been masked could be detected by gamma ray spectrometer, such as ^{137}Cs, ^{88}Y, and ^{54}Mn.

Some overturned cans were set out in advance of the explosion 1,675 m north from ground zero to disprove the theory proposed by Itek that the fluffy dust observed around unclear explosions has been shaken loose from the ground by the physical shock and therefore is of local origin. The samples collected 6 months after the event contained in pci/g of gamma radiation:

	^{60}Co	^{95}ZrNb	^{144}Ce	^{88}Y
Soil under can 1------------	1.01	122.	100	1.54
Soil outside can 1----------	3,720	157,000	107,000	601.
Soil under can 2------------	2.46	31.7	29.4	--
Soil outside can 2----------	1,780	78,000	53,300	1,010.

The soil was undisturbed under the cans and the loose material outside of the cans is presumbed to be entirely fallout. A counter held 0.9 m above the ground read 30 beta and 20 gamma. Rhoads, Kantz, and Ragsdale (1972) describe an experiment in which plastic was put over areas of shrubs near the Schooner explosion. The survival of shrubs under the plastic was ascribed to exclusion of beta radiation as shrubs under plastic received 15 percent less gamma and 60 percent less beta radiation. Our data suggests that protective covering excludes large amounts of gamma radiation as well as beta by preventing contact of the vegetation and soil with fallout.

Shrubs and trees south of ground zero were not killed; those both west and north died, demonstrating that plant demise was not due to physical causes but to radioactivity. Contents of gamma radionuclides were greater west of ground zero and considerably greater to the north. Twelve days after the event, measurement of total beta + gamma were taken 0.9 m above the ground as follows:

180 m south of ground zero	--	20 mr/hr
180 m north of ground zero	--	2 R/hr
330 m north of ground zero	--	1 1/2 R/hr

Readings taken 18 months after the explosion on different sides of the crater are given in table 19.

The beta radionuclides would include those shown in table 7a and have more than doubled the total radiation for at least 1,800 m to the north (See table 19). A plant of *Ephedra nevadensis* that was protected somewhat by its location under a juniper tree but that was dying at 2 2/3 months after the event, was dug up and the root analyzed. The washed root contained unusual amounts of all gamma radionuclides found in the throwout including 31 pci/g ^{60}Co, 307 pci/g ^{106}Ru-Rh, 403 pci/g $^{95}ZrNb$, and 4,660 pic/g of ^{144}Ce. These amounts were necessarily absorbed from the ground in which the tree grew.

Table 19. Ground readings taken 18 months after Palanquin explosion on different sides of the crater rim (mr/hr, milleroentgens per hour)

mr/hr		Distance and direction from crater	Condition of vegetation
gamma	beta		
0.2	0.1	150 m south of crater rim--	Old established *Artemisia* fruiting.
1	3	East side of crater rim----	*Sphaeralcea*, *Oryzopsis*, *Salsola*. (*Artemisia* all dead)
90	110	North side of crater rim---	No living plants
40	60	75 m north of crater rim-	*Cryptantha*, *Eurotia*, seedling *Artemisia*, *Machaeranthera*.

Wood sections show the development of radial and concentric traumatic canals filled with ergastic material in *Artemisia* growing well beyond the area of rock fracture on a mesa top and subjected only to the highly radioactive dust cloud (fig. 66). Canal development in wood was observed in *Artemisia* for at least 6,250 m north of ground zero but lessened in intensity beyond 5,790 m, as shown in figure 66d. The nearest live *Artemisia* 650 m north from ground zero, from which a sample was collected 75 days after the explosion, died shortly thereafter.

6

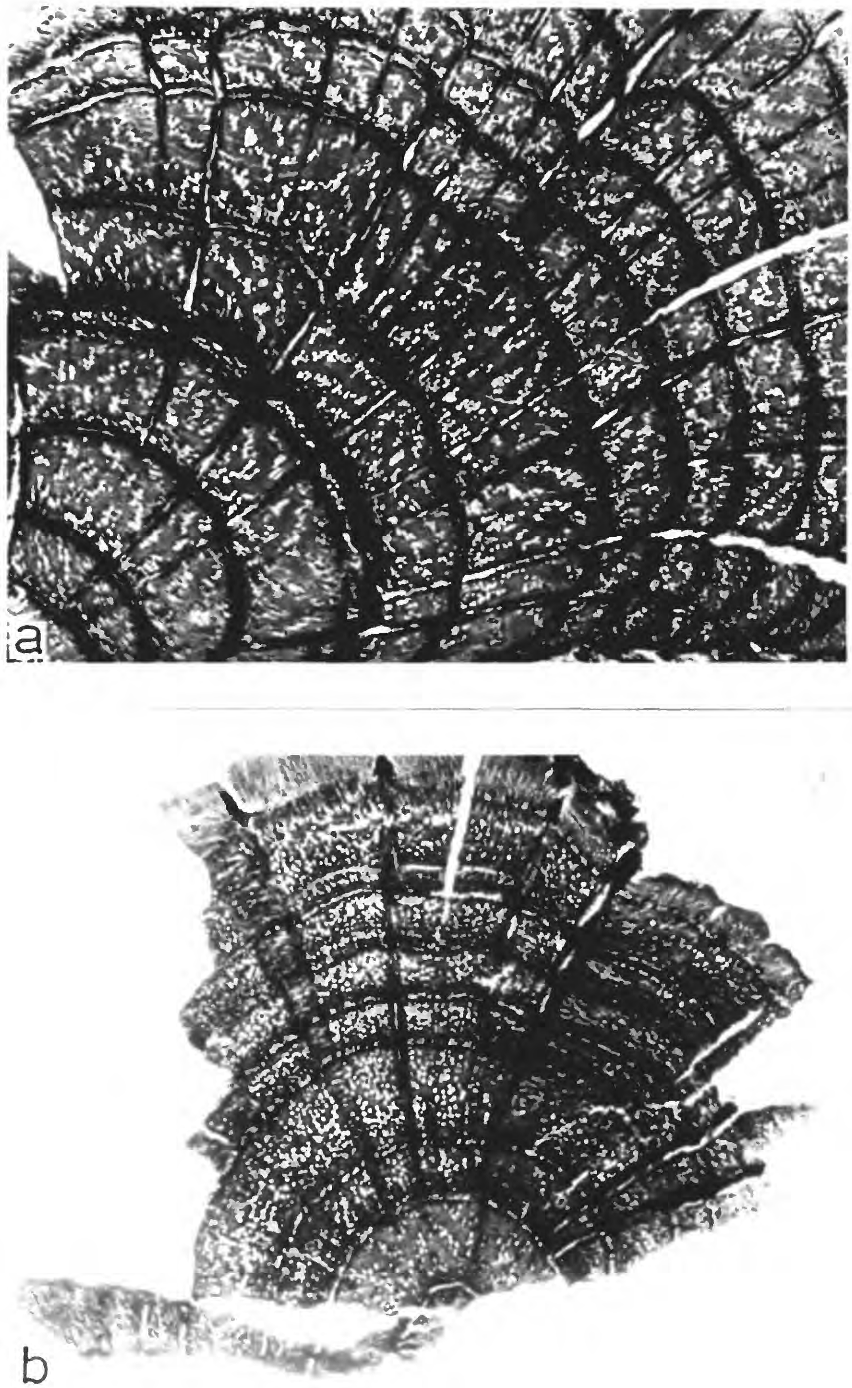
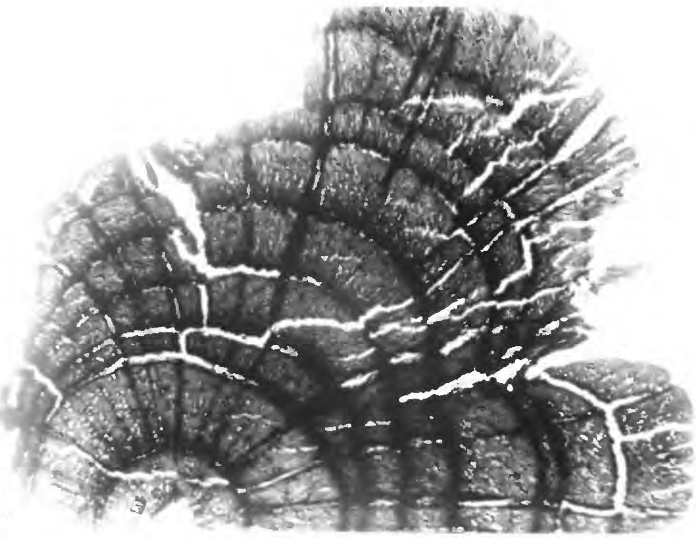
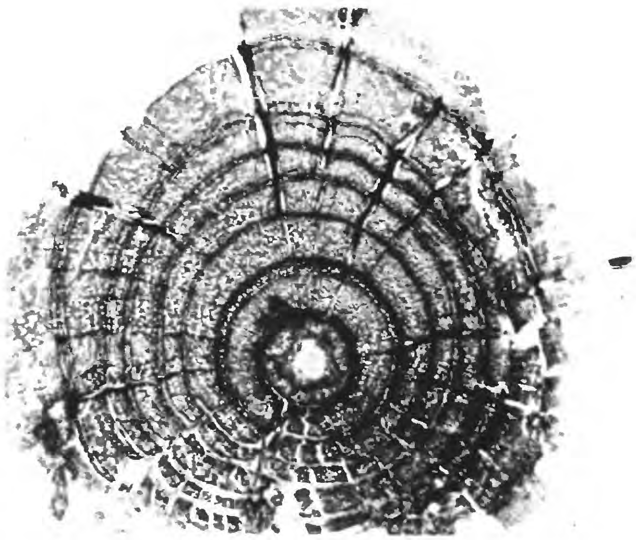


Figure 66.--Traumatic canals in Artemisia in path of radioactive cloud produced at time of Palanquin event. (a) Section of sage stem 650 m from ground zero. At the time of collection was closest living sage to ground zero. Sail read specimens which later died 100 mr/hr. (b) Sage stem, 3,500 m from ground zero collected in July 1965. 4 mr/hr reading. (c) Artemisia 5,790 m north of ground zero. Collected 5/1/66. (d) Artemisia 6,250 m north of ground zero. Collected 10/27/65.



c



d

Figure 66.--continued

Autoradiographs were made of many samples from the Palanquin area. Radionuclides were, in general, confined to the exterior bark for the first 2 1/2 months (fig. 67). Ephedra and Artemisia 180 m south of ground zero, where the plants received insufficient damage to kill them, produced good autoradiographs on old wood, poor on new wood (fig. 68). Shrubs for 655 m north of ground zero were killed outright or died a short time later. Autoradiographs after 1 week exposure were bright on unwashed wood with bark, faint on washed wood, and blank on peeled wood (fig. 69). Shrubs farther from ground zero that were not all killed, produced clear autoradiographs for 2 1/2 years on old wood after the explosion, and faint on new growth. Some of the data on autoradiographs are shown in table 20 and in figures 70 and 71. Absorption is definite in samples of new shoots on healthy plants after a relatively long exposure but cannot be detected in young growth of dying shrubs, which suggests a reduction in the absorption of water and of radionuclides in stressed plants.

Subsequent to our early studies and 2 years after the event, a team from UCLA began studying the Palanquin vegetative changes. Wallace and Romney (1972) established 30 X 30 m ecologic plots in an area of total destruction, an area of 80-90 percent destruction and non-irradiated area. They observed that Salsola was dense in the heavily damaged plot where the sage seedlings had died; that the seedlings were surviving in the area of 80-90 percent destruction with a high percentage of grasses and few Salsola; and that Grayia spinosa and, to a lesser extent, Eurotia lanata, Ephedra nevadensis, Tetradymia axillaris and Chrysothamnus nauseosus, had reestablished themselves.

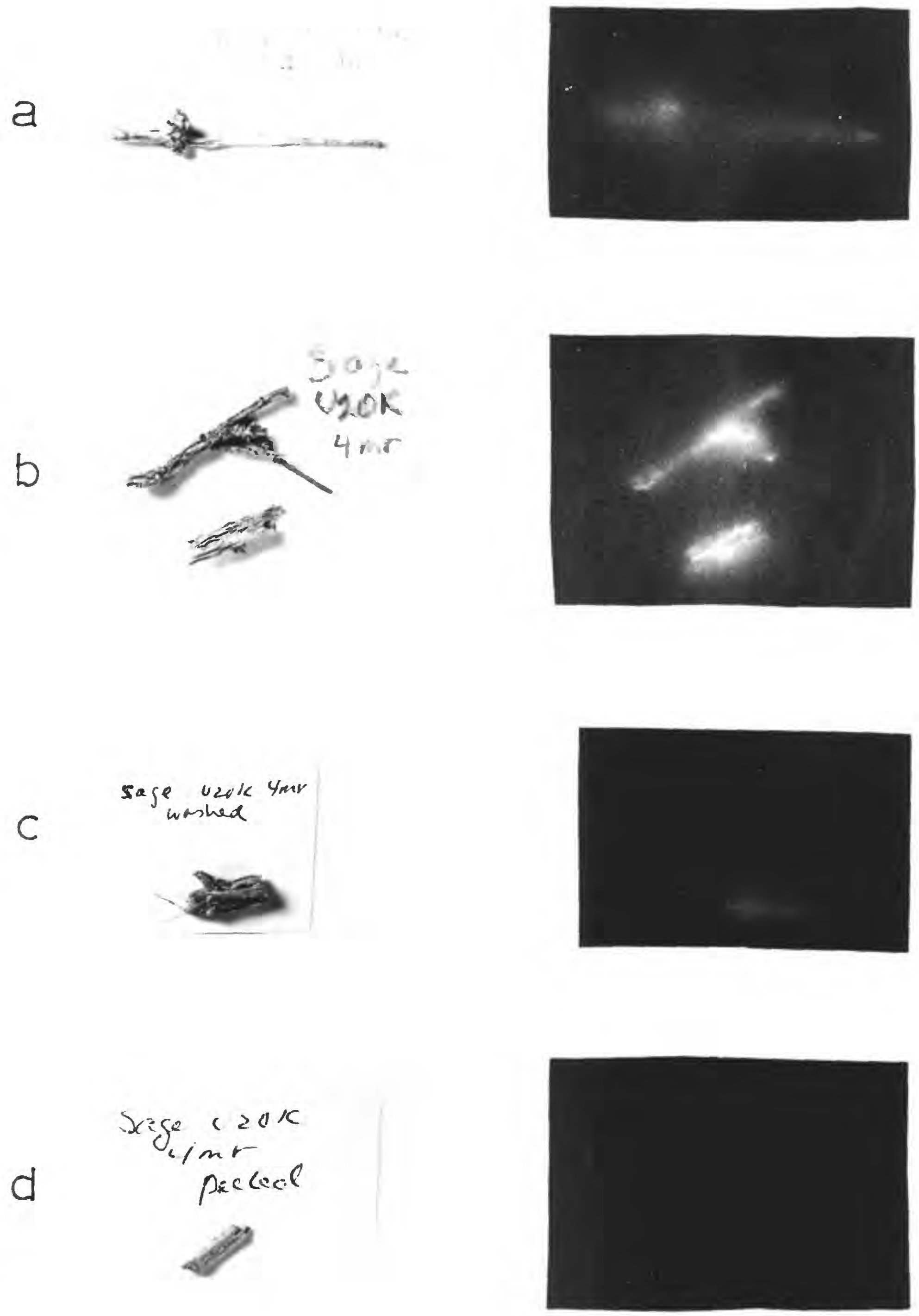


Figure 67.--Autoradiographs of Artemisia and Ephedra collected 2,740 m north of Palanquin ground zero 2 1/2 months after detonation in area reading 4 mr/hr. a, Ephedra, unwashed; b, Artemisia unwashed; c, Artemisia, washed; d, Artemisia, peeled.

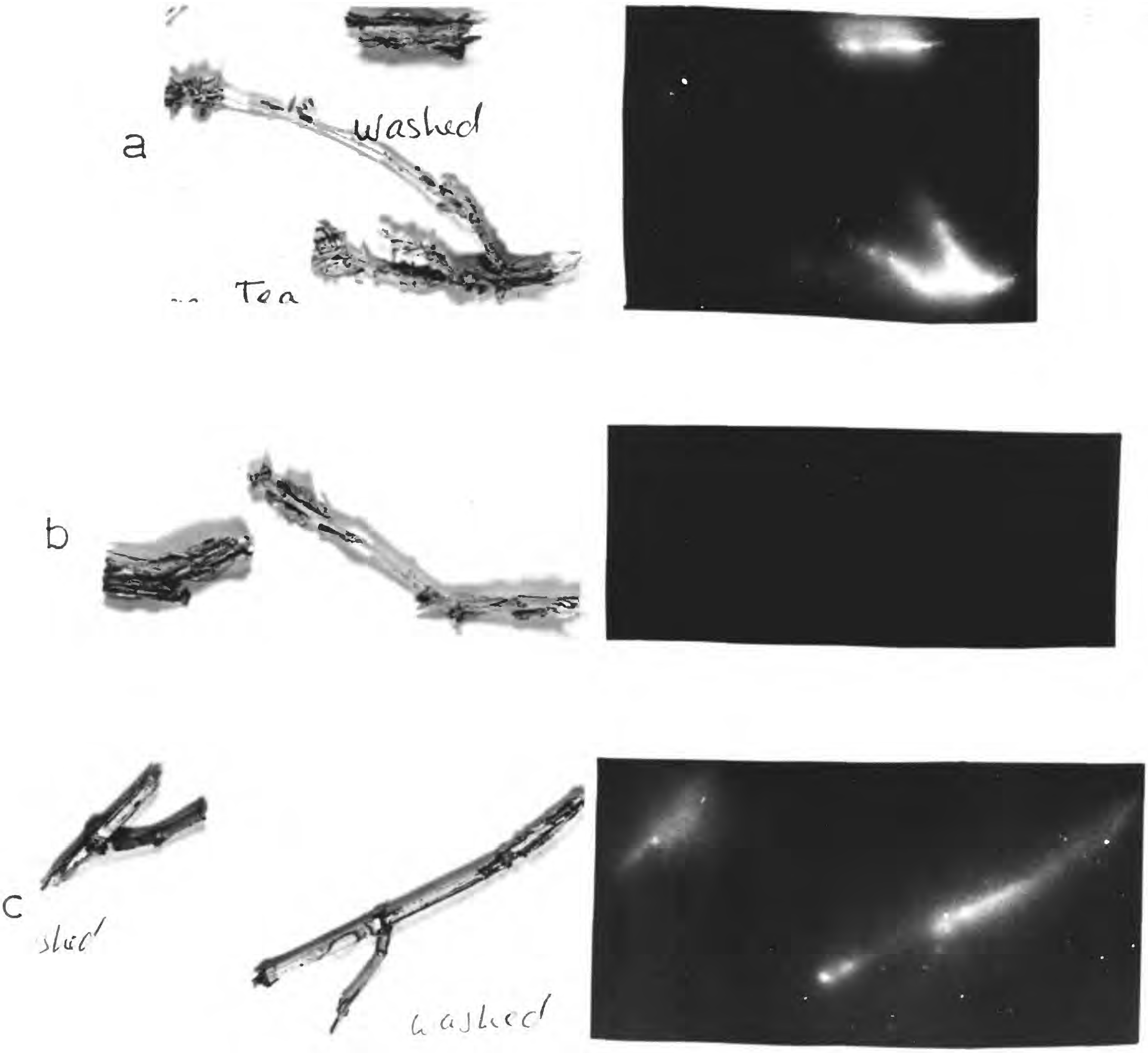


Figure 68.--Autoradiographs of Artemisia arbuscula (sage) and Ephedra nevadensis (Mormon tea) collected 180 m south of Palanquin crater. a, Sage collected 6 months after event. Brilliant autoradiographs on washed old wood but none on new growth after 6 months exposure time. b, Sage collected 14 months after event. Autoradiographs show disappearance of radionuclides from old and new growth after 6 months exposure time. c, Washed and unwashed Mormon tea 6 months after the event. Autoradiographs show inability to clean wood easily of contamination. Exposure time 12 months.

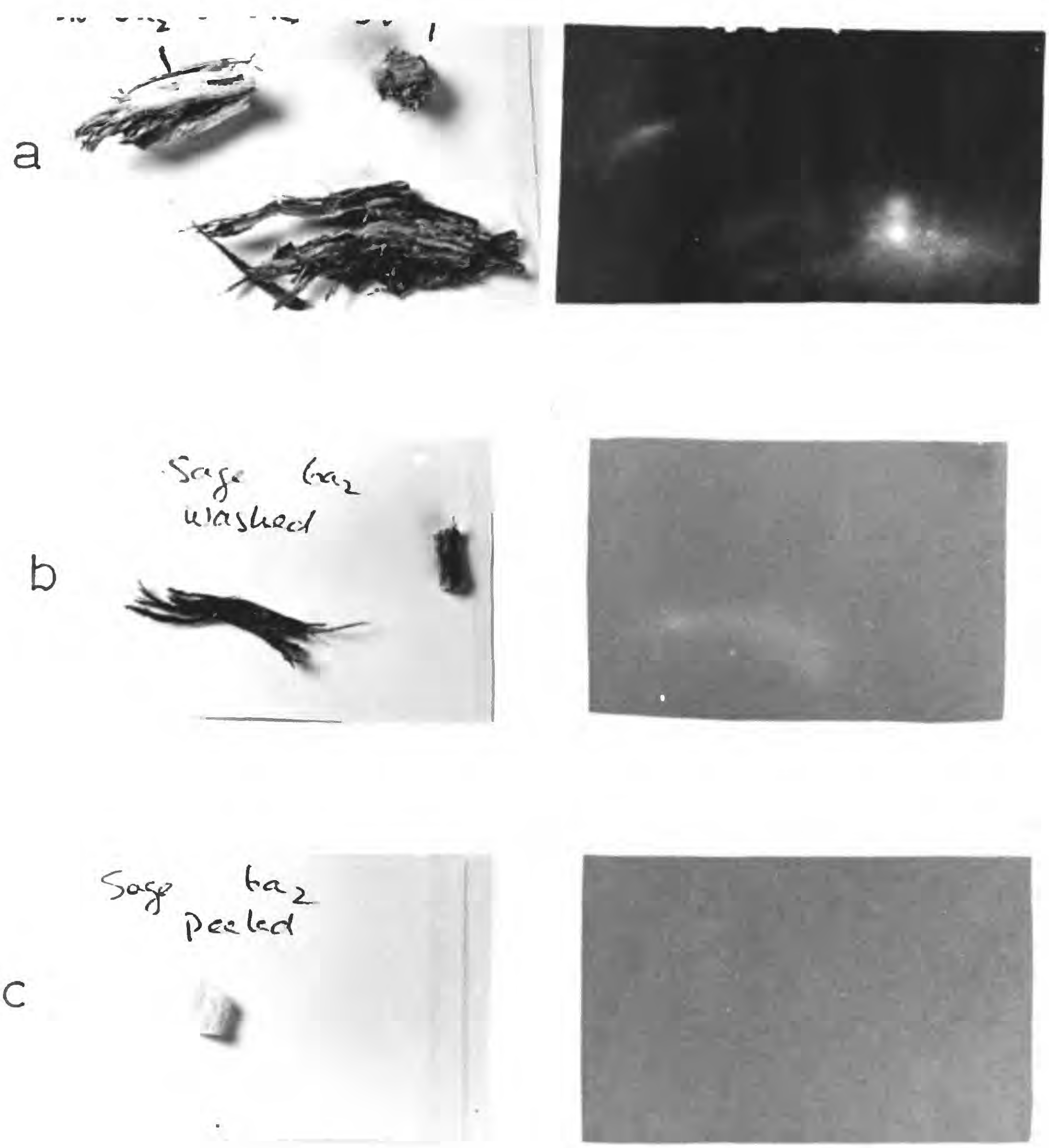


Figure 69.--Autoradiographs of Artemisia arbuscula (sage) collected 655 m north of Palanquin crater, 3 months after event. Ground reading 100 mr/hr. Nearest live sage to ground zero, dead 6 months after event. a, Unwashed wood and bark, after 1 week exposure time. b, Washed wood and bark, after 1 week exposure time. c, Peeled wood, after 1 week exposure time.

Table 20.--Autoradiograph data on Palanquin samples

Distance and direction from crater feet (meters)	Time of collection from date of explosion	Plant	Exposure of film	Result
600 S (180)	18 months	Artemisia--------------------------	6 months	Bright on old wood, less bright on new shoots.
	18 months	Ephedra----------------------------	6 months	Less than sage.
			9-12 months	Unwashed as bright as 6 month sage.
2,150 N (650) (these all died later)	6 weeks	Nearest live Artemisia (washed)-----	4 weeks	Bright.
	3 months	------do---(unwashed)---------------	2 months	Slight.
	---do-------	Grayia--------do--------------------	---do-------	Bright.
	---do-------	Ephedra-------do--------------------	---do-------	Bright, especially at nodes.
8,500 N (2,550) (all killed)	2 1/2 years	Eurotia, new plant------------------	9-12 months-	Slight shadow.
10,000 N (3,050) (later all dead)	6 months	New shoot (washed)------------------	2 months	Bright.
		On nearly dead Artemisia------------	9 months	Very bright.
11,500 (3,500) (later all dead)	3 months	Artemisia---------------------------	4 weeks	Bright.
	6 months	Live shoot on Artemisia-------------	9 months---	Slight shadow.
	6 months---	Dead wood on sage-------------------	2 months---	Bright.
	3 months---	Grayia------------------------------	2 weeks----	Light.
	2 years----	--do--------------------------------	9 months---	Bright.
	3 months---	Ephedra-----------------------------	4 weeks----	--do---
16,000 (4,860)	6 months---	Artemisia, old and new wood---------		Very bright.
	1 year-----	-----do-----------------------------		----do------
	18 months--	-----do-----------------------------		Only slight on new.
	2 years----	-----do-----------------------------		Very bright on new wood, only cambium layer of old wood.
19,000 (5,790)	18 months--	Artemisia, new wood-----------------	2 months---	Bright.
	6 months---	Artemisia, old wood-----------------	12 months--	--do---
	6 months---	Ephedra-----------------------------	12 months--	--do---
	18 months--	Ephedra, old wood-------------------	12 months--	Bright, especially nodes.
	18 months--	Ephedra, new shoot------------------	12 months--	None.
20,500 (6,250)	6 months---	Artemisia, old wood-----------------	6 months---	Bright.
	6 months---	Growing tips------------------------	6 months---	None.
	6 months---	Ephedra-----------------------------	6 months---	Less bright than sage
			6 months---	None.
	6 months	Atriplex canescens------------------	6 months old	Good

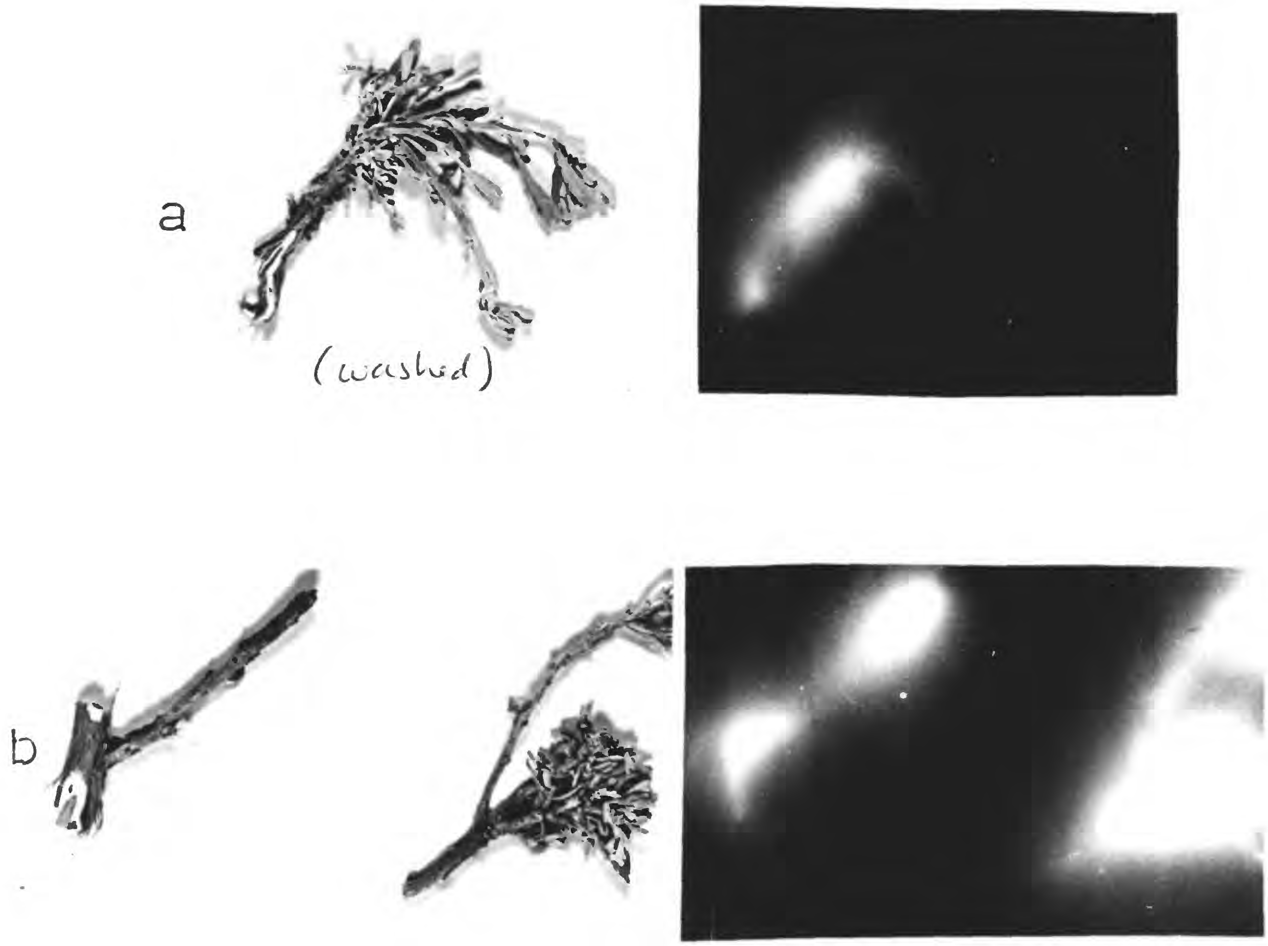


Figure 70.--Autoradiographs of Artemisia arbuscula (sage) collected 6 months after the Palanquin event. a, Sage 3,050 m north of ground zero. Autoradiograph bright on old wood and faint on new shoot after 9 months exposure time. Plant dead after 1 year. b, Sage 3,500 m north of ground zero. Autoradiograph brilliant on wood and old leaves after 9 months exposure time. Plant dead 1 year after explosion.

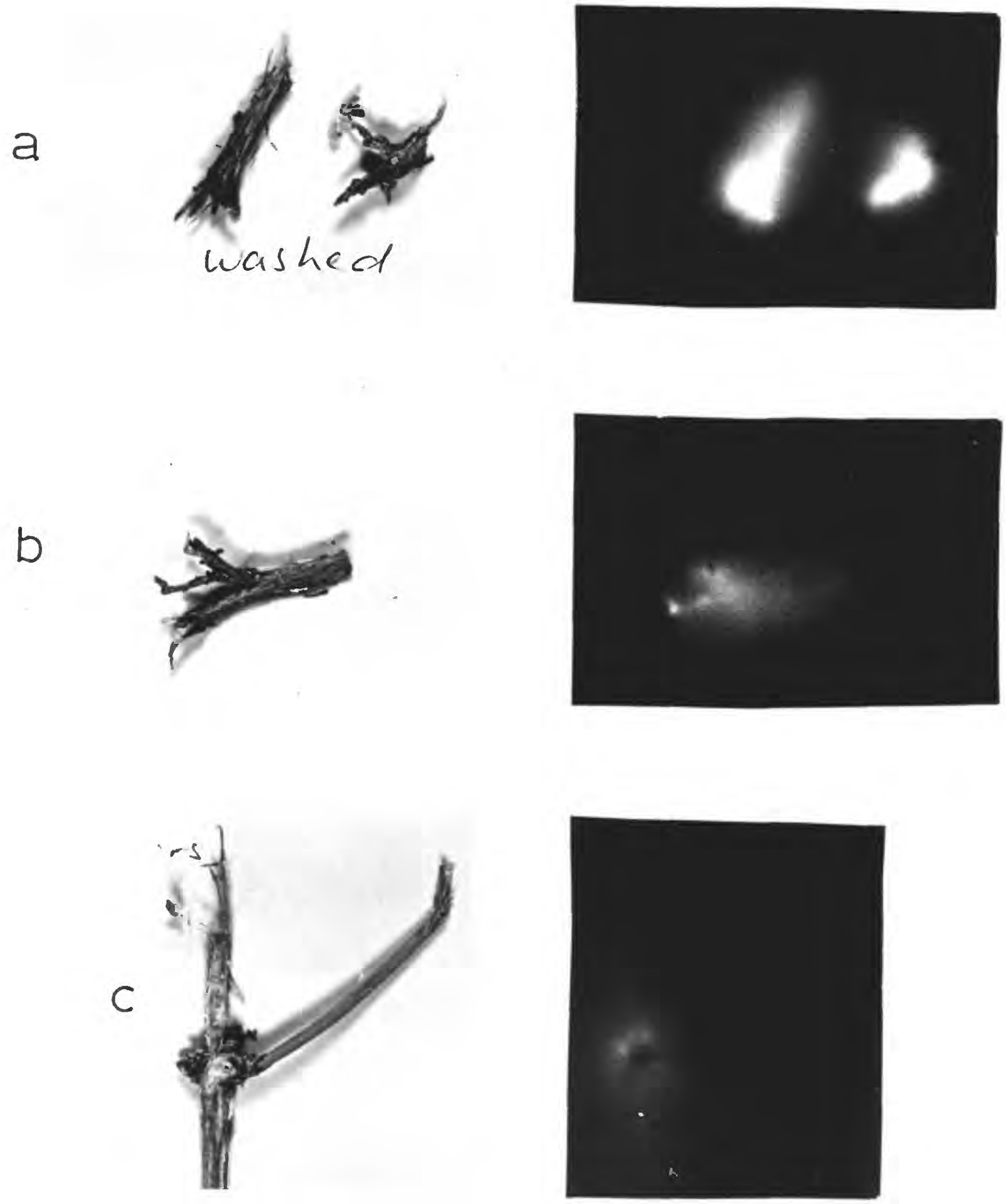


Figure 71.--Autoradiographs of Artemisia arbuscula (sage) and Ephedra nevadensis (mormon tea) collected 5,790 m north of Palanquin explosion. a, Sage, alive and apparently unaffected, collected 6 months after event. Autoradiograph of old twig after 6 months exposure time. b, Sage collected 1 year after event. Autoradiograph of new twig, but no indication of radionuclides in leaves after 6 months exposure. c, Mormon tea collected 14 months after event. Autoradiograph of wood, but not of green stems, after 6 months exposure.

References cited

Anderson, R. Y., and Kurtz, E. B., Jr., 1955, Biogeochemical reconnaissance of the Annie Laurie uranium prospect, Santa Cruz County, Arizona: Economic Geology, v. 50, p. 227-232.

Beasley, T. M., and Palmer, H. E., 1966, Polonium ^{210} in biological samples from Alaska: Science, v. 152, p. 1062-1063.

Beatley, J. C., 1966, Winter annual vegetation following a nuclear detonation in the northern Mojave Desert (Nevada Test Site): Radiation Botany, v. 6, p. 69-82.

Brandenberg, M. K., Mills, H. L., Rickard, W. H., and Shields, L. M., 1962, Effects of acute gamma radiation on growth and morphology in Pinus monophylla Torr. and Frem. (pinyon pine): Radiation Biology, v. 2, no. 3/4, p. 251-263.

Brown, G. N., 1964, Cesium in Liriodendron and other woody species, organic bonding sites: Science, v. 143, p. 368-9.

Bunker, C. M., and Bush, C. A., 1967, A comparison of potassium analyses by gamma-ray spectrometry and other techniques, in Geological Survey Research 1967: U.S. Geological Survey Professional Paper 575-B, p. B164-B169.

Cannon, H. L., 1957, Description of indicator plants and methods of botanical prospecting for uranium deposits on the Colorado Plateau: U.S. Geological Survey Bulletin 1030-M, p. 399-514.

______ 1964, Geochemistry of rocks and related soils and vegetation in the Yellow Cat area, Grand County, Utah: U.S. Geological Survey Bulletin 1176, p. 1-127.

Chandler, R. P., and Weider, S., 1963, Radionuclides in the NW Alaska food chain, 1959-61: Radiology Health Data, v. 4, p. 317-324.

Chappell, H. G., 1963, The effect of ionizing radiation on Smilax with special reference to the protection afforded by their production of underground vegetation structures, in V. Schultz and A. W. Klement, Jr., eds., Radioecology: New York, Reinhold Publishing Corp. and AIBS, p. 289-294.

Esau, Katherine, 1965, Plant Anatomy, 2nd ed. Wiley and Sons, N.Y., 767 pp.

Fritts, H. C., 1966, Growth-rings of trees, their correlation with climate: Science, v. 154, no. 3752, p. 973-979.

Gabay, J. J., Dapolito, J. A., and Sax, N. I., 1965, Annual bioassay meeting, Albuquerque, New Mexico. October 7-8.

Gabay, J. J., and Sax, N. I., 1969, Retention of Ra, due to ingestion of Brazil nuts: Health Physics, v. 16, p. 812-813.

Glock, W. S., and Agerater, S., 1963, Anomalous patterns in tree rings: Endeavor, v. 22, no. 85, p. 9-13.

Gulyakin, I. V., Dergunov, I. D., and Moroz, V. D., 1968, Behavior of radioactive fission products in some soils of the sierozem zone of Uzbekistan: Izr. timiryazev. sel'-khoz. Akad., p. 84-93.

Hill, C. R., 1962, Identification of alpha emitters in normal biological materials: Health Physics, v. 8, p. 17-25.

Hoffman, Josef, 1941, Experimental assimilation of uranium in fresh water algae: Naturwissenschaften, v. 2, p. 403-404.

______ 1943, A further contribution of uranium in plant material: Bodenkunde u. Pflanzenernahr, v. 32, p. 295-306.

Johnson, G. O., and Edwards, K. W., 1967, Determination of strontium-90 in water: U.S. Geological Survey Water-Supply paper 1696-E, p. 1-10.

Jorgensen, C. D., Allred, D. M., and Beck, D. E., 1962, Close-in effects of an underground nuclear detonation on small animals and selected invertebrates: Operation Sedan Preliminary Report Project 62, 87 p., Department of Entomology, Brigham Young University.

Kauranen, P., and Miettinen, J. K., 1967, Po^{210} and Pb^{210} in environmental samples in Finland; International Symposium radioecology concentrated processes, Stockholm, 1966, Proceedings: Oxford, Pergamon Press.

Kunasheva, K. G., 1939, Distribution of radium and uranium in plants raised on media with different concentrations of these elements: Trav. lab. biogeochim. acad. sci., USSR, v. 5, p. 197-200.

Martin, W. E., and Turner, F. B., 1965, Food chain relationships of radiostrontium in the Sedan fallout field, Project Sedan, Plowshare Program: USAEC PNE-237 F, 61 p.

Mericle, L. W., Mericle, R. P., and Sparrow, A. H., 1962, Cumulative radiation damage in oak trees: Radiation Botany, v. 2, p. 265-271.

Miksche, J. P., Sparrow, A. H., and Rogers, A. P., 1961, Effects of chronic gamma irradiation on the apical meristems of Pinus strobus and Taxus media: American Journal of Botany, v. 48, p. 529.

Mills, H. L., and Shields, L. M., 1961, Root absorption of fission products by Bromus rubens L. from AEC Nevada Test Site soil contaminated by an underground explosion: Radiation Botany, v. 1, no. 1, p. 84-91.

Miskel, J. A., 1964, Characteristics of radioactivity produced by nuclear explosions, Engineering with nuclear explosives: U.S. Atomic Energy Commission TID-7695, p. 153-160.

Moisenko, U. I., 1959, Biogeochemical surveys in prospecting for uranium in marshy areas: Geokhimiya no. 1, p. 96-99.

Odum, E. F., 1959, Radiation ecology, in Fundamentals of Ecology: Philadelphia, W. B. Saunders Publishing Co., p. 452-486.

Pedigo, R. A., 1963, Effects of ionizing radiation on Pinus taeda L., in V. Schultz and A. W. Klement, Jr., eds., Radioecology: New York, Reinhold Publishing Corp. and the AIBS, p. 295-299.

Penna-Franca, E., and Gomes de Freitas, D., 1963, Radioactivity of biological materials from Brazilian areas rich in Th compounds: Nature, v. 197, p. 1062-1063.

Platt, Robert, 1962, Radiation and plant life: Discovery, Nov., 6 p.

Rhoads, W. A., 1976, Ground motion effects of underground nuclear testing on perennial vegetation at Nevada Test site: EGG 1183-2317, S-625-R, 52 p.

Rhoads, W. A., Kantz, A. D., and Ragsdale, H. L., 1972, Ecological and environmental effects from local fallout from Schooner 2. The beta and gamma radiation effects from close-in fallout: USAEC Report PNE-529, 41 p.

Rhoads, W. A., and Platt, R. B., 1971, Beta radiation damage to vegetation from close-in fallout from two nuclear detonations: Bioscience, v. 21, no. 22, p. 1121-1125.

Rhoads, W. A., Platt, R. B., Harvey, R. A., and Romney, E. M., 1969, Ecological and environmental effects from local fallout from Cabriolet. I. Radiation doses and short-term effects on the vegetation from close-in fallout: USAEC Report PNE-956, 65 p.

Rhoads, W. A., Ragsdale, H. L., Platt, R. B., and Romney, E. M., 1970, Radiation doses to vegetation from close-in fallout of project Schooner: USAEC Report EGG 183-2254, 562-TP, 16 p.

References cited--Continued

Rickard, W. H., and Shields, L. M., 1963, An early stage in the plant recolonization of a nuclear target area: Radiation Botany, v. 3, p. 41-44.

Romney, E. M., Nishita, H., and Wallace, A., 1960, Transfer of radioactive fallout debris from soils to humans investigated: California Agriculture, v. 14, no. 3, p. 6 and 14.

Shields, L. M., and Rickard, W. H., 1959, A botanical study of nuclear effects at the Nevada Test Site, 1959 (annual report to USAEC): New Mexico Highlands University, 159 p.

_____ 1960, A botanical study of nuclear effects at the Nevada Test Site, 1960, Pt. II (annual report to USAEC): New Mexico Highlands University, 93 p.

Shields, L. M., and Wells, P. V., 1962, Effects of nuclear weapons on desert vegetation at the Nevada Test Site: Science, v. 135, no. 3497, p. 38-40.

Shields, L. M., Wells, P. V., and Richard, W. H., 1963, Vegetational recovery on atomic target areas in Nevada: Ecology, v. 44, no. 4, p. 697-705.

Sparrow, A. A., and Christensen, E., 1950, Non-random distribution of chromosome fragmentation in unirradiated Trillium: U.S. Atomic Energy Commission U-691, no. 1, 1 p.; [abs.] Nuclear Science Abstracts, March, 1950, v. 4, p. 1619.

Sparrow, A. H., and Miksche, J. P., 1961, Correlation of nuclear volume and DNA content with higher plant tolerance to chronic radiation: Science, v. 134, no. 3474, p. 282-283.

Sparrow, A. H., and Pond, Virginia, 1956, Some cytogenetic and morphogenetic effects of ionizing radiation on plants, in A conference on radioactive isotopes in agriculture: U.S. Atomic Energy Commission TID-7512, p. 125-139.

Sparrow, A. H., Schairer, L. A., Sparrow, R. C., and Campbell, W. F., 1963, The radiosensitivity of gymnosperms I--the effect of dormancy on the response of Pinus strobus seedlings to acute gamma irradiation: Radiation Botany, v. 3, p. 169-173.

Sparrow, A. H., Schairer, L. A., and Woodwell, G. M., 1965, Tolerance of Pinus rigida trees to a ten-year exposure to chronic gamma irradiation from ^{60}Co: Radiation Botany, v. 5, p. 7-22.

Stead, F. W., 1963, Tritium distribution in ground water around large underground fusion explosions: Science, v. 142, p. 1163-65.

Stoklasa, J., and Penkava, J., 1928, Biology of uranium: Biochemistry Ztschr., v. 194, p. 15-17.

Vasilev, I. M., 1962, Effect of ionizing radiations on plants: Publ. House of Acad. Sci. USSR, Moscow, translated by Lydia Venters, U.S. Atomic Energy Commission TR-5836 (see Library 815-UN 31).

Wallace, A., and Romney, E. M., 1972, Radioecology and ecophysiology of desert plants at the Nevada Test Site: USAEC Report TID-25954, 439 p.

Watters, R. L., and Johnson, J. E., 1968, A study of unsupported Po^{210} for ion exchange in soil and uptake in vegetation: Rep. U.S. Atomic Energy Commission Contribution AT(11-1)-1733 C60-1733-1, 27 p.

Winograd, I. J., and Thordarson, Wm., 1975, Hydrogeologic and hydrochemical framework, south-central Great Basin, Nev.-Calif., with special reference to the Nevada Test Site: U.S. Geological Survey Prof. Paper 712-C, 126 p.

Woodwell, G. M., 1962, Effects of ionizing radiation on terrestial ecosystems: Science, v. 138, no. 3540, p. 572-577.

Woodwell, G. M., and Miller, L. N., 1963, Chronic gamma radiation affects the distribution of radial increment in Pinus rigida stems: Science, v. 139, p. 222-223.