SURFACE-EXPOSURE DATING OF YOUNG VOLCANIC ROCKS USING THE IN SITU BUILDUP OF COSMOGENIC ISOTOPES

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Abstract

The development of accelerator mass spectrometry (AMS) provides a solution to current problems in dating some very young rocks. The extremely high sensitivity of AMS makes feasible the measurement of light, rare radionuclides produced by cosmic-ray induced reactions within rocks exposed at the earth's surface. The concentration of these isotopes is a function of the time that a material was exposed to cosmic rays, and thus cosmogenic isotope buildup in situ may be used as an indicator of surface-exposure age.

$^{36}Cl/Cl$ was measured in a number of volcanic rocks less than 700,000 years old and correlated with published ages for the rocks derived by other techniques. The predictable buildup of ^{36}Cl in situ allows the use of this method for the determination of exposure ages of volcanic rocks and surficial materials less than about 10^6 years old.

^{10}Be and ^{26}Al buildup in situ hold promise for application to dating as well, but the present uncertainty in the in situ production rate of ^{10}Be and a lack of sufficient analytical sensitivity for ^{26}Al in whole-rock samples make the use of these isotopes less attractive at this time for geochronometry.

The ^{36}Cl buildup geochronometer was applied to dating of several young basalt flows of equivocal age in southern New Mexico. ^{36}Cl buildup dates indicate that these flows are in the range of 45,000-250,000 years, which is in very good agreement with the geomorphological history of the lower Rio Grande valley.

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Introduction

The commonly used radiometric dating techniques described in Part 1 are of two general types. One, of which K-Ar is an example, utilizes the buildup of daughter products of primordial radionuclides; the other, exemplified by ^{14}C dating, uses the decay of cosmogenic isotopes that are produced in the atmosphere and then incorporated into terrestrial reservoirs. This study investigates a third approach, the measurement of cosmogenic radionuclides in geological materials exposed to cosmic rays at the surface of the earth. While the first two techniques measure the time since an object to be dated became a closed geochemical system, the third method measures the time of exposure at the surface. Therefore, this method has the potential for dating features which are currently undatable, such as geomorphic surfaces, as well as determining the exposure age of volcanic rocks.

The use of cosmogenic isotopes such as ^{36}Cl and ^{10}Be has been considered for the past 30 years as a means of dating young terrestrial materials (Davis and Schaeffer, 1955; Arnold, 1956; Lal and Peters, 1962). Although such radionuclides have been routinely measured in meteorites and lunar materials for many years, traditional analytical procedures such as decay counting were not sensitive enough to measure most terrestrial concentrations of these nuclides, which are very low in abundance relative to their stable isotopes. The development of accelerator mass spectrometry (AMS) provides a solution to this problem (Elmore and Phillips, 1987; Doe and others, 1984; Bentley and Phillips, 1983; Brown and others, 1982), as the extremely high sensitivity of AMS makes feasible the measurement of very rare radionuclides.

Part 1: Background

1.1 Dating techniques currently used in Quaternary studies

1.1.1 Introduction

A number of well-established methods for accurate absolute-age determination of materials older than about 500,000 years exist; unfortunately, these methods can be applied to younger materials only when circumstances are particularly favorable. Other techniques currently used for dating young materials give only relative ages, or if they do yield absolute ages, the uncertainty is frequently of the same order of magnitude as the age. This problem has hampered many studies of volcanology, neotectonics, and archeology. A brief survey of several of these methods follows; this is not intended to be an exhaustive discussion of these methods, but should serve to point out the major difficulties involved with Quaternary geochronology.

The dating of young volcanic rocks is a geological problem that has hampered many studies of Quaternary geology. Methods such as Rb-Sr, K-Ar, or fission-track may be used for dating relatively old rocks, but such techniques, and others, have not been as successful for rocks less than 500,000 years old. Rocks in the 10,000-100,000 year range have been analysed using K-Ar, fission-track, radiocarbon, $^{40}Ar/^{39}Ar$, uranium-series disequilibrium, and thermoluminescence, among others, but these have yielded equivocal results (Faure, 1977; di Brozolo, 1981; Allegre, 1968; Sables, 1963). Several methods currently in use for young materials are described below, and summarized in Figure 1-1.

1.1.2 K-Ar

This method is based on the decay of naturally-occurring ^{40}K to stable ^{40}Ar, and is applicable to K-bearing minerals and rocks that will retain Ar. ^{40}Ar has a long half-life (1.3 Ga), and K is one of the most abundant elements, present in easily measurable amounts in most rocks. These factors permit the analysis of a wide range of ages and materials (Faure, 1977; Dalrymple and Lanphere, 1969; Damon, 1968). Most rocks contain enough K to allow dating from several hundred thousand to billions of years; high-K materials (2-3% K_2O) may extend this range to several tens of thousands of years (Dalrymple and Lanphere, 1969). However, young materials dated using the whole-rock K-Ar method typically have large analytical uncertainties, due to low K content, poor retention of Ar, or excess Ar. The potential for accumulation of excess Ar is great in continental areas, where volcanic rocks must traverse a great thickness of K-rich crust before extrusion (McDougall and others, 1969). The only reliable dates for very young rocks have been determined using sanidine separates from felsic volcanics. Although sanidine, because of its high K content, is suitable for K-Ar analysis, this mineral is not found in a wide variety of surficial materials. K-Ar dating of young volcanic rocks and sediments may be reliable under particularly favorable conditions (Dalrymple, 1967), but it is not useful for many young materials.

1.1.3 $^{40}Ar/^{39}Ar$

The $^{40}Ar/^{39}Ar$ method attempts to overcome the problems of Ar loss and excess Ar encountered when using the K-Ar method (Faure, 1977; Dalrymple and Lanphere, 1974, 1971). It is based on the formation of

^{39}Ar by the neutron activation of ^{39}K and the subsequent analysis of the ratio of radiogenic ^{40}Ar to ^{39}Ar by mass spectrometry. Several reactions involving Ca, Cl, and other isotopes of K during irradiation interfere, and the irradiation time and neutron flux must be monitored with great precision. Also, the cross-section for the ^{39}Ar-forming reaction is not known well and cannot be calculated easily from first principles, so a known standard must be analysed with all unknowns. These factors are critical for samples less than one million years in age. Since the technique relies on the production of ^{39}Ar from ^{39}K, high-K materials must be used, necessitating the same sort of separations as used for the K-Ar method. The most useful minerals, such as sanidine, biotite, or hornblende, are not common in all rocks. One successful variation of this approach was the dating of a Pleistocene basalt flow by analysis of the ^{40}Ar/^{39}Ar ratio of some partially degassed K-rich granitic xenoliths found as inclusions in the basalt (Gillespie and others, 1984, 1983). While reasonable results were obtained using this technique, it was the K-rich inclusions that were dated, not the basalt itself, and such inclusions are not common to all young volcanic rocks. Some workers have reported success in directly dating certain young volcanic rocks using the ^{40}Ar/^{39}Ar method (di Brozolo and others, 1981), but it may be used most profitably only with rocks several millions of years old or more (Faure, 1977; Sutter, pers. comm.).

1.1.4 Radiocarbon (^{14}C)

The ^{14}C method is of great use to archeologists and anthropologists in dating sites and artifacts of early cultures. In general, the scarcity of carbon-bearing materials in most geologic materials makes this technique somewhat less useful for geologists. The limit for the ^{14}C method (half-life 5700 yr.) is about 70,000 years, and the greatest accuracy and precision in conventional ^{14}C analysis is achieved with materials no older than 24,000 years b.p. (Faure, 1977). The use of AMS has increased the maximum datable age for some samples (Damon and others, 1983) but has not markedly improved analytical precision over conventional counting methods. The greatest impact of AMS for ^{14}C work is the reduction in the size of the sample required for measurement (Mook, 1984). In some cases it may be possible to date very young rocks such as lava flows, diatremes, or phreatomagmatic rocks by using the ^{14}C method for organic materials that were buried by or included in the rocks during eruption. Lockwood and Lipman (1980) presented guidelines for the recovery of datable charcoal from beneath young lavas, but their techniques are of limited value in most situations. Not only does formation of preservable charcoal require fairly massive organic materials (trees vs. small shrubs or grasses), but these materials are preserved -and hence must be recovered from- beneath lava flows.

1.1.5 Particle track methods

The fission-track method, as well as the related alpha-recoil and pleochroic halo methods, is based on the examination of damage tracks caused by charged particles emitted during the spontaneous fission of ^{238}U in minerals and glass (Faure, 1977; Fleischer and others, 1968; Naeser, 1979; Wagner, 1979a,b). Many common U-bearing minerals (micas, apatite, sphene, epidote, zircon) as well as volcanic glasses have produced reliable dates from as little as 20 years to several billions of years (Fleischer and others, 1968). However, the application of this method to young volcanic rocks, particularly basalts, is restricted by low abundance of suitable minerals, low abundance of uranium, and the long counting times (typically >40 hours for <100,000 year-old rocks) necessary for reasonably accurate age determinations.

1.1.6 Uranium-series disequilibria

These methods are based on the fact that, if undisturbed for several million years, a state of secular equilibrium will be established between the parent and daughter nuclides in a radioactive decay series. Due to the different chemical behavior of parent and daughter nuclides, various geochemical processes, such as generation of magma by partial melting, crystallization of minerals (magmatic or authigenic), or diagenesis, will cause elemental and isotopic fractionation which results in disequilibrium between parent and daughter nuclides (Harmon and Rosholt, 1982; Ivanovich and Harmon, 1982; Faure, 1977; Allegre and Condomines, 1976; Ku, 1976; Fukuoka, 1974; Oversby and Gast, 1968). The U-series methods are numerous, but may be divided into two general groups: 1) methods based on the accumulation of decay products of U, and 2) those based on the decay of daughter products in the series. The most commonly-used methods in Quaternary studies are of the first type, notably the $^{230}Th/^{234}U$, $^{231}Pa/^{235}U$, and $^{226}Ra/^{238}U$ systems in carbonates and volcanic rocks. Methods of the second type have been used mainly in the study of deep-sea sedimentation rates (Ivanovich and Harmon, 1982).

Although the above studies appear to have established this method as feasible for young volcanic rocks, the method is limited by the necessity of separating and analysing two or more cogenetic minerals, usually phenocrysts, with different parent-to-daughter ratios. This is frequently not possible; Ivanovich and Harmon (1982) cite an overlapping range of U/Th ratios for all typical basalt minerals. As shown by Allegre (1968), dating of such phenocrysts can have equivocal results; U-series dating of volcanic rocks reported by Taddueci and others (1967) illustrated a two-stage evolution for the U-series distribution in the analysed rocks. This phenomenon was also reported by Baronowski and Harmon (1978) and Fukuoka (1974). In the case of terrestrial carbonates, detrital material or groundwater having a different isotopic ratio often contaminates the material being analysed. Although some workers have reported that they are able to correct for such factors (Ku and others, 1979), this is not always possible, and anomalous ages result. The problem of U-series nuclide loss or gain has been approached by using "open-system" methods (Szabo and Rosholt, 1969; Rosholt, 1967), notably the "uranium-trend" methods of Rosholt (1980). Successful U-trend dating of alluvial, glacial, and eolian units has been reported (Schwarcz and Gascoyne, 1984), but these methods are useful only as relative age indicators unless it is possible to calibrate them against similar materials of known age.

1.1.7 "Trapped Charge" methods

This heading includes several related methods: thermoluminescence (TL), optical dating, and electron spin resonance (ESR). These techniques are similar in that they measure the accumulation of charges trapped within minerals due to ionization caused by radioactive impurities. Thermoluminescence (TL) involves the thermal activation of charge carriers (electrons or holes) in a material and the associated emission of light in addition to the normal incandescent glow) when the material is heated. Although this method has seen active use and reasonable success in the dating of pottery and other archeological artifacts, it has not enjoyed much use in geochronology. One of the principal disadvantages of this method is the fact that the light emitted during the measuring process is not necessarily directly proportional to the number of trapped charges. Other limitations include the difficulty in determining the natural dose rate, determining the ratio of natural to induced glow, spurious glow induced by sample processing, and loss of glow through weathering. In a relatively successful geologic application of this method, Sables (1963) noted that it is not feasible to date single, isolated samples. TL can give only relative age determinations for rocks, and that at least one absolute age in a series of related rocks must be known a priori. Recent work by Huntley and others (1985) suggests that some of the difficulties inherent in TL analyses may be overcome by the use of a related method, "optical dating," which measures the time since a material was last exposed to sunlight. An argon-ion laser is used to excite electrons from light-sensitive traps, which are presumed to be thermally stable, thus eliminating interfering incandescence. However, the optical behavior of geologic materials, other than the soils used in the above study, is unknown. Electron spin resonance (Zeller and others, 1967; Zeller, 1968; McMorris, 1969) measurements are based on the absorption or emission of energy by electrons or electronic "holes" in a crystal lattice, under the influence of a magnetic field. Although it measures the same quantities as thermoluminescence, it has several advantages over TL. The ESR signal is directly proportional to the number of trapped charges, the method is non-destructive, and allows mesurement of traps deep within the mineral (TL is more or less a surface phenomenon). Several of the same restrictions apply to ESR as to TL (Berger, 1986); it is still difficult to determine the natural dose rate, traps are annealed at geologically low temperatures, trapped charges may not be retained for periods that are long relative to the age of the sample, and the method yields only relative ages. Under the proper conditions, however, ESR has been used successfully to date archeological artifacts (Garrison and others, 1981), volcanic ash (Imai and others, 1985), ages of alteration of volcanic rocks (Shimokawa and Imai, 1987), and fault movement (Ikeya and others, 1982; Fukuchi and others, 1986), with a range of ages from 0.06 to 2 million years.

1.1.8 Paleomagnetic secular variation

The secular variation of the earth's magnetic field, as recorded in the remanent magnetism of igneous rocks and sediments has been suggested as a possible means of dating such rocks (Irving, 1968; Doell and Cox, 1963; Cox and Doell, 1960). However, effects caused by secular variation are regional in character, and the application of the technique is thus necessarily local in nature. Standard variation scales are built up by systematic studies in control areas, but these may not reasonably be extrapolated to test rocks of unknown age at great distances from the control locality. Moreover, since the value of the secular variation is not unique over long periods of time, one must have some prior knowledge of the age of the sample.

Much like the TL method, it is not feasible to date single, isolated samples by secular variation. This method is most helpful for correlating rock units within a small area (Bogue and Coe, 1981) where one or more ages are already known. Perhaps the most important consideration in using the secular variation method is that standard variation scales are built up using some independent record of rock ages, so that these scales are only as accurate as the method used for the original dating, such as radiocarbon or K-Ar. Also, large numbers of oriented cores (10-12 per site) must be collected in order to accurately define the field direction preserved in a rock unit.

1.1.9 Amino acid racemization

The amino acid racemization method is based on the measurement of the extent of structural alteration of amino acids present in organisms after death. In living organisms, amino acids consist almost exclusively of one structural type, the L-isomer; after death, structural rearrangement, or "racemization," occurs, with L-isomers being converted to D-isomers until equal quantites of each are present. The age of a fossil is thus proportional to the ratio of the L- and D-isomers of a particular amino acid, and the estimated rate at which this racemization takes place (Schroeder and Bada, 1978). Although in theory any proteinaceous material may be used for this method, in practice only a few materials, notably foraminifera and mollusc shells, are suitable. Studies of the use of bone have been reported (Hare, 1974), but the generally unsuitable nature of this material severely restricts the use of this method in terrestrial Quaternary studies. The rate at which racemization occurs is strongly temperature-dependent, and thus is limited by accurate estimation of average temperature since the death of the organism. The rate also differs among genera at any specific site, and care must be taken to analyse sufficient numbers of individuals to exclude the possiblity of recycled fossils from older deposits. While apparently useful for relative age determination of a series of deposits in a specific locality, absolute ages cannot be obtained without calibration against independently dated material.

1.1.10 Obsidian hydration

Fresh obsidian will hydrate over time to form perlite, which appears as a surface rind. The thickness of such rinds increases approximately as the square root of exposure time, but hydration rate is dependent upon both temperature and obsidian glass composition (Andrews and Miller, 1980; Friedman and Long, 1976; Friedman and others, 1966). Hence the rate constant must be determined for each particular locality and obsidian type being investigated. Hydration occurs faster with increased silica content; obsidian with 72-78% SiO_2 is generally considered best for dating purposes. Dacitic glass has been used, but basaltic glass is unsuitable. Exposure to direct sunlight can cause anomalously high temperatures, so that the most suitable material must be recovered from depth (1-2 meters). A large number (10-15) of rinds per sample site must be measured in order to minimize uncertainty in the age determination, but accuracy is usually on the order of ±20-30%, due to uncertainties in temperature estimates.

1.1.11 Rock varnish

Rock varnish is the thin coating of manganese and iron oxides and hydroxides, trace elements, and clays that accretes on stable rock surfaces exposed to the atmosphere (Dorn and Oberlander, 1981). Two theories are proposed to explain the formation of such coatings, a physico-chemical process (Elvidge and Moore, 1979), and a biological one (Dorn and Oberlander, 1981). Various characteristics of rock varnish, such as darkness, thickness, and Mn content, have been used to estimate exposure time. However, these are not only dependent upon time, but are strongly influenced by alkalinity, rock type, and other microenvironmental factors. A variant of the varnish techniques is the "cation-ratio" technique of Dorn (1983). This is based on the analysis of minor elements in varnish that are not as sensitive to the same factors that affect Mn deposition. The premise of the method is that mobile cations such as Na, K, Mg, and Ca are gradually depleted by leaching relative to less mobile cations such as Ti. The decrease in the ratio of the leachable cations to Ti is an indication of the length of time that the varnish has been exposed.

This latter technique has been used with some success in a number of arid areas (Dorn, 1983) but its usefulness in humid regions has not been proven. One problem with cation-ratio dating by Dorn's method is the requirement of scraping varnish from a large area of the surface to be dated; the more recent methodology improvement of Harrington (1986) allows the non-destructive measurement of ratios by SEM analysis, a significant improvement. The greatest limitation in application of this method is that it can only estimate the date of the beginning of varnish formation, which is not necessarily coincident with the exposure of the surface, and hence can yield only a minimum age for the age of the surface upon which the varnish is deposited. Also, the input of airborne cations is location-dependent and will affect the cation ratios in varnish, so this factor must be accurately estimated, and assumed to have been constant throughout the entire time of exposure. Furthermore, it can be used only as a relative age indicator unless it is calibrated against materials or surfaces of known age in an area of interest.

1.1.12 Weathering rinds

This method involves the measurement of the development of weathering rinds on stones at shallow depth (soil "B" or "C" horizon, about 20-50 cm depth) below stable exposed surfaces in humid environments (Colman and Pierce, 1981). These rinds are zones of oxidation which form concentrically around the surfaces of the stones and are best displayed in fine-grained mafic rocks such as basalt and andesite. A number of factors other than exposure time influence rind development, among them climate, topography, vegetation on the surface, and parent material. Rigorous sampling criteria and site selection, as well as elimination of statistical variations by the analysis of very large groups of stones at each sample site, can minimize the effects of all of these except climate. Hence the method can only be used with relatively small geographic areas, and then only as an indicator of relative age among several units. Furthermore, since the stable rind forms only after a period of soil development (possibly several thousand years) has passed, the age estimated by the rind thickness is a minimum age for the unit. As with several other methods outlined above, calibration to independently dated material is necessary if the weathering rind technique is to yield the absolute age of unknown, or to correlate among geographically separate units.

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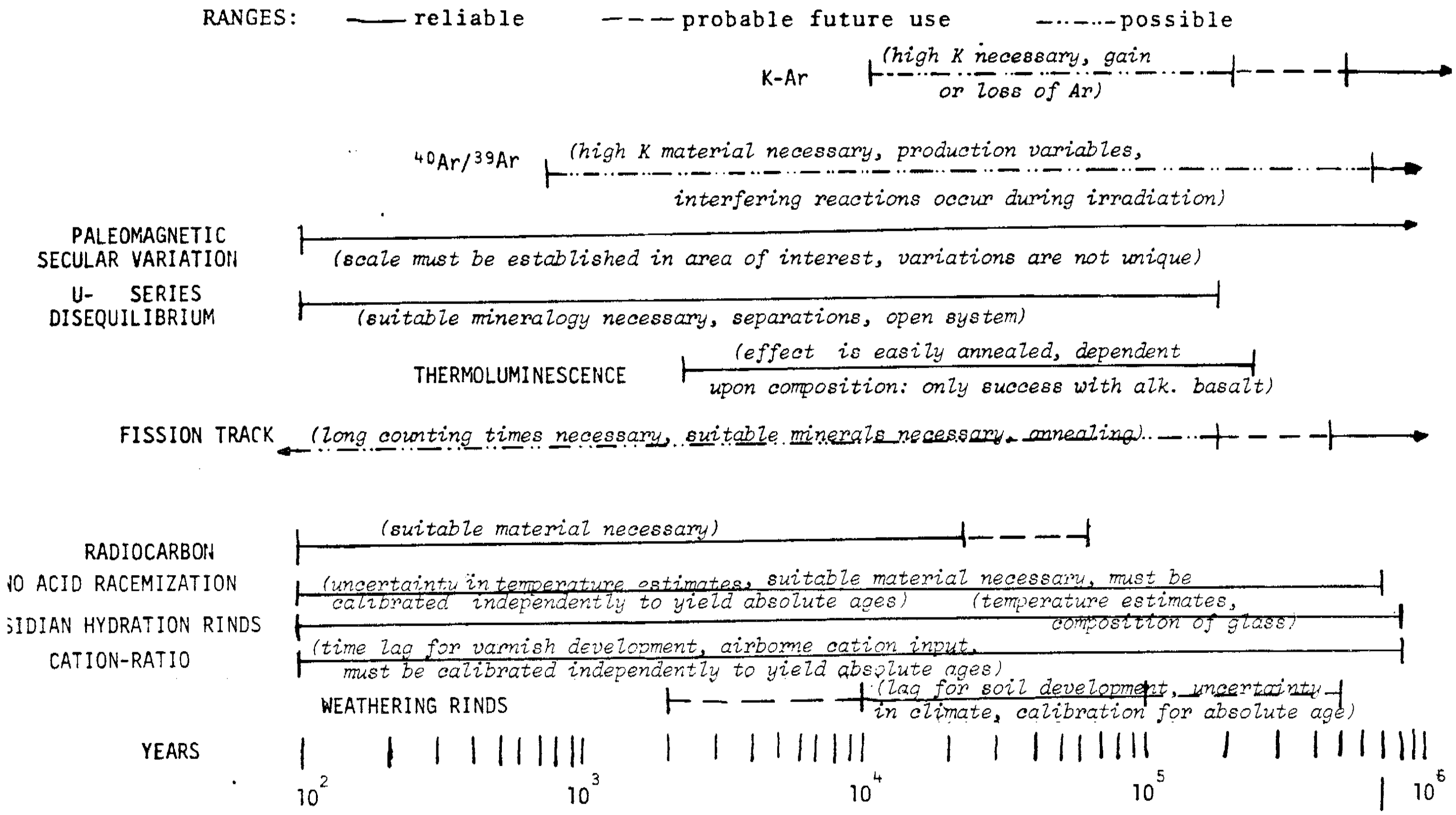
Figure 1-1:

DATING METHODS CURRENTLY USED IN QUATERNARY STUDIES



1.2 Cosmogenic isotope studies in the earth sciences

1.2.1 Introduction

The investigation of cosmic rays during this century has produced many fundamental discoveries in physics, notably the detection and identification of a variety of unstable subnuclear particles (Peters, 1958). It is the understanding of these particles and their interactions with solid matter which has led to applications of cosmic-ray phenomena to studies in the earth sciences during the last thirty years, first in geophysics and most recently, geology.

The existence, at the earth's surface, of some sort of ionizing radiation, far more penetrating than gamma rays, with an unidentified source was identified in the course of electroscope experiments as early as 1900. At first, this radiation was believed to be produced by radioactive substances in surrounding materials. Following unsuccessful attempts at shielding radiochemical experiments from this effect, balloon ascents were made to isolate them from the ground. However, it was soon shown that the ionizing effect increased, rather than decreased, with altitude; hence the conclusion that this radiation had an extraterrestrial source. Its constituents and energy spectrum were studied vigorously in the early 20th century, and the radiation was termed "cosmic" in 1925. Although a variety of particles arrive at the upper atmosphere, including electrons, protons, neutrons and some nuclei, few heavy particles penetrate to the ground. What are measured at the surface as "cosmic rays" consist mainly of secondary particles, neutrons and mesons produced by collision of primary particles with nuclei in the upper atmosphere (Hillas, 1972). The flux of cosmic rays, and hence production of cosmic-ray-produced nuclides, is affected by several factors, including the earth's magnetic field, galactic cosmic rays, solar cosmic rays, and other cosmic phenomena (Lal and Peters, 1967). This variation has been studied in detail by many workers concerned with its effect on radiocarbon dating. Short-term variations will affect ^{14}C chronology since the time intervals of interest are short, but long-term variations have been small, possibly as great as 2x (but likely only ±5%) over the last 0.1 to 1 Ma, and hence have little effect on geochronology (Kohl and others, 1978; Higdon and Lingenfelter, 1973; Yokoyama and others, 1973; Finkel and others, 1971; Oeschger and others, 1969; Lal and Peters, 1962).

1.2.2 Cosmogenic isotopes with potential application to dating

The nuclides considered here are extremely rare in relation to their stable isotopes. Dating using these isotopes does not involve the decay of primordial radioactive material such as in the Rb-Sr or K-Ar systems, but is based upon the buildup of these nuclides that is produced by cosmic rays incident on the earth and its atmosphere, the moon, or meteorites, as well as by energetic particles produced in situ by decay of radioactive nuclides (Lal and Peters, 1967; Reedy and others, 1983). Although an extraterrestrial origin for these cosmogenic nuclides has been cited (McCorkell and others, 1967), their presence in the earth's crust is primarily due to atmospheric and lithospheric production. One of the most attractive aspects of cosmogenic nuclide buildup dating is that the isotopes of interest are produced from elements which are common in all types of earth materials, so that production rates are rapid relative to the half-life of the isotope.

1.2.3 ^{36}Cl

^{36}Cl is produced by several reactions: neutron activation of ^{35}Cl, neutron activation of ^{36}Ar, spallation of heavier nuclei (Ar, K, Ca) by energetic cosmic rays, muon capture by ^{40}Ca, and ^{39}K(n,a)^{36}Cl. Meteoric ^{36}Cl and stable chloride are washed out of the atmosphere by precipitation or become associated with aerosols which fall out. Most ^{36}Cl in rocks is produced by thermal neutron activation of ^{35}Cl; a second method of production, important mainly in rocks with low chlorine content, is direct spallation of ^{36}Cl from ^{40}Ca and ^{39}K. Spallation from titanium and iron is not significant at the earth's surface, due to attenuation by the atmosphere of the highly energetic cosmic rays necessary for these reactions. Production by spallation from ^{40}Ar and neutron activation of ^{36}Ar also are minor sources of ^{36}Cl in the lithosphere due to the low abundance of Ar in most rocks. Calculation of the spallation production rate is discussed by Yokoyama and others (1973) and representative values for spallation production are given by Yokoyama and others (1977). Additional reactions that produce ^{36}Cl include negative muon capture by ^{40}Ca (Kubik and others, 1984) and neutron activation of ^{39}K. Although potentially significant at depth, these reactions may be ignored in calculations for surficial materials.

The half-life of ^{36}Cl (0.3 Ma) should allow dating of materials in the range of 500 to 500,000 years. It is assumed that all ^{36}Cl in unaltered rocks is produced by cosmic ray interaction from the time they were exposed at the surface and by neutron activation caused by the U and Th contained in the rock. Since levels of ^{36}Cl/Cl in the 5×10^{-15}

range have been routinely measured (Bentley and others, 1986; Elmore and others, 1979), measurement of ^{36}Cl in young volcanic rocks should certainly be feasible, with sample sizes of a few grams of rock.

1.2.4 ^{10}Be

^{10}Be is produced in the atmosphere and lithosphere mainly through the spallation of nitrogen and oxygen caused by energetic cosmic rays. In the atmosphere, the isotope becomes fixed to aerosols, and within a year after production falls out to the earth's surface (Raisbeck and others, 1983). Several heavier elements may serve as targets for ^{10}Be production by spallation, but these are not significant at the surface; the more energetic particles necessary for these reactions are shielded by the atmosphere. Meteoric ^{10}Be tends to be adsorbed on materials in the soil, particularly clays, and remain in residence there (Klein and others, 1983). In an area where erosion has not been significant, the ^{10}Be content of surface materials will be a result of meteoric input and decay of the isotope, as well as in situ production.

The systematics of ^{10}Be are similar to those of ^{36}Cl, except that there is no thermal neutron production of the isotope. In areas without appreciable soil cover, ^{10}Be in a fresh, impermeable volcanic rock exposed at the surface should reflect in situ production alone. The 1.5 Ma half-life of ^{10}Be will allow dating of materials in the range of several hundred to 3 Ma, and like ^{36}Cl, provide an alternative to K-Ar dating of materials at the lower end of the range of that method's sensitivity. Where soils have developed on rocks, both the fresh rock and its associated soil may be dated using ^{10}Be.

Studies of ^{10}Be in volcanic rocks (Brown and others, 1982) have measured ^{10}Be in rocks several years to tens of millions of years old, using approximately 50 g of rock. Nishiizumi and others (1986) measured ^{10}Be/^{26}Al in quartz from glacially polished rocks to determine the ratio of these isotopes at production. In addition, a variety of meteoritic rock types have been analysed for ^{10}Be, so that principles of analysis of this isotope in hard rocks are well-established.

1.2.5 ^{26}Al

^{26}Al is introduced to the lithosphere and atmosphere by spallation reactions from Si and Ar, muon capture by Si, and through accretion of extraterrestrial material (McCorkell and others, 1967). Al is similar to Be in its geochemical behavior and, like Be, has been used with some success in studies of deep-sea sedimentation rates (Amin and others, 1975, 1966; Tanaka and others, 1968; Guichard and others, 1978). The 0.7 Ma half-life of ^{26}Al should permit dating in a range of several thousand to about 40 Ma. Until recent years, the high natural abundance of stable Al and the relatively low anlytical sensitivity of even accelerator mass spectrometers for ^{26}Al have precluded the use of this isotope for geochronological work, but recent advances in ion sources may make such analyses practical. Nishiizumi and others (1986) have attempted to overcome the problem of common Al abundance by measuring ^{26}Al in quartz.

1.2.6 ^{41}Ca

This isotope has been considered as a dating tool with applications in paleontology and $CaCO_3$-rich sediments (Raisbeck and Yiou, 1979). ^{41}Ca is produced in the atmosphere and at the surface of the earth by neutron activation of ^{40}Ca, and its half-life of 10^5 years makes it suitable for dating to several million years. $^{41}Ca/Ca$ has been successfully employed in studies of the irradiation history of meteorites (Kubik and others, 1986), and has shown potential as a geochronometer for Pleistocene bone (Henning and others, 1987). However, most of the production of this isotope occurs in the upper meter or so of the crust, rather than in the atmosphere (as with ^{14}C), introducing several complications. ^{41}Ca produced in soil, as well as meteoric ^{41}Ca, will be taken up by plants and later be incorporated into bone by ingestion of the plant as food; local mixing and erosional effects may cause significant variation of $^{41}Ca/Ca$ among different environments; and samples buried near the surface will continue to have ^{41}Ca produced in situ after burial. While its use as a paleontological dating tool is not assured, with detection limits of 10^{-15} for $^{41}Ca/Ca$ using AMS, analysis of this isotope in rocks should also be feasible.

1.2.7 ^{3}He

Until very recently, the primary interest in $^{3}He/^{4}He$ measurements of terrestrial materials has been in studies of mantle-derived rocks (Craig and Lupton, 1976); high $^{3}He/^{4}He$ is generally interpreted as indicating the presence of primitive or primordial gas. However, several recent studies of basalts from Hawaii (Craig and Poreda, 1986; Kurz, 1986a,b) have shown that cosmogenic ^{3}He in situ produced comprises a significant portion of the ^{3}He which can be measured in surficial terrestrial rocks. There are a number of features which make this isotope attractive as a dating tool: the production rate for ^{3}He is one of the highest for cosmogenic nuclides, as it is produced by virtually all cosmic-ray induced spallation reactions in rocks, and it is produced at depths below the first meter or so by stopped-muon induced neutron activation of ^{6}Li; measurement by conventional mass spectrometry is quite sensitive, so AMS is not necessary for ^{3}He analysis; and unlike other cosmogenic radionuclides, this isotope is stable, so it has potential for measuring very long time periods (>10^{6} years). Terrestrial production rates for ^{3}He are not well known; although estimated by Lal and Peters (1967) and Yokoyama (1977), these figures are not considered to be as accurate (Kurz, 1986a) as those calculated, for example, for ^{36}Cl by the same authors and have not been experimentally verified. Furthermore, production mechanisms (other than spallation) for ^{3}He are only qualitatively understood, and hence depth dependence of the production rate is also unknown. In spite of these difficulties, Kurz (1986b) has shown that in situ cosmogenic helium production, at least in the Hawaiian basalts used in his study, is comparable to the calculated values, and thus ^{3}He production in the upper meter or so of the crust may be used as a method surface-exposure dating.

1.2.8 ^{129}I

Although hardly a "light" rare nuclide, this isotope is cosmogenic, measured using AMS, and often used in conjunction with ^{36}Cl for terrestrial studies. The decay of primordial ^{129}I to ^{129}Xe has been investigated in meteorites (Hohenberg, 1970; Rowe, 1970), as well as in natural gas (Boulos and Manuel, 1972) and in terrestrial ores (Srinivasan and others, 1971). Geologically young ^{129}I produced in terrestrial materials by spallation of xenon, cesium, barium, and rare-earth elements, as well as by spontaneous fission of ^{238}U and muon capture by ^{130}Te (Takagi and others, 1974), has been suggested as a tracer in biological and groundwater studies (Edwards, 1962), and for dating and tracing groundwater in salt-dome studies (Fabryka-Martin, 1982). The isotope's 15.7 Ma half-life should allow dating in a range of 0.03 to 50 Ma, but its complicated epigene production scheme and the rarity of even stable I make it difficult to apply ^{129}I measurements in geochronology.

Fabryka-Martin (1982) has calculated saturation values for juvenile ^{129}I/I in various rock types. For a basalt having 1 ppm U and 0.2 ppm I, the calculated ratio is approximately 1.3×10^{-12}, well within the limit of sensitivity for analysis of this isotope. The system is similar to that of the other cosmogenic isotopes discussed here, but, as in the case of ^{10}Be, there is no neutron activation production. However, since ^{129}I is produced by other non-cosmogenic reactions, it will be produced to depths beyond the limit of penetration for energetic cosmic rays. While ^{129}I has been measured in minerals (Srinivasan and others, 1971; Hennecke and Manuel, 1977), no analyses have been reported for rocks.

1.2.9 Applications of cosmogenic isotope buildup to dating

To date, most studies involving the measurement of terrrestrial cosmogenic radionuclides have utilized the buildup, in crustal reservoirs, of isotopes produced in the atmosphere. In this regard, ^{36}Cl has been used to date groundwater (Bentley and others, 1984) and polar ice (Nishiizumi and others, 1983), and ^{10}Be has been used as a tracer of sediment input to island arc volcanics (Tera and others, 1986), to date marine, fluvial, and lacustrine sediments (Amin and others, 1966), polar ice (Nishiizumi and others, 1983), and soils (Pavich and others, 1983, 1985). Nishiizumi and others (1986) have begun to apply the measurement of ^{10}Be to in situ production rate studies related to surface-exposure dating of rock, but none of the above studies have been directly applicable to dating volcanic rocks. The cosmogenic isotopes considered herein are produced from common elements in the earth's crust by cosmic-ray induced reactions within rocks exposed at the surface. The concentration of these isotopes within materials exposed at the surface should be a function of the exposure time, i.e., the time since eruption. It must be emphasized that the periods of time which can be measured by the buildup of such isotopes are for surface-exposure, not dates of closure of an isotopic system. This gives buildup dating broad applications beyond simple rock dating, but makes it critical that the exposure history of the analysed material is known or may be reasonably estimated, as with young volcanic rocks. Much of the work done previously has been on materials whose ages were poorly constrained, so that no accurate evaluation of any dating techniques could be made.

1.3 In situ Production of Cosmogenic Isotopes

1.3.1 Production and dating calculations

Cosmogenic isotopes accumulate at a rate proportional to the exposure time of the material; at the same time, they decay at a rate proportional to their decay constants. Thus the buildup with time is given by the equation (Bentley and others, 1984):

$$N = (PR/\lambda)\,(1-\exp(-\lambda t)) \qquad (1\text{-}1)$$

where

λ= decay constant

t= time in years

PR= production rate of the isotope

N= number of atoms

The method of calculating the spallation production rate is given in Yokoyama and others (1972) and representative values for spallation production in Yokoyama and others (1977). Muon production rates are discussed by Kubik and others (1984).

In the case of ^{36}Cl, production by thermal neutron activation must be considered:

$$(PR)_a = nf \qquad (1\text{-}2)$$

where

$(PR)_a$= neutron activation production rate of ^{36}Cl

n= neutron flux

f= fraction of neutrons absorbed by ^{35}Cl

The method for calculating f is:

$$f = \frac{(N_{35}s_{35})}{(N_i s_i)} \qquad (1\text{-}3)$$

where

s_i= neutron absorption cross-section (barns) of an isotope

s_{35}= neutron activation cross-section of ^{35}Cl for ^{36}Cl

The denominator considers the total cross-section for all elements in a rock. Representative values of f for common rock types are shown in Figure 1-2.

The measured cosmogenic isotope content of a rock (usually expressed as the ratio of the number of atoms of the isotope to the number of atoms of the stable element) is thus a function of the production rate, decay rate, and initial element content of the rock, given as:

$$N_c/N_e = \frac{(PR)(ELD)\ (1-e^{-\lambda t})}{\lambda N} + (N_c/N_e)_0(e^{-\lambda t}) \qquad (1-4)$$

where

E= factor accounting for elevation of sample site
L= factor accounting for geomagnetic latitude of site
D= factor accounting for depth of sample below surface
N_c= #atoms of the cosmogenic isotope
N_e= #atoms of the stable element
$(N_c/N_e)_0$= initial ratio of the isotope to the stable element

The E term corrects for the attenuation of cosmic rays in the atmosphere; tables for this correction and for L are given in Yokoyama and others (1977). Lal and Peters (1967) provide theoretical values for D, the correction for cosmic-ray attenuation with depth; Nishiizumi and others (1984) estimate this correction using an empirical method based on data for lunar soils.

1.3.2 Variations in cosmic-ray flux

As noted above (1.2.1), one source of uncertainty in the evaluation of cosmic ray-produced nuclides is the variation of cosmic ray flux with time. In absolute radiocarbon chronology as applied to anthropological or archeological studies (where precision of ±1% is frequently desirable) this variation is important, but this should not present a problem in geological investigations over longer time spans where ±10% precision is often adequate. However, the question of cosmic ray flux variations may be eliminated altogether by use of a "double-dating" method such as discussed by Muller (1977). Whenever two isotopes with different mean lives can be used to date a sample, the age may be determined without needing to know the cosmic ray flux that produced them (Muller, 1977):

$$r(t) = r(o)e^{(-t(\lambda_1 - \lambda_2))} \qquad (1\text{-}5)$$

where $r(t)$= measured ratio of isotopes
$r(o)$= ratio of production rates of the isotopes

^{10}Be and ^{26}Al, due to the assumed similarity in their geochemical behavior, have been suggested as an ideal pair for this technique (Reedy and others, 1983; Lal and Peters, 1962). Equation (1-5) considers only decay of the radioisotopes; however, in cosmogenic isotope buildup systems, the concentration of the isotopes at any time is a function of both decay and buildup from cosmic-ray induced production, so that:

$$\frac{(^{10}\mathrm{Be/Be})}{(^{26}\mathrm{Al/Al})} = \frac{(PR_{10}/\lambda_{10}N_{Be}) \quad (1-e^{-\lambda_{10}t})}{(PR_{26}/\lambda_{26}N_{Al}) \quad (1-e^{-\lambda_{26}t})} \qquad (1\text{-}6)$$

if initial ratios are considered to be negligible. This equation is independent of the factors affecting cosmic ray intensity.

The double dating method should be useful in the 0.01-1 Ma range, where long-term cosmic-ray flux may be a factor. At younger ages, as discussed above, cosmic ray flux may be considered constant, and either of the systems alone should be applicable to dating calculations.

1.4 Accelerator Mass Spectrometry

Separation of the isotopes of interest is accomplished using relatively simple wet-chemical methods. Isotope ratios are determined using accelerator mass spectrometry (AMS) which enables isotope ratios to be be determined using milligram aliquots of the elements of interest.

AMS is a significant improvement over older methods of counting. It involves counting the actual number of nuclei in a sample, rather than decays of the isotope of interest (Elmore and others, 1979; Litherland and Rucklidge, 1981). This increases sensitivity and decreases analysis time, since at any time there are many more total nuclei of an isotope present than are actually decaying. The tandem van de Graaf accelerator mass spectrometer (TAMS) at the University of Rochester is a typical AMS system. Basically, the TAMS consists of two mass spectrometers connected by a linear accelerator and inert gas or metal foil "stripper" (Figure 1-3). The sample is ionized and molecules of the desired mass are selected by the first MS. These are reduced to the elemental state by collision with inert Ar gas or metal atoms in the stripper and accelerated before passing on to the second MS; this MS separates isotopes of the element of interest. Accelerating the nuclei to high velocity enables the use of highly sensitive detectors that determine atomic number by comparing the total energy of the nuclei to the energy lost in passing through the detector. The operation of the Rochester TAMS and the statistical basis for data analysis is described in detail by Elmore and others (1984).

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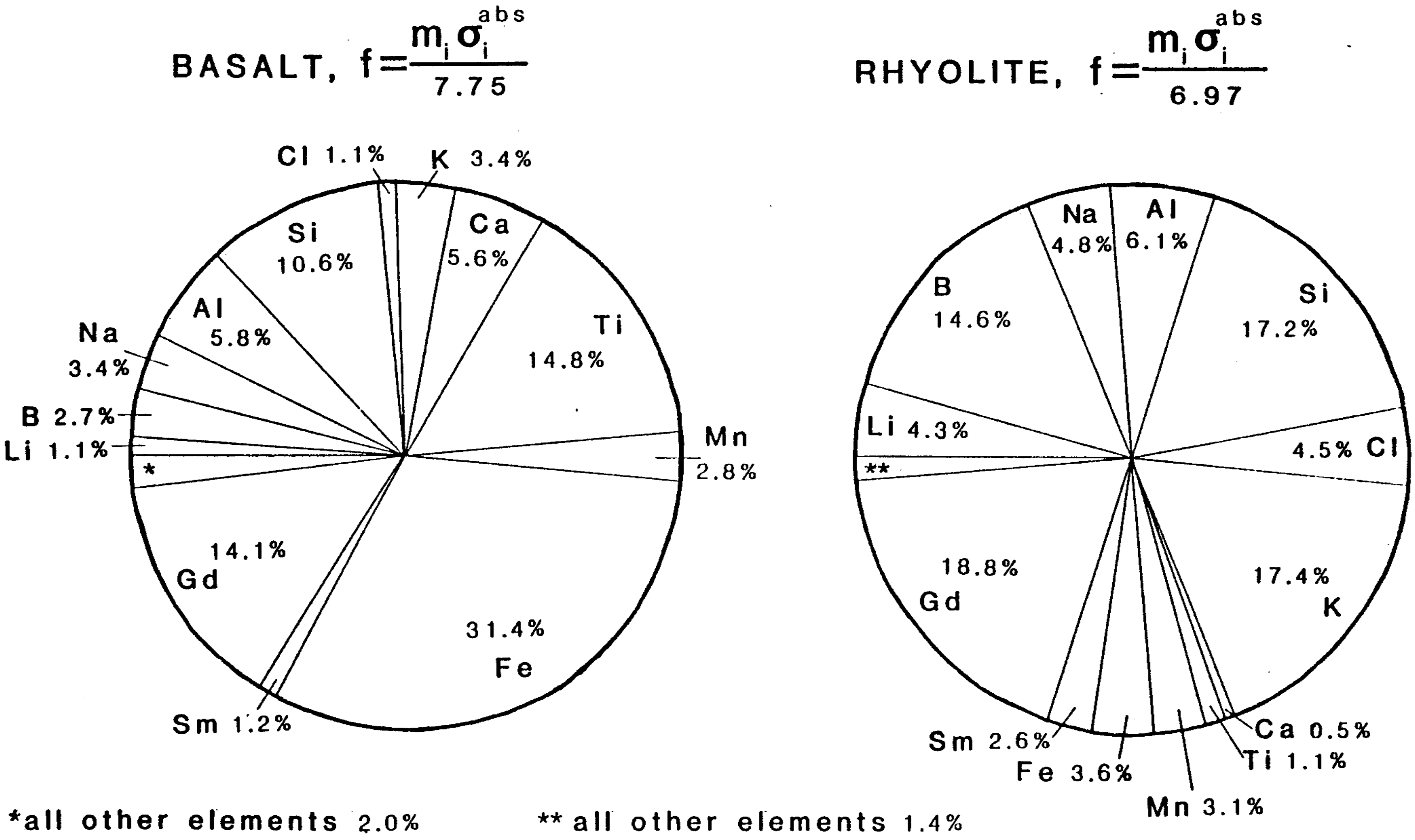

Figure 1-2: Representative f values for the elements in a typical basalt and rhyolite. Elemental concentrations, m_i, were obtained from Wedepohl (1978) and converted to units of cm^2kg^{-1}. Thermal neutron-absorption cross sections, σ_i, in barns, were obtained from Hampel (1968).

Figure 1-3:

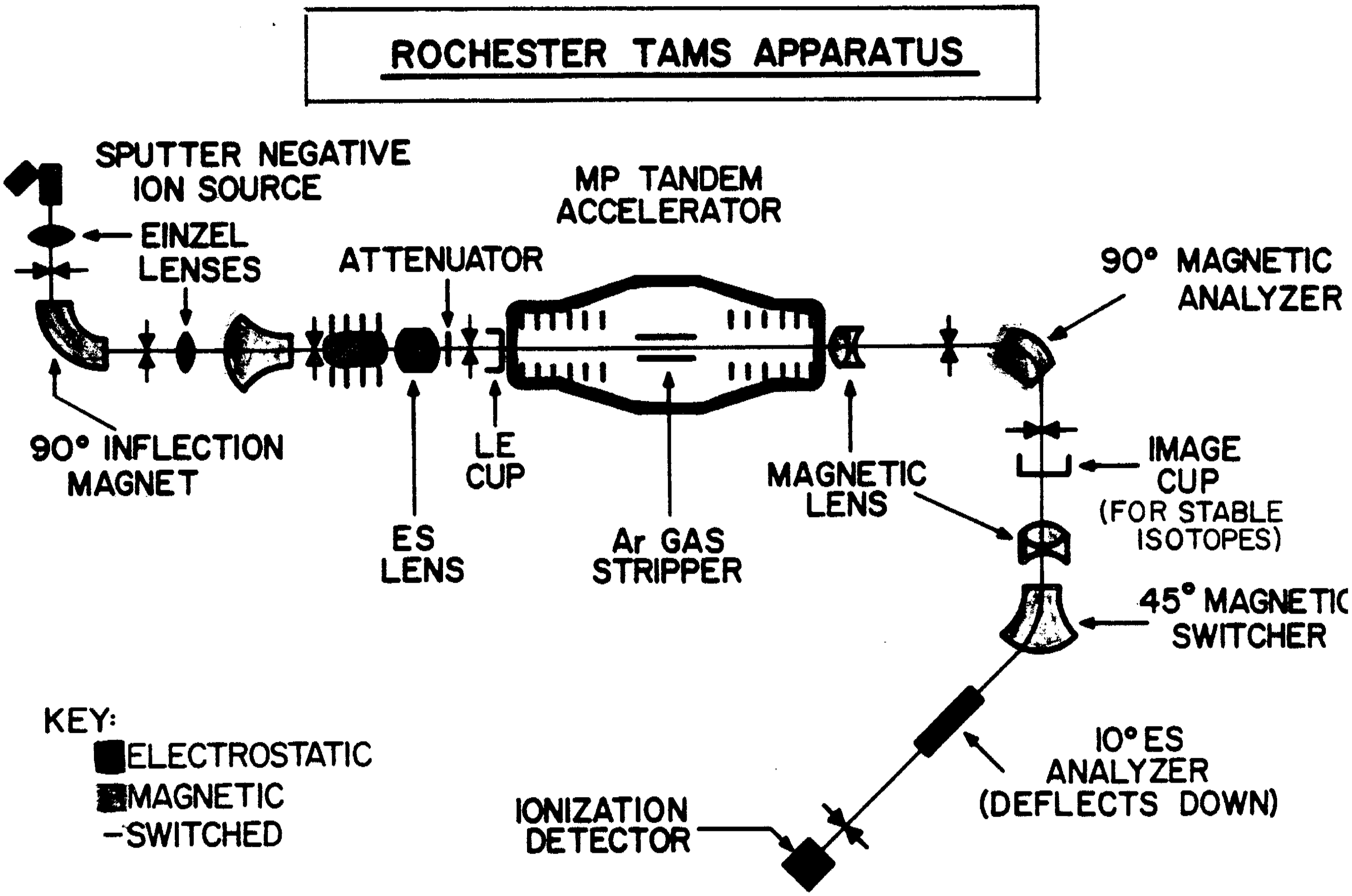
ROCHESTER TAMS APPARATUS
SPUTTER NEGATIVE ION SOURCE
EINZEL LENSES
MP TANDEM ACCELERATOR
ATTENUATOR
90° MAGNETIC ANALYZER
90° INFLECTION MAGNET
LE CUP
ES LENS
Ar GAS STRIPPER
MAGNETIC LENS
IMAGE CUP (FOR STABLE ISOTOPES)
45° MAGNETIC SWITCHER
10° ES ANALYZER (DEFLECTS DOWN)
IONIZATION DETECTOR
KEY:
■ ELECTROSTATIC
▨ MAGNETIC
- SWITCHED

Plate 1-1: Sample wheel for Rochester TAMS as used in this study. Wheel above is shown actual size. On left, wheel before loading; on right, after run in TAMS. The bright areas show the diameter of the Cs ion beam.

Part 2: Calibration of a ^{36}Cl buildup geochronometer for young volcanic rocks

2.1 Introduction

A study of dated volcanic rocks in the 0-700,000 year range was conducted to test the feasibility of using cosmogenic isotope buildup methods for geochronological work. Several considerations, including preliminary analyses of both ^{36}Cl and ^{10}Be in dated rocks (Phillips and others, 1986; Leavy and others, 1985) suggested that ^{36}Cl would hold the greatest potential for geochronological work at this time. Measurement of ^{36}Cl has therefore been emphasized in this study.

^{36}Cl has several characteristics which make it suitable for buildup dating. It builds up to measurable levels relatively quickly since the product element (chlorine) is present in most rocks only in trace quantities; ^{36}Cl activities produced by nuclear processes within rocks, due to the decay of uranium and thorium, are much lower than the cosmogenic activity after only a few thousand years of exposure; and the mobile, hydrophilic nature of chlorine aids in the separation of in situ produced ^{36}Cl from that derived from an atmospheric (meteoric) source.

This latter property of Cl may allow some chloride to be leached from rocks by meteoric waters. However, in a study of the release of in situ ^{36}Cl from rocks, Izmirian (1984) determined that for rocks having chloride contents of less than 1%, release of ^{36}Cl from the rock is not significant, except in areas with high rates of chemical weathering. Leaching of chlorine will affect the total chloride content of the rocks, but the isotopic ratios probably will remain unaffected. Recent studies of stable chlorine isotope fractionation (Kaufmann and others, 1984) suggest that fractionation of ^{36}Cl relative to the stable isotopes of Cl under such conditions should not be significant.

The hydrophilic nature of Cl also can be used to advantage when it is necessary to separate in situ and meteoric radionuclides. Due to its negative charge and small ionic radius, Cl is not readily adsorbed on solid surfaces (Bentley and others, 1986). Hence in rocks above the groundwater table it is unlikely that pore-water chloride will react significantly with minerals, so that in unaltered rocks contamination of in-situ produced ^{36}Cl by meteoric chloride is not expected.

As described in a general manner in Part 1, cosmogenic isotopes accumulate at a rate proportional to the exposure time of the material; at the same time, they decay at a rate inversely proportional to their decay constants. The measured ^{36}Cl content of a rock (usually expressed as the ratio of the number of atoms of the ^{36}Cl to the total number of atoms of chlorine) is a function of the production rate, decay rate, and initial element content of the rock (Bentley and others, 1986). ^{36}Cl produced in situ prior to exposure of the rock at the surface is assumed to be at secular equilibrium, so that there is no decay function applied to the initial ratio. The buildup equation is hence a modification of equation 1-4:

$$(^{36}\mathrm{Cl}/\mathrm{Cl})_m = \frac{[\mathrm{ELD(PR)}](1-e^{-\lambda t})}{\lambda\,\mathrm{Cl}} + (^{36}\mathrm{Cl}/\mathrm{Cl})_0 \tag{2-1}$$

where

λ= decay constant for ^{36}Cl
t= time in years
PR= production rate of ^{36}Cl
Cl= total number of atoms of Cl
E= factor accounting for elevation of sample site
L= factor accounting for geomagnetic latitude of site
D= factor accounting for depth of sample below surface

and the subscripts (m) and (0) refer to measured and initial ratios, respectively. The initial ratio is the background value due to nuclear reactions caused by uranium and thorium in the rock. This ratio is calculated using the method described by Bentley and others (1986), and is typically small (ranging from 5×10^{-15} to 30×10^{-15} depending upon rock type) compared to the cosmogenic buildup after a few thousand years of exposure (Phillips and others, 1986). The measured ratio for a dacite from the 1983 eruption of Mt. St. Helens was 15×10^{-15}, which is in excellent agreement with the calculated value (16×10^{-15}) for this rock (Appendix 13).

The E term corrects for the attenuation of cosmic rays in the atmosphere; a table for this correction, modified from the data of Yokoyama and others (1977) is given in Appendix 11. D, the depth correction for subsurface samples, is calculated (Appendix 16.3) using the measured density (Appendix 12) and an attenuation mean free path of 132 g/cm^2 according to the empirical method of Nishiizumi and others (1984).

2.2 Sampling

Equation (2-1) assumes that the material to be dated was completely shielded from cosmic-ray exposure until exposed suddenly at the surface. Volcanic rocks meet these conditions, and enough very young rocks that have been dated by conventional methods are available to provide a sufficient number of calibration samples. Additionally, volcanic flows (particularly those of basaltic composition) typically have distinctive surface features which form upon extrusion and cooling. These make it possible to determine whether a given site has been covered, or has had material removed, since the time of emplacement. Hence volcanic rocks are an ideal subject for a test of a cosmogenic isotope buildup chronometer. Samples selected for this study include young volcanic rocks that are fresh, relatively dense and impermeable to groundwater, located at high elevations that will provide maximum cosmic-ray flux, and have been dated by reliable methods with ages that are compatible with the observed geology of the sample site. Also, wherever possible, samples were collected through a vertical section at a given site in order to allow evaluation of the variation of cosmogenic isotope production rates with depth below the ground surface.

The primary sampling localities (Figure 2-1) include several young basalt flows in central New Mexico that were reliably dated by K-Ar methods (Bachman and Mehnert, 1978) and are well-constrained geologically (Kelley, 1977; Hawley and others, 1978, 1976). Flows of the Albuquerque Volcanoes (0.190+/-0.040 Ma), the basal Cat Hills flow (0.140+/-0.038 Ma), and the Rio San Jose flow (0.320+/-.200 Ma) are located on terraces of the Rio Grande and/or its tributaries along the western side of the Rio Grande Rift (Kelley and Kudo, 1978). The flows lie on terraces correlative with strata which have been independently dated by fossils, paleomagnetic stratigraphy, K-Ar dating, tephrochronology, and caliche buildup in soils (Hawley and others, 1978, 1976; Bachman and Machette, 1977; Gile and others, 1981).

Other primary sampling localities (Figure 2-1) include: (1) Sunset Crater in central Arizona, part of the San Francisco volcanic field (Moore and others, 1976) which includes rocks dated by K-Ar, ^{14}C, and dendrochronology in a range from 700,000 to 1,000 yr b.p.; (2) basalts from the Cima (California) volcanic field (Turrin and others, 1985; Dohrenwend and others, 1984); and (3) rhyolites from Mono Craters (California) (Dalrymple, 1967; Wood, 1977), which span a range of 60,000 to 700,000+ years. Secondary sources of calibration samples (Figure 2-1) include the Long Valley caldera, California (Bailey and others, 1976); the Lassen Volcanic Field (Clynne, 1984); and Mt. St. Helens, Washington (Crandell and others, 1981). These localities include a large number of young, well-dated flows, but the humid climate and soil development in these areas make them less desirable for calibration purposes. Mt. St. Helens, along with several other active volcanoes in Hawaii and Japan, provided recent samples for the evaluation of initial isotope concentrations in various types of volcanic rocks. Published ages of the samples are given in Appendix 3 and the sampling localities are described in detail in Appendix 1.

Three basalt units were of interest because their published ages fill several gaps in the range of dated rocks used for calibrating the cosmogenic isotope geochronometers. These include two flows from the Cima volcanic field in southern California (Turrin and others, 1985), and the Suwanee flow of Nichols (1933) along the valley of the Rio San Jose in central New Mexico (Bachman and Mehnert, 1978). The latter flow is called herein the Cerro Verde flow, since it originates from Cerro

Verde volcano to the southwest (Kelley and Kudo, 1978; Baldridge and others, 1987).

While these flows satisfy criteria 1 and 3 above, the large analytical uncertainties of the previously-published dates (Table 2-1) do not fully satisfy criterion 2. Hence these basalts were sampled and re-analysed in an effort to improve the precision of the age determinations. In each case, K-Ar was measured on groundmass plagioclase concentrates, using procedures described in Damon and others (1983). Analytical data and calculated ages are given in Table 2-1; the reported precision for all analyses is 2σ.

In two cases (C84-40 and C84-41) the precision of the analyses was improved, but only marginally so. The uncertainty in the analysis of the Cerro Verde basalt is greater than that determined by Bachman and Mehnert (1978). The large analytical uncertainty associated with all determinations are due to the low K content and the large amount of atmospheric Ar in the flows. Two of the new ages (C84-41 and SG-1C) compare extremely well with those published previously. The third (C84-40) compares less well, but agrees within the limits of analytical error. The agreement of the new analyses of these young basalts with previously- published data strongly suggests that the ages are correct, in spite of the large analytical errors associated with all determinations.

2.3 Preparation and analysis

The samples were prepared by splitting to remove any surface rind and then crushed and sieved to <100 mesh (Murphy, unpublished LANL manual). The ground samples were leached with deionized water to remove pore-water meteoric chloride. After leaching, the rock powders were digested by total fusion with NaOH and dissolved in deionized water. Chloride was precipitated from this solution as AgCl by addition of an excess of $AgNO_3$. Since ^{36}S is an interfering nuclide in AMS analysis of ^{36}Cl, the AgCl was carefully purified by repeated dissolution in NH_4OH and reprecipitation with HNO_3. This procedure is described in detail in Appendix 14.

$^{36}Cl/Cl$ ratios were determined using the TAMS at the Nuclear Structure Research Laboratory at the University of Rochester (Elmore and others, 1984, 1979). Long-term reproducibility of approximately 5% was determined from repeated analysis of two samples, FF-1 and SLR-7 over the period November 1984-June 1987 (Table 2-2). One concern with the preliminary ^{36}Cl data was possible inter-sample contamination within the sample changer of the TAMS. Results from ^{36}Cl measurements made in December 1986 demonstrated that, at least for the samples measured in this study, this is not a source of error; blanks run deliberately with high ratio standards did not show contamination. Another potential source of error in the measurements was contamination during the sample loading procedure. Although my results indicate that such contamination did not affect my samples, it apparently has been a problem on occasion for other users of the Rochester system. Contamination during loading was eliminated by redesigning the sample holder to accept disks holding only one sample each, which can be loaded by the investigator in his own laboratory and then brought to Rochester.

In addition to the isotopic analyses, the samples were characterized petrographically in order to select only fresh rock for analysis, and geochemically, since all of these systems involve isotopes produced from stable elements within the rock matrix. Whole-rock major and minor element analyses were performed by x-ray fluorescence and neutron-activation analysis at the Los Alamos National Laboratory (Valentine, 1983; Gladney and others, 1980; Garcia, unpublished data).

2.4 Results and discussion

Since the analysed rocks were collected at different locations and elevations and are of different chemical compositions, all measured $^{36}Cl/Cl$ ratios were normalized to sea-level cosmic-ray flux and an arbitrary reference composition by the equation:

$$[(^{36}Cl/Cl)-(^{36}Cl/Cl)_0]\left(\frac{Cl}{Cl_r}\right)\left(\frac{[K_2O(PR_K)_r+CaO(PR_{Ca})_r+Cl_r(PR_a)_r]}{[K_2O(PR_K)\ +CaO(PR_{Ca})\ +Cl\ (PR_a)\ ]}\right)\frac{1}{(ELD)} \quad (2\text{-}2)$$

Reference compositions were 165 ppm Cl, 2.35 weight per cent K_2O, and 5.00 weight percent CaO. The production rates for ^{36}Cl from spallation of K and Ca were 2670 atoms/kg per $\%K_2O$, and 710 atoms/kg per %CaO (Yokoyama and others, 1977). The reference production rate of ^{36}Cl by neutron activation of ^{35}Cl was 81 atoms/year per ppm Cl, based on a sea-level neutron flux of 10^6 neutrons/kg/year (Lal and Peters, 1967). Several of the samples from the Mono Craters/Long Valley area and Lassen Volcanic Park also experienced cosmic-ray attenuation due to seasonal snow cover. Using snowfall data from the California Department of Water Resources and narrative data describing seasonal snow conditions in these areas from the National Park Service (P. Fitzmaurice, personal communication), estimated attenuation due to snow cover has been incorporated into the normalization of $^{36}Cl/C/$ for these rocks. The

April 1 water content (cm) of the snowpack (Appendix 10) has been used in addition to the sample depth in the attenuation equation. This calculation (Nishiizumi and others, 1984) assumes that cosmic-ray intensity is dependent on density regardless of the composition of the shielding material. This attenuation has been considered for periods of 4 to 6 months of the year depending upon location. Since snowfall data is limited to 50 years or so at most locations, the attenuation estimated by this procedure should be regarded as a minimum, particularly for samples older than about 10,000 years.

Normalized ratios (Table 2-3) are shown relative to the predicted buildup for the reference composition on Figure 2-2. These ratios are shown in a more quantitative manner in figures 2-3a and 2-3b, where $^{36}Cl/Cl$ is plotted vs. $[(1-e^{-\lambda t})/(\lambda N)]$. The slope of the regression line is equal to the ^{36}Cl production rate (atoms $kg^{-1}year^{-1}$).

The regression which considers all of the normalized ratios implies a ^{36}Cl production rate of 19716 atoms $kg^{-1}year^{-1}$, with a correlation coefficient of 0.9871. These results demonstrate the validity of the hypothesis upon which this study is based, namely, that cosmogenic ^{36}Cl produced in situ builds up with time in a predictable manner and that measurement of this buildup may be used to determine the exposure age of young volcanic rocks. Ratios estimated using the regression lines shown on Figure 2-3a are within 10% of the normalized ratios for most rocks for which attenuation by snow is not a factor in ^{36}Cl buildup.

In general, the buildup rate of ^{36}Cl shown by these data is less than that calculated from published data. The buildup rate implied by the data reported herein (Figure 2-3a) is nearly 20% less than that predicted by the theoretical production rates of Yokoyama and others (1977) and Lal and Peters (1967). Although several of the ratios measured have fairly large uncertainties due to shielding at depth or from snow cover, the data suggest that this effect overall is not great. The regression line which includes on those ratios measured for rocks for which shielding is not a factor is nearly the same as that fit to all the data.

Figure 2-3b illustrates attempts to define new production rates for individual reactions (spallation from K, spallation from Ca, and neutron activation of ^{35}Cl) contributing to the overall production rate.

Several subsets of the data were examined: 1) rocks having PR_n>>(PR_K+PR_{Ca}; 2) rocks for which PR_K>>PR_{Ca}; and 3) rocks with PR_{Ca}>PR_K. The buildup rate implied by the data for rocks in which neutron activation of ^{35}Cl contributes the most ^{36}Cl is very close (+3%) to that calculated using all measured ratios, not surprising considering the fact that this mechanism dominates in most rocks.

The regression lines for case (2) and (3) above suggest that the actual production rate of ^{36}Cl by spallation from K is only slightly higher than that predicted by Yokoyama and others (1977) but that from Ca it is much less. In most of these rocks, neutron activation of ^{35}Cl is still the major source of ^{36}Cl. Also, the K line is relatively unconstrained at its upper (older) end, as is the Ca at its lower (younger) end. Hence assigning specific production rates for the production of ^{36}Cl by spallation of K and Ca based on the data reported herein would be premature.

The deviation from the predicted curve may have one or more causes:

1) Since the dominant production of ^{36}Cl in these rocks is from neutron activation of ^{35}Cl (Table 2-6), variation in production by this mechanism should have the greatest effect on the measured ratio. This suggests that the cosmic-ray neutron flux is less than that calculated by Lal and Peters (1967).

2) The published rates for ^{36}Cl production by spallation, based upon semi-empirical data for production of ^{22}Na from Al, have not been tested previously and may not be accurate.

3) The attenuation of cosmic ray flux with depth is also based on empirical data which has been tested only on lunar material (Nishiizumi and others, 1984). Although the half-attenuation length should be independent of the type of material, other factors, such as the production of thermal neutrons by stopped muons (Kubik and others, 1984) may be more or less significant than has been assumed. Thermal neutron production by stopped muons has been cited as a factor in deviation of ^{3}He data from predicted values by Kurz (1986).

Additionally, data from the study reported herein were used by O'Brien (1985) to calculate cosmic-ray particle spectra and attenuation underground. He showed that attenuation of cosmic-ray flux with depth is _not_ totally independent of rock composition, nor is it strictly dependent upon density. Comparing the variation of calculated cosmic-ray flux with depth in both rhyolite and basalt, he found that attenuation is more rapid in rhyolite. The attenuation mean-free-path determined by O'Brien (1985) is 131 g/cm^2 in basalt and 126 g/cm^2 in rhyolite. At depths exceeding 6000 gm/cm^2 this will result in a difference in attenuation of nearly an order of magnitude between these two rock types. At the depths sampled in this study (<1000 g/cm^2), however, attenuation is effectively independent of both rock type and density.

Similarly, O'Brien (1985) found showed the cosmic-ray particle spectra varies with depth; this will affect the production rate of isotopes which depend upon different types of particles (e.g., neutrons or protons _vs._ muons). These results show that it would not be correct to determine the ratio of some cosmogenic isotope to the cosmic-ray particle flux or to some other isotope at one depth in the earth and then attempt to infer the yield at other depths. The variation in cosmic-ray particle spectral shapes and proportions will cause these ratios to vary from depth to depth. This latter observation is of critical importance to studies which depend upon measured ratios of cosmogenic isotopes (e.g., $^{10}Be/^{26}Al$) to establish in situ cosmogenic isotope production rates. A similar variation in cosmic-ray particle spectra occurs in the atmosphere, but this effect is small (Allkofer and Grieder, 1984; O'Brien, 1979) over the range of elevations at the surface of the earth.

The data reported herein also indicate that potential problems in ^{36}Cl analysis associated with the "mobility" of Cl (Nishiizumi and others, 1986) can be overcome. Recent research on ^{137}Cs (Kimura and others, 1983) has shown that even relatively immobile and/or non-reactive radionuclides can penetrate rocks in geologically short time periods. Preliminary analyses of several samples did not show good correlation of measured $^{36}Cl/Cl$ with the predicted values (Izmirian, 1984); in several cases the measured ratio was similar to that of groundwater in the sample locality (Figure 2-4). It is quite possible that some of the "extracted" chloride was merely pore-water meteoric chloride, rather than intrinsic, cosmogenic ^{36}Cl from within the mineral grains. This effect may have been enhanced by the fact that the extraction method used was a sulfuric acid leaching procedure (Izmirian, 1984) which did not result in a total digestion of the sample.

These rocks appeared fresh and unaltered under petrographic examination, but they had not been treated for removal of pore-water meteoric chloride. This problem was overcome by devising an alternative extraction procedure: first leaching the samples with deionized water to remove soluble, and assumedly mostly meteoric, chloride, followed by a fusion procedure which totally digests the rock (Appendix 14). Subsequent analyses showed that a single leaching with deionized water was sufficient to remove meteoric chloride and eliminate its effect on the measured ratios. Table 2-5 shows the results of pre-extraction leaching for a number of rocks analysed in this study. These data show that, at least within the limits of error typical for Cl determination by XRF, no measurable chloride is removed by subsequent leaching following a single leaching with deionized water. Figure 2-4 shows the measured ^{36}Cl/Cl for several samples both before and after such leaching; while the unleached samples have ratios which may be influenced by meteoric ^{36}Cl, leached samples have measured ratios very much like those predicted by the buildup equation. Some samples with higher than calculated ratios have been attributed to "bomb" ^{36}Cl (Phillips and others, 1986) contamination. "Bomb" ^{36}Cl fallout was much higher than natural ^{36}Cl fallout (Figure 2-5), so if indeed pore-water chloride is effectively removed by leaching, then "bomb" chloride cannot be a factor in these high ratios.

One very attractive aspect of dating using ^{36}Cl has been the assumption that this method may be used for rocks of virtually any composition, and the data reported here bear this out. At first glance, differences in the production rates of ^{36}Cl by different mechanisms would suggest that production of this isotope may be optimized by selection of rock types with compositions more favorable for ^{36}Cl production. The percentage contribution of ^{36}Cl production from different targets to the total ratio, shown in Figure 2-6 and Table 2-6, may be helpful in this regard.

It is desirable to select rocks with high chloride contents; chloride in excess of 100 ppm generally simplifies extraction and eliminates the need for spiking the extract to provide sufficient chloride to handle. This, however, is not a useable criteron for selection of samples in the field.

There is a broad range of production from ^{35}Cl in these samples, particularly in the basalts, influenced both by Cl content and the total neutron absorption of the rock. Basalts are particularly vulnerable to this due to their wide variation in Fe, with its large neutron-capture cross-section. Recognizing the fact that the rocks sampled may have low Cl content, it would appear that it might be possible to select samples so as to obtain maximum ^{36}Cl production from spallation of K and Ca, constituents which may be estimated, in gross terms, in the field. Typically, more mafic rocks have relatively low K_2O and high CaO; the reverse is true for felsic types. Since the production rate per %oxide for ^{36}Cl from K_2O is almost a factor of 4 larger than from CaO, it would seem that ^{36}Cl production may be optimized by the selection of rocks of intermediate to felsic composition.

It is apparent from Table 2-6, however, that while the production rate of ^{36}Cl from K exceeds that from Ca by a factor of 20 in rhyolites, the total production from K and Ca in these rocks is only comparable to, or slightly more than, the total from K and Ca in basalts. This supports the idea that ^{36}Cl buildup may be used effectively for virtually any type of rock. One case in which the higher spallation rate from K may be used to best advantage is in the case of very young sanidine-bearing rocks; K_2O in sanidine exceeds 10 weight per cent. This has been used to advantage by Dalrymple (1967) to obtain K-Ar ages for rhyolites <10,000 years old, and may be effective in ^{36}Cl buildup dating as well.

The dominant mechanism producing ^{36}Cl in most rocks is the in situ production of 36Cl by neutron activation of 35Cl. The production rate for this reaction is governed by several factors, the most important of which is the absorption of thermal neutrons by other elements in the rock (Bentley and others, 1986). Hence any uncertainty in the chemical composition of the rock, upon which the total neutron-absorption cross-section of the rock depends, can have a profound effect on the normalization of measured $^{36}Cl/Cl$.

Estimation of the total neutron-absorption cross-section has been approached by a number of recent studies (Andrews and others, 1986; Fontes and others, 1984; Izmirian, 1984; Andrews and Kay, 1982), all of which determined that the total neutron-absorption cross-section for a given rock may be estimated quite accurately by analysis of as few as 12 of the elements in the rock. Based on these assumptions, the authors presented total neutron-absorption cross-sections for various rock types (Appendix 8) which were calculated using either representative rock compositions for the rocks, or the specific composition of a rock in their study area. Although none of these authors suggested that these cross-sections be used as representative for a given rock type in other studies, it is often tempting to do so; indeed, in several current studies, we hoped to do just that. It would simplify our analysis if we could calculate representative cross-sections using representative rock compositions and thus eliminate the necessity of performing complete geochemical analysis of every rock we sampled.

Appendix 8 contains calculated total neutron-absorption cross-sections for a wide range of igneous rock types based on representative rock compositions found in the literature (LeMaitre, 1976; Wedepohl, 1978). Appendix 9 lists analyses of rocks used in the study reported herein. The rocks included in the list of representative compositions were intended to cover a wide range of rocks, but should not be viewed as representative of all common rock types. The rocks listed were chosen only on the basis of available representative compositional data in the literature.

The range of compositions for any given rock type in the field is large enough to make the cross-sections calculated for "representative" compositions not truly representative. Since the total neutron-absorption cross-section is a critical factor in the estimation of 36Cl production by neutron activation of 35Cl, it is necessary to calculate this factor as accurately as possible.

Figure 2-6 illustrates the problems in using representative compositional values. Although the felsic rocks tend to cluster around the representative values, and the andesite value is remarkably similar to that of the representative andesite, notable differences are apparent. A particularly good example of this may been seen in Table 2-4. Normalized ratios for the rocks listed were reported by Phillips and others (1986) before complete geochemical analyses were available, and measured ^{36}Cl/Cl were normalized using representative values. Phillips and others (1986) noted in that paper that the divergence of the normalized values from the calculated curve might be due to the use of representative values for the total neutron-absorption cross-section for several rocks.

As shown in Table 2-4, this would not present a serious problem for some rocks such as C-41 (particularly since the ^{36}Cl measurement was at the $\underline{+}$10% level), but that for others large errors may result if actual analyses are not used. Hence a complete geochemical analysis - at least "complete" enough to include the critical elements - is necessary when analysing 36Cl production in rocks. Elements which are not commonly measured in routine geochemical analysis, such as Li, may be omitted since even at the extreme range of reported values for these elements they will not make up more than 2% of the total neutron-absorption cross-section in common rocks. However, in some rocks (Li-rich pegmatites, for example) even such elements will need to be determined if the neutron-activation production rate for 36Cl is to be estimated accurately.

Other elements which contribute less than 2% of the total neutron absorption in specific rock types (for example, Mg and Mn in rhyolites as shown in the Appendices) may also be omitted from the total. These elements are, however, routinely reported in whole-rock major-element analyses and as such may be included easily in the total cross-section.

Although it will be necessary to accumulate more data before these production rates can be fully evaluated, in general the results reported herein demonstrate that ^{36}Cl buildup can be used for surface-exposure dating. In addition to data for volcanic rocks, preliminary ^{36}Cl/Cl analysis of granitic boulders from Tioga-age (10,000-20,000 years b.p.) moraines from the Sierra Nevada (Phillips and Jannik, unpub. data) indicate that buildup dating will be applicable to this type of material as well.

2.5 Summary

^{36}Cl analyses were obtained for a number of well-dated young volcanic rocks as part of an evaluation of the use of this isotope as a dating tool. Although uncertainties remain in the interpretation of our data, there is a predictable buildup of ^{36}Cl with time, produced in situ since the emplacement of these flows at the surface. We expect that, with refinement, ^{36}Cl buildup can be used to date surface-exposure ages for volcanic rocks and other surficial materials. The ability to directly date very young materials of a wide range of compositions, such as archeological artifacts, glacial moraines, geomorphic surface, and soils, as well as volcanic rocks, will constitute a powerful tool for many of the earth sciences.

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Table 2-1: New K-Ar Analyses for Basalts from Cima and Cerro Verde

Sample #	Sample	Locality	age (my), this study	age (my), published*
UAKA86-62	C84-40	Cima	0.480+/-0.057	0.670+/-0.130
UAKA86-63	C84-41	Cima	0.227+/-0.042	0.270+/-0.100
UAKA86-64	SG-1C	Cerro Verde	0.278+/-0.151	0.320+/-0.200

*Turrin and others, 1985 (Cima); Bachman and Mehnert, 1978 (Cerro Verde)

TABLE 2-2: MEASURED ^{36}Cl/Cl FOR REPEATED ANALYSIS OF FF-1 AND SLR-7

SAMPLE	MEASURED RATIOS (DATE)	MEAN RATIO	UNCERTAINTY
FF-1	452±47, 401±38 (12/85)		
	433±22 (3/87)		
	445±19 (6/87)	433±23	5%
SLR-7	1129±28 (4/85)		
	1158±199, 1231±56 (12/85)		
	1148±66 (3/87)	1167±45	4%

TABLE 2-3: DATA FOR SAMPLES USED FOR THE CALIBRATION OF COSMOGENIC ^{36}Cl GEOCHRONOMETER

DATA FOR SAMPLES COLLECTED IN NEW MEXICO

SAMPLE	LATITUDE (N)	LONGITUDE (W)	ELEV (m)	DEPTH (cm)	S.G. (gm/cm^3)	K_2O (wt.%)	CaO (wt.%)	Cl (ppm)	ABSf$_{(tot)}$ (cm^2/kg)	AGE (Kyr)	^{36}Cl/Clx10^{-15} (calculated)*	^{36}Cl/Clx10^{-15} (measured)	^{36}Cl/Clx10^{-15} (initial)	^{36}Cl/Clx10^{-15} (normalized)
SG-1A	34°50'18"	107°03'06"	1585	20	2.46	0.76	8.49	58	6.42	299+/-209	1792±161	6770±62	6	1739±16
SG-1B	34°50'18"	107°03'06"	1585	330	2.33	0.78	8.59	25	6.31	299+/-209	1792±161	137±8	6	1410±82

DATA FOR SAMPLES COLLECTED AT MONO CRATERS AND LONG VALLEY CALIFORNIA

SAMPLE	LATITUDE (N)	LONGITUDE (W)	ELEV (m)	DEPTH (cm)	S.G. (gm/cm^3)	K_2O (wt.%)	CaO (wt.%)	Cl (ppm)	ABSf$_{(tot)}$ (cm^2/kg)	AGE (Kyr)	^{36}Cl/Clx10^{-15} (calculated)*	^{36}Cl/Clx10^{-15} (measured)	^{36}Cl/Clx10^{-15} (initial)	^{36}Cl/Clx10^{-15} (normalized)
SLR-2	37°48'54"	119°01'30"	2365	10	1.71	4.62	0.56	428	4.92	10.58±4.84	86±8	182±23	92	28±4
SLR-3	37°49'00"	119°02'48"	2457	10	1.56	4.61	0.57	401	4.96	6.45±1.84	53±5	70±5	92	3±1
SLR-7	37°40'36"	118°59'06"	2682	10	1.81	4.54	0.76	221	5.55	106±3	806±73	3900±200	84	771±40
MC-1	37°48'54"	119°01'30"	2365	10	1.39	4.51	0.56	475	4.81	10.58±4.84	86±8	95±9	94	15±2
MC-2	37°49'00"	119°02'48"	2457	0	1.94	4.65	0.57	484	4.99	6.46±1.84	53±5	90±20	92	9±3
MC-4	37°49'30"	119°00'48"	2536	0	2.25	4.55	0.56	493	5.12	6.60±2.13	54±5	118±5	112	9±1
MM-2	37°42'30"	118°56'48"	2305	100	1.00	1.89	7.08	113	5.56	149±16	1046±94	1248±123	12	1078±106

* on the basis of the normalized curve

TABLE 2-3 (continued): DATA FOR SAMPLES USED FOR THE CALIBRATION OF COSMOGENIC ^{36}Cl GEOCHRONOMETER

DATA FOR SAMPLES COLLECTED IN THE CIMA VOLCANIC FIELD CALIFORNIA

SAMPLE	LATITUDE (N)	LONGITUDE (W)	ELEV (m)	DEPTH (cm)	S.G. (gm/cm^3)	K$_2$O (wt.%)	CaO (wt.%)	Cl (ppm)	ABSf$_{(tot)}$ (cm^2/kg)	AGE (Kyr)	^{36}Cl/Clx10^{-15} (calculated)*	^{36}Cl/Clx10^{-15} (measured)	^{36}Cl/Clx10^{-15} (initial)	^{36}Cl/Clx10^{-15} (normalized)
C84-40	34°15'30"	115°43'00"	1219	200	2.32	1.89	8.55	400	7.71	575±100	2829±255	350±35	13	2190±219
C84-41	35°15'30"	115°43'00"	1201	200	2.69	2.02	8.09	380	8.22	249±75	1665±150	155±55	16	1414±502

DATA FOR SAMPLES COLLECTED IN LASSEN VOLCANIC FIELD

SAMPLE	LATITUDE (N)	LONGITUDE (W)	ELEV (m)	DEPTH (cm)	S.G. (gm/cm^3)	K$_2$O (wt.%)	CaO (wt.%)	Cl (ppm)	ABSf$_{(tot)}$ (cm^2/kg)	AGE (Kyr)	^{36}Cl/Clx10^{-15} (calculated)*	^{36}Cl/Clx10^{-15} (measured)	^{36}Cl/Clx10^{-15} (initial)	^{36}Cl/Clx10^{-15} (normalized)
L724-1	40°32'24"	121°34'24"	1768	300	1.60	2.70	2.79	461	4.43	51±4	50±4	149±12	58	340±8
L724-2	40°32'24"	121°34'24"	1768	150	1.68	2.49	2.95	399	4.50	51±4	421±38	280±5	57	406±8
L683-A	40°28'12"	121°26'30"	2316	650	2.39	2.54	3.77	25	4.28	212±6	1513±136	83±8	48	1317±127
L391	40°30'00"	121°36'30"	1853	150	2.34	2.10	6.64	146	5.77	304±8	1811±163	685±34	18	1454±155
L915-B	40°28'30"	121°30'12"	2633	0	2.50	2.75	3.02	189	4.12	10±2	240±22	291±29	60	346±65
SF-1	40°33'30"	121°32'00"	1853	0	2.07	2.77	3.08	299	4.11	36±24	286±26	153±12	60	246±18

* on the basis of the normalized curve

TABLE 2-4: NORMALIZATION OF ^{36}Cl/Cl

COMPARISON OF THE USE OF REPRESENTATIVE <u>VS</u>. ACTUAL COMPOSITIONS

SAMPLE	NORMALIZED ^{36}Cl/Cl		DIFFERENCE
	(representative)	(actual)	
C-41	1850	1414	14%
C-40	3500	2190	37%
MC-4	20	9	222%

TABLE 2-5: TOTAL CHLORIDE CONTENT OF ANALYSED ROCKS BY XRF

SAMPLE	ppm Cl UNLEACHED (± 9 ppm)	ppm Cl LEACHED (1) (± 9 ppm)	ppm Cl LEACHED (2) (± 17 ppm)
AF-1	275	93	83
ST-2	525	279	268
SLR-2	554	462	432
SLR-3	609	436	464
MM-3	179	175	178

(1) total chloride measured after 1 leaching with DI water

(2) total chloride measured after 2 leachings with DI water

TABLE 2-6: SEA-LEVEL PRODUCTION RATES OF ^{36}Cl (atoms kg^{-1} yr^{-1}) BY TARGET ELEMENT AND TOTAL

SAMPLE	PR(K)	%	PR(Ca)	%	PR(Cl)	%	TOTAL	ROCK TYPE
SG-1	2029	16	6028	46	4988	38	13045	basalt
C-40	5046	13	6071	15	28640	72	39757	basalt
C-41	5393	15	5744	15	25536	70	36673	basalt
MM-2	5046	24	5027	24	11221	52	21294	basalt
represent.	2937	15	6724	34	9947	51	19608	basalt
L391	5607	23	4714	19	13972	58	24294	andesite
represent.	4325	19	4821	22	13052	59	22198	andesite
L915	7449	19	2158	6	29526	76	39133	dacite
SF-1	7396	15	2187	4	40156	81	49738	dacite
represent.	5794	21	3067	11	19146	68	28007	dacite
L683	6782	53	2677	21	3225	25	12684	rhyodacite
L724	7209	11	1981	3	57441	86	66631	rhyodacite
represent.	8010	24	2570	8	23333	69	33913	rhyodacite
MC-1	12189	19	398	1	51245	80	63831	rhyolite
MC-2	12362	20	405	1	49095	79	61862	rhyolite
MC-3	12522	17	405	1	60089	82	73017	rhyolite
MC-4	12149	18	398	1	53145	81	65692	rhyolite
SLR-6	12362	18	398	1	52852	81	65611	rhyolite
SLR-7	12242	38	547	2	19678	60	32467	rhyolite
represent.	11481	29	809	2	26904	69	39194	rhyolite
Ref. comp.	6275	27	3550	15	13365	58	23190	intermediate

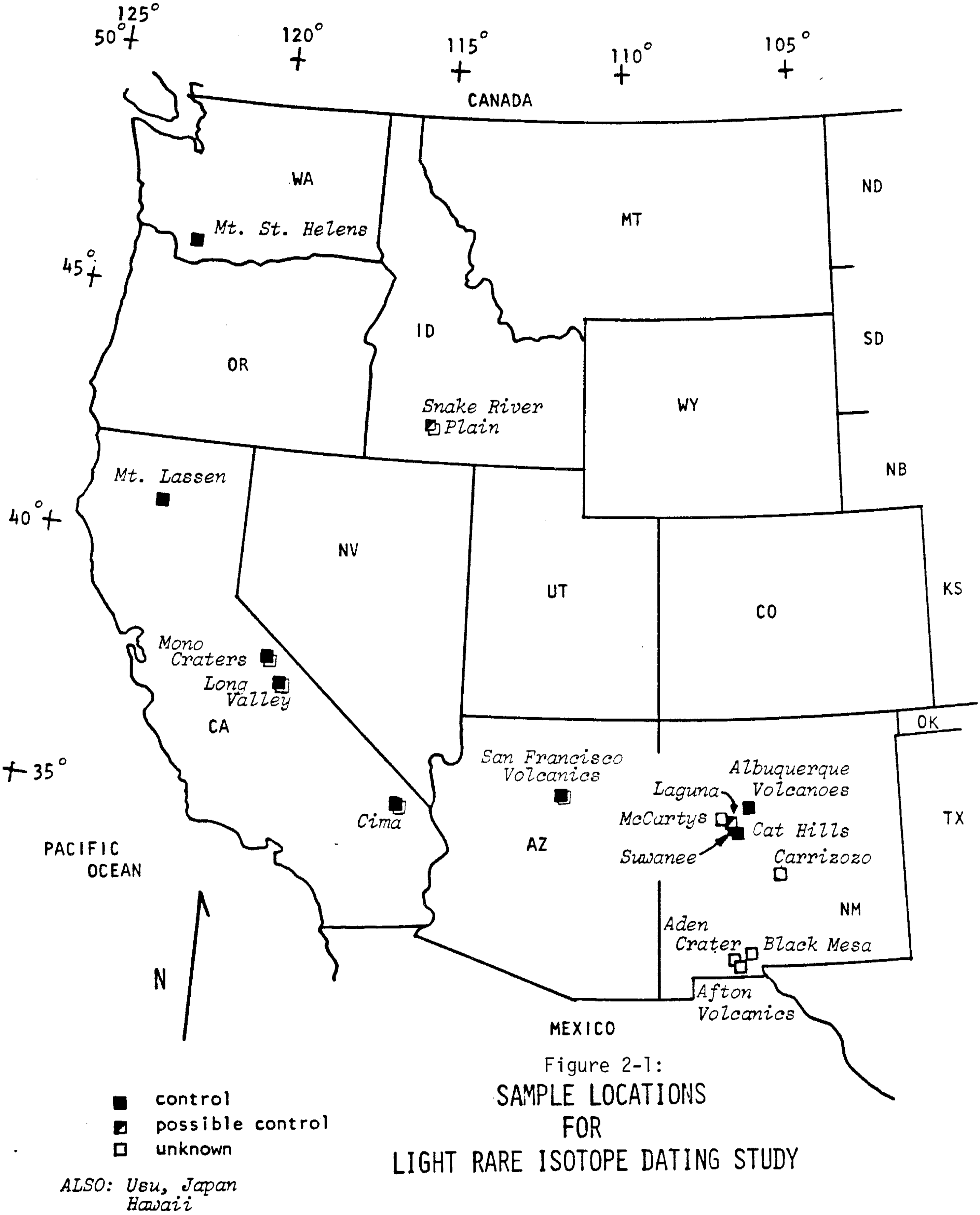


Figure 2-1:
SAMPLE LOCATIONS
FOR
LIGHT RARE ISOTOPE DATING STUDY

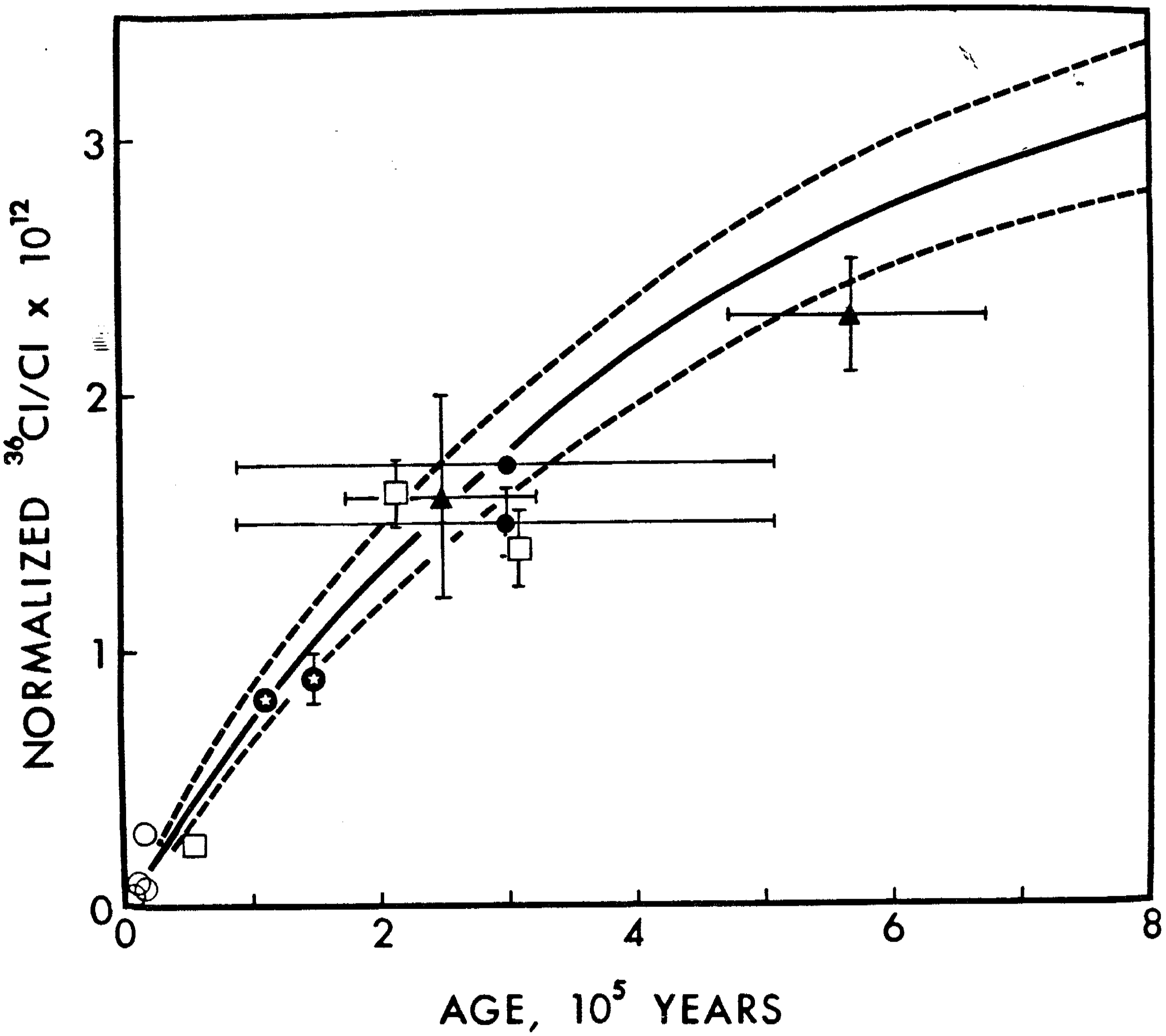


Figure 2-2: Comparison of ^{36}Cl/Cl from dated samples with the calculated sea-level ^{36}Cl/Cl buildup curve. Solid line is buildup calculated using data cited in text; dashed lines include the ±20% uncertainty for production rate of ^{36}Cl by spallation from ^{40}Ca and ^{39}K. Measured ratios are normalized for chemical composition, geomagnetic latitude, elevation, and sample depth below ground surface. Error bars represent 2 σ analytical uncertainty for sample ages and 1σ for ^{36}Cl/Cl. Symbols indicate sample localities: ● Cerro Verde flow, NM; ▲ Cima volcanic field, CA; ✪ Long Valley, CA; ○ Mono Craters, CA; □ Lassen volcanic field, CA.

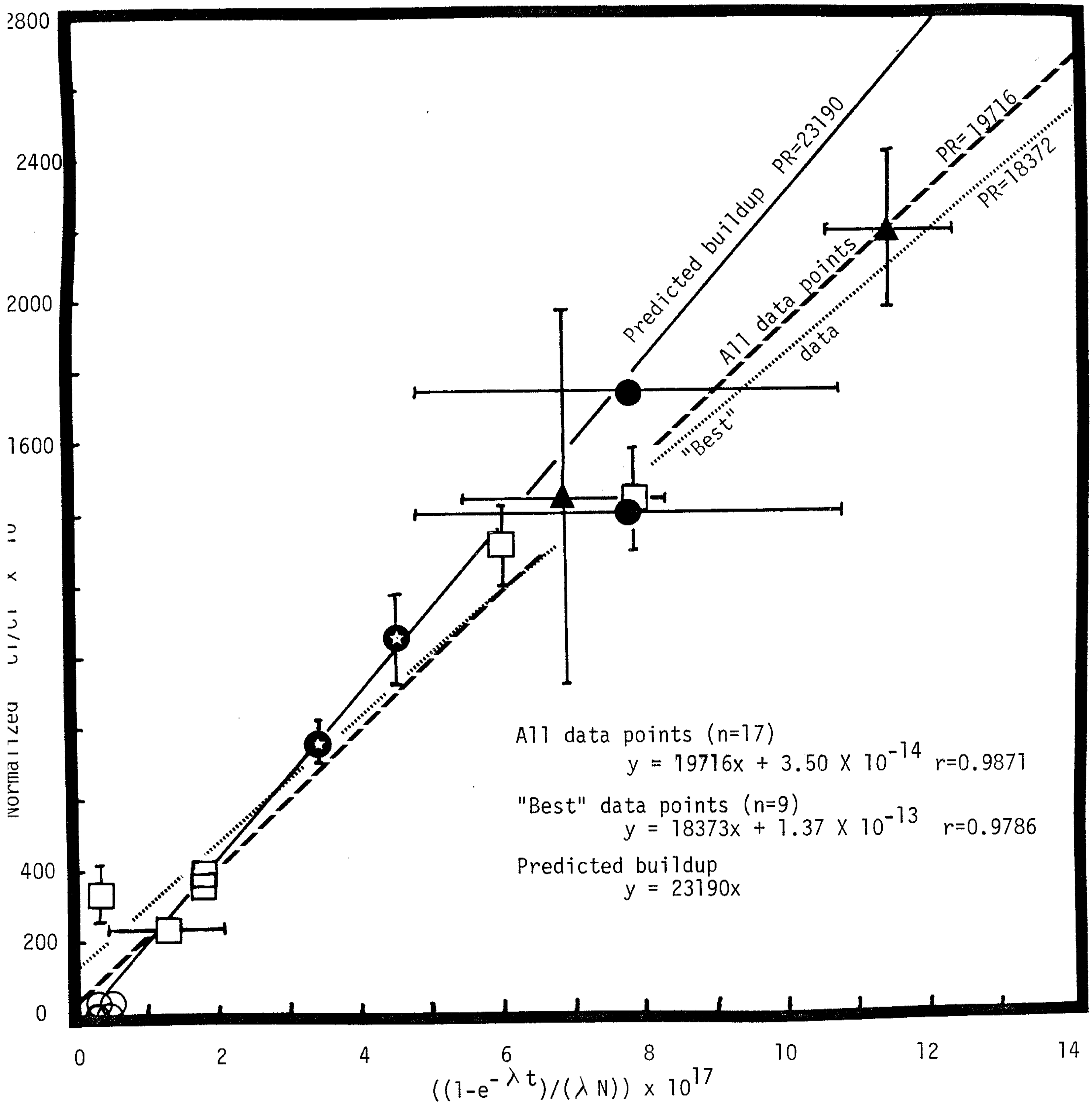


Figure 2-3a: $^{36}Cl/Cl$ vs. $((1-e^{-\lambda t})/(\lambda N))$. Regression lines are for subsets of data described in text. Symbols for data points are described in caption for Figure 2-2. Production rates (PR) in atoms kg^{-1} yr^{-1}. For samples without error bars, uncertainty is within the size of the symbol.

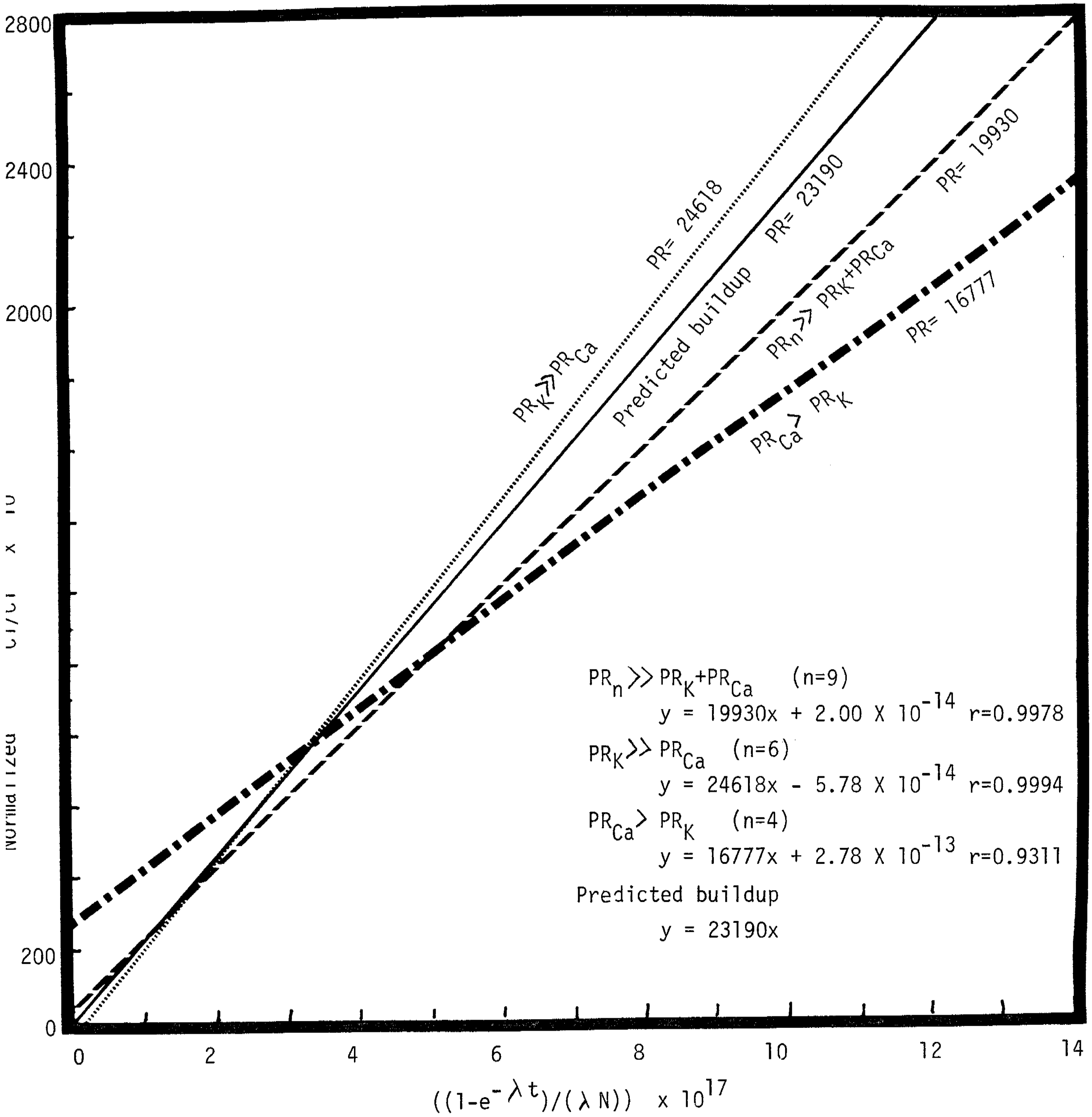


Figure 2-3b: ^{36}Cl/Cl vs. $((1-e^{-\lambda t})/(\lambda N))$. Regression lines are for subsets of data described in text. Production rates (PR) in atoms kg^{-1} yr^{-1}.

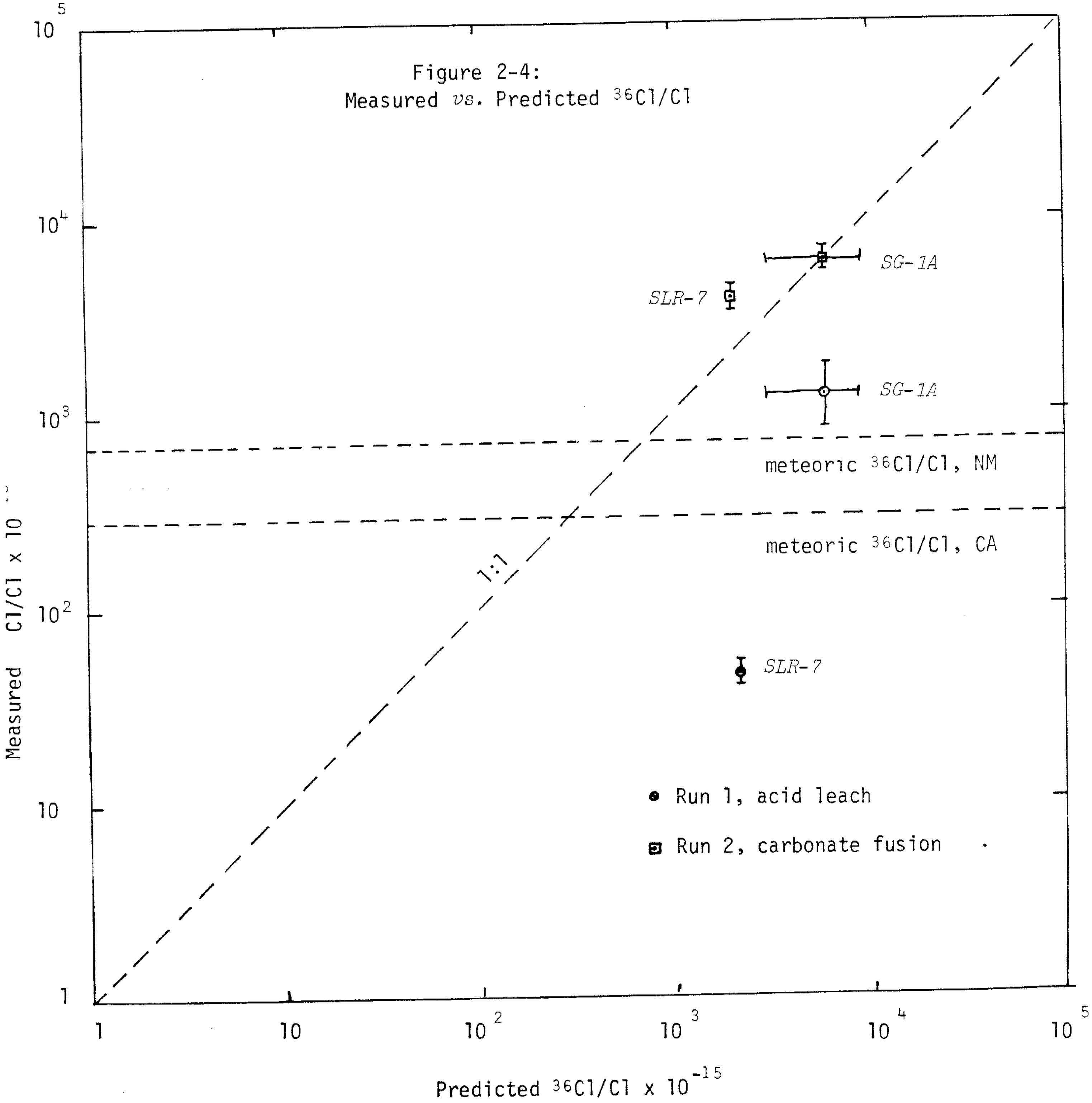


Figure 2-4:
Measured *vs.* Predicted $^{36}Cl/Cl$

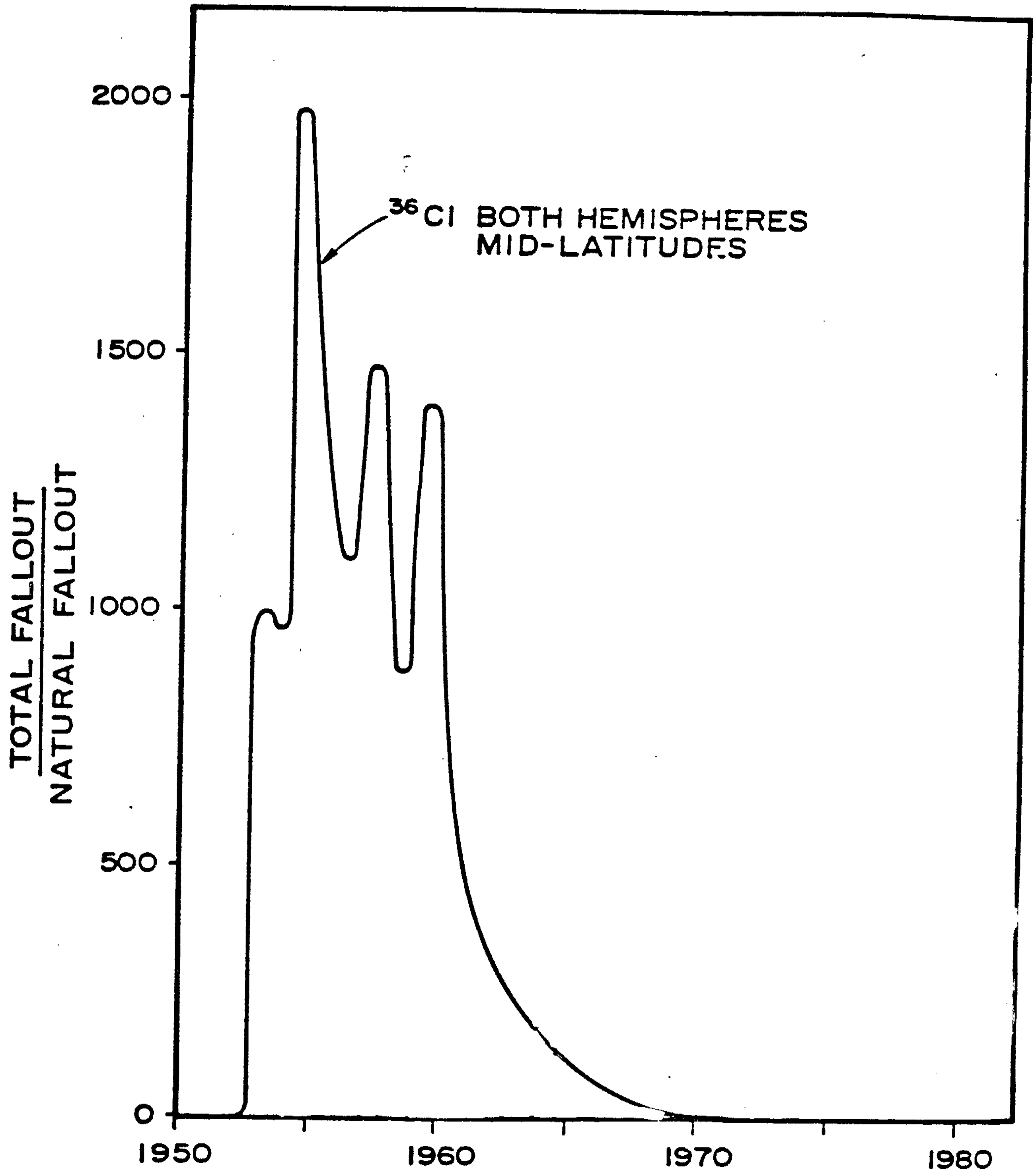
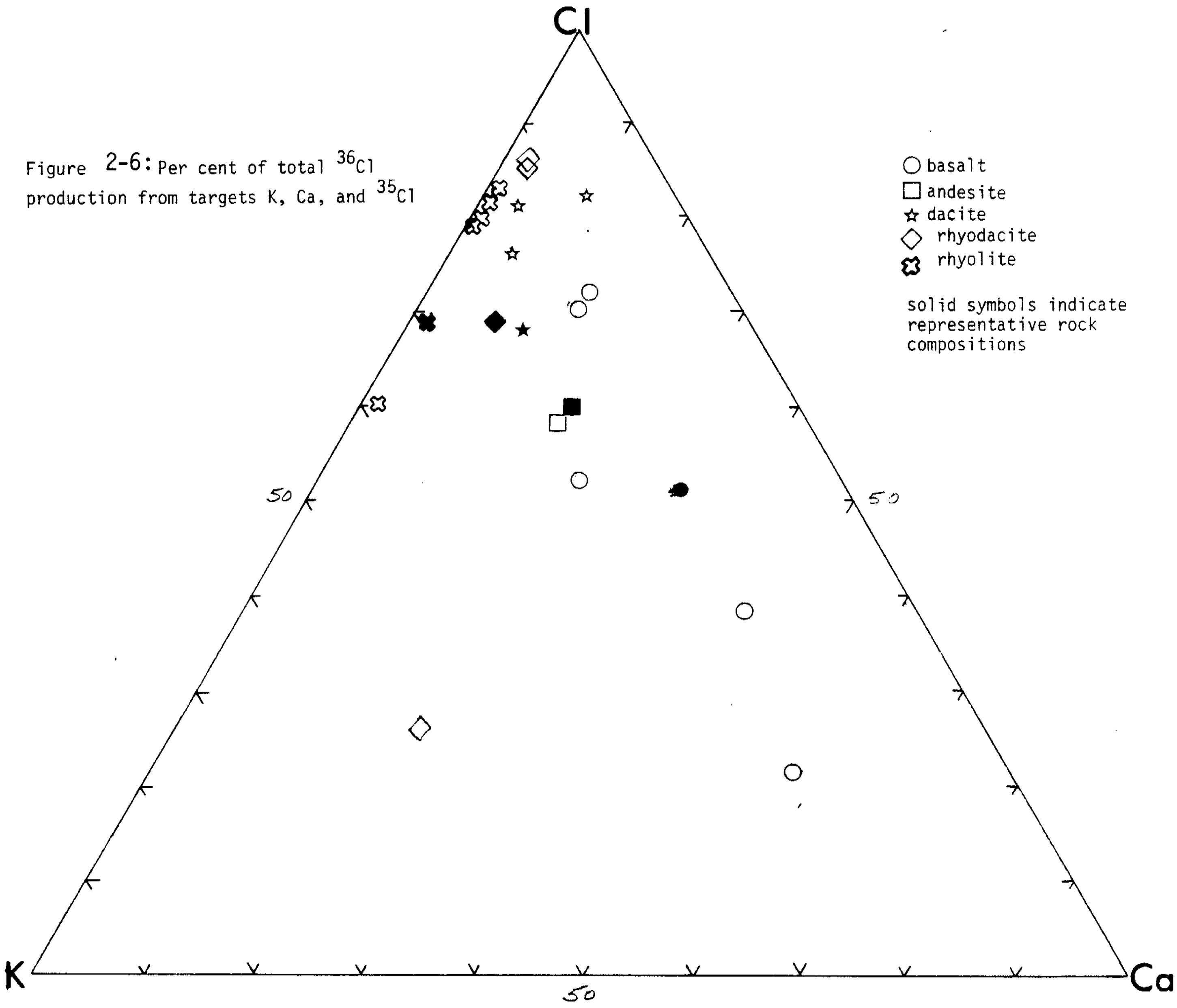


Figure 2-5:"Bomb" ^{36}Cl fallout (decay corrected to 1983) in the Northern and Southern Hemispheres, on arithmetic scale.

Figure 2-6: Per cent of total ^{36}Cl production from targets K, Ca, and ^{35}Cl



Part 3: ^{10}Be and ^{26}Al in Young Volcanic Rocks

3.1 Introduction

Like ^{36}Cl, ^{10}Be has several characteristics which make it suitable for buildup dating. ^{10}Be builds up to measurable levels relatively quickly since the product element (beryllium) is present in most rocks only in trace quantities, and determination of its production rate is relatively simple since the only mechanism for in situ production of this isotope is spallation from heavier elements, primarily oxygen.

Previous applications of ^{10}Be to dating earth materials have used the buildup of meteoric ^{10}Be for dating soils (Pavich and others, 1983). Meteoric ^{10}Be also was used (Brown and others, 1982) to document the assimilation of subducted oceanic sediments in island arc volcanics. In situ production of ^{10}Be was not considered as a contributing factor in the ^{10}Be content of volcanic arc rocks, but the authors noted this source of ^{10}Be in discussion of the ^{10}Be content of Columbia River basalt, which presumably has no sediment input. While some very young basalts in the study had no time for in situ development of ^{10}Be, having been collected immmediately after eruption, it is not possible to evaluate the role of in situ production of ^{10}Be in most of the published data since no indication is given of the depth from which the samples were taken, or of their ages. Since the ^{10}Be values in all of the reported analyses are within the range that might be expected for in situ production of this isotope by cosmic ray interaction, the question of the ultimate source of ^{10}Be in these rocks remains unanswered. Quantification of the ^{10}Be values in other young continental volcanic rocks will permit the evaluation of all sources of ^{10}Be input to island arc volcanics.

^{10}Be/^{26}Al ratios in quartz were reported by Nishiizumi and others (1986) on rocks of unknown exposure age, and Monaghan and others (1985) measured ^{10}Be in mineral separates from young (but undated) volcanics. The use of the isotope pair ^{10}Be/^{26}Al has been highly touted as a dating tool since the use of the two in tandem will obviate the necessity of knowing variations of cosmic-ray flux with time (Muller, 1977). Moreover, these studies are significant in that they represent a radically different approach to the analysis of in situ produced radionuclides. Recent research (Kimura and others, 1983) showed that even relatively immobile radionuclides can penetrate rocks in geologically short time periods, altering the concentration of these isotopes in situ. For example, it is believed (Klein and others, 1986) that contamination of in situ produced ^{10}Be by meteoric ^{10}Be is a major problem in analysis of that isotope. The measurement of ^{10}Be in quartz has been regarded as a means to eliminate this problem (Nishiizumi and others, 1986). Furthermore, Nishiizumi and others (1986) and Lal and Arnold (1985) note that the ^{10}Be/^{26}Al ratio may be used as a check on contamination by meteoric cosmogenic nuclides, since the meteoric ratio is well known.

These arguments are less compelling as reasons for using this approach when one realizes that Be and Al probably are not as similar geochemically as previously thought (Pavich, personal communication), that the variations of cosmic-ray flux with time are small enough to make them insignificant to geochronology (Kohl and others, 1978; Higdon and Lingenfelter, 1973; Yokoyama and others, 1973; Finkel and others, 1971; Oeschger and others, 1969; Lal and Peters, 1962), that the influx of meteoric ^{10}Be to rocks is much less than initially thought (Tera and others, 1986), and that using suitably fresh and unaltered rocks and a reasonable pre-analysis cleanup procedure will eliminate what little meteoric ^{10}Be does enter the rocks (Tera and others, 1986). Although the use of pure quartz has certain analytical advantages (specifically, a simple chemical system, essentially free of Al, from which to extract the Be), the advantage of whole-rock analysis is that rocks of any composition may be analysed, not only those which contain free quartz. This greatly expands the number of available samples for study.

This is not to say that "meteoric" ^{10}Be is not a problem in the analysis of the in situ isotope; indeed, it can and does pose great difficulties, even when using quartz separates. It is essential to note in this regard that there is more than one type of "meteoric" ^{10}Be to contend with. The sort of meteoric ^{10}Be which Nishiizumi and others (1986) seek to eliminate using quartz, which they regard as being the mineral most resistant to alteration in surficial materials, is meteoric Be which may be introduced to minerals through water-rock interaction in situ.

The work of Tera and others (1986), and the data shown below indicate that through the judicious choice of samples and appropriate pre-extraction cleaning, this sort of "meteoric" ^{10}Be may be eliminated as a factor in even whole-rock analysis. Dr. D. Lal (personal communication) has expressed interest in the ^{10}Be analysis of whole-rock samples and olivine separates from the suite of rocks collected for the study reported herein, which suggests that contamination by this sort of "meteoric" ^{10}Be is no longer thought to preclude whole-rock ^{10}Be analysis.

A second type of "meteoric" ^{10}Be can indeed be a serious problem no matter what the material being analysed. This Be is incorporated into samples during sample processing if they are allowed to stand exposed to the outside air in the laboratory. This sort of contamination caused significant errors in the $^{10}Be/^{9}Be$ measured in the early part of this study. Tera and others (1986) identified this problem and solved it by simply isolating the samples within a box which excluded turbulent room air, and their procedure has been used in the latter part of this study.

3.2 Production and dating calculations

Cosmogenic isotopes accumulate at a rate proportional to the exposure time of the material and they decay at a rate proportional to their decay constants. The measured ^{10}Be content of a rock (usually expressed as the number of atoms of the radioactive isotope per gram of rock) is thus a function of the production rate and the decay rate. The Be content of most terrestrial rocks is negligible and is not a factor in ^{10}Be buildup; similarly, it is assumed that thereis no initial ^{10}Be content in continental volcanic rocks. Thus ^{10}Be buildup is defined by a modification of equation 1-4 (Bentley and others, 1984):

$$(\text{atoms/gram})_m = \frac{[ELD(PR)]}{\lambda}(1-e^{-\lambda t}) \qquad (3\text{-}1)$$

where

λ = decay constant

t = time in years

PR = production rate

E = factor accounting for elevation of sample site

L = factor accounting for geomagnetic latitude of site

D = factor accounting for depth of sample below surface

and the subscripts (m) and (0) refer to measured and initial ratios, respectively. The E term corrects for the attentuation of cosmic rays in the atmosphere; tables for this correction and for L are given in Yokoyama and others (1977). Lal and Peters (1967) provide theoretical values for D, the correction for cosmic-ray attenuation with depth below the ground surface; Nishiizumi and others (1984) calculate this value using an empirical method derived from cosmogenic isotope data for lunar soils.

3.3 Preparation and analysis

The samples were prepared by splitting to remove any surface rind and then crushed and sieved to <100 mesh. These powders were leached with 8N HNO_3 + 2N HF followed by 4N HCl to remove adsorbed meteoric beryllium (Brown and others, 1983). After leaching, an aliquot of 10 grams rock powder was spiked with 1-2 mg ^{9}Be and digested using HNO_3/HF. Be was separated from this solution by a method which was modified from that of Tera and others (1986) to accomodate the much larger sample size. Since ^{10}B is an interfering nuclide in AMS analysis of ^{10}Be, the BeOH was carefully purified by repeated dissolution and treatment with perchloric acid. ^{10}Be was determined using the TAMS at the Institut fur Mittlenergiephysik, Zurich (Suter and others, 1983), with long-term reproducibility of approximately 2%.

3.4 Results and discussion

Since the analysed rocks were collected at different locations and elevations, all measured ratios were normalized to sea-level cosmic-ray flux. Normalized ratios are shown relative to predicted buildup on Figure 3-1. The values were normalized by:

$$\text{(atoms/gram)/(ELD)} \qquad (3\text{-}2)$$

Samples from depth were normalized using their density as measured by specific gravity and a half-attenuation length of 132 g/cm^2 (Nishiizumi and others, 1973). The production rate for ^{10}Be was assumed to be 6 atoms/g/year (Nishiizumi and others, 1986), as adjusted for typical rock vs. composition that of quartz.

^{10}Be data, normalized to sea-level cosmic-ray flux are shown in Figure 3-1. The upper line is buildup based upon the measurements of Nishiizumi and others (1986) and a presumed exposure age of 12,000 years for the sample they measured. The slope of this line implies a sea-level production rate for ^{10}Be of 6 atoms gram^{-1} year^{-1}. The lower line is fit to the data of this study, ^{10}Be measurements of rocks with K-Ar dates between 100,000 to 700,000 years, and yields a sea-level production rate of 4 atoms gram^{-1} year^{-1}. Excluding the two samples for which the accompanying blank had high ^{10}Be and B values, there is a predictable buildup of ^{10}Be with time, albeit somewhat lower than would be predicted using the production rates of Nishiizumi and others (1986).

Only semi-quantitative measurements of ^{26}Al (J. Klein, personal communication) were obtained in this study. It appears from these preliminary analyses that analytical sensitivity at the University of Pennsylvania AMS is not sufficient to see ^{26}Al above the background of common Al on whole-rock samples, except, perhaps, in the very oldest (>600,000 years) rocks.

Two major points must be considered in discussion of the ^{10}Be results reported herein. The first is problems which were experienced with the Be extraction and purification, in part due to the complex chemistry of rock samples, and the need to use large (10 grams) samples in order to extract sufficient Be for analysis; the second is the possibility of meteoric ^{10}Be contamination. At this time, however, the acceptably low values obtained for B in the latest analyses indicate that B contamination can be eliminated, and the measurable ^{10}Be/^{9}Be ratios in the analysed rocks show that good extractions can be made.

The latter question is difficult to resolve, due in part to the fact that there currently is no consensus concerning in situ ^{10}Be production rates. At first the rates estimated by Yokoyama and others (1977) were used, and for ^{36}Cl these rates appear to be correct. However, using Yokoyama and others' ^{10}Be production rates, the predicted ^{10}Be/^{9}Be ratios are much lower than those measured. That this is due to the effects of meteoric ^{10}Be has been suggested (J. Klein, K. Nishiizumi, personal communication), but this is is unlikely for several reasons. The pre-extraction leaching, similar to the procedure used in for ^{36}Cl and to that used by Tera and others (1986), is adequate to remove this contaminant. Furthermore, excessive ^{10}Be in the first dozen samples that were processed may be attributed to high ^{10}Be content in the ^{9}Be spike (provided by L. Brown, DTM), a fact noted recently (Tera and others, 1986). Later analyses (Table 3-1) using a cleaner spike provided by Brown still have ratios that are high relative what would be predicted by Yokoyama and others' (1977) data.

More significant is the fact that Yokoyama and others' (1977) production rates may be too low by a factor of 2-4x (Lal and Arnold, 1985; Klein and others, 1986). Use of the higher production rates calculated by Lal and Arnold (1985) or Klein and others (1986) would bring the predicted values into agreement with the values measured (Table 3-1). It is difficult to assess the validity of these production rate estimates since the exposure ages of the materials analysed in the above studies are unknown. Nishiizumi and others (1986) have begun to address the question of in situ ^{10}Be production rates with samples that have better-constrianed ages. Perhaps the greatest strength of the work reported herein is that the calibration suite consists of rocks with well-known ages. In addition, it is possible to reasonably assume the exposure histories of these rocks.

The rocks analysed by Nishiizumi and others (1986) are granitic rocks exposed during the Tioga glaciation in the Sierra Nevada, which they assumed to have been exposed since 12,000 years B.P. While this age is certainly a reasonable estimate for the close of the Tioga (=Wisconsinan; Mickelson and others, 1983) glaciation in the Sierra Nevada (Porter, 1983; Wright, 1983), many Sierra Nevada valleys were completely ice-free by 14,000 years B.P. (Porter, 1983). Hence it is likely that the rocks sampled by Nishiizumi and others (1986) have exposure ages in excess of the 12,000 years they assumed. A more precise determination of exposure age for these samples is difficult to determine inasmuch as precise sample location for these samples have not been made available to date. Brief oral site descriptions and site photographs displayed at two meetings (1986 Fall AGU and the 4th International Symposium on Accelerator Mass Spectrometry) suggest that the sample sites were not at the heads of valleys but somewhere further downslope. If this is indeed the case, an exposure age in excess of 12,000 years seems quite probable. If we assume that the production rate calculated from the data in this study is correct, using the ^{10}Be measurements of Nishiizumi and others (1986) indicates an exposure age of approximately 17,000 years for their samples, not unreasonable in light of the what is known about deglaciation in the Sierra Nevada.

The main objective in the Nishiizumi and others (1986) study was to measure the ratio at production of ^{10}Be and ^{26}Al. This ratio would preclude variations due to changes in cosmic-ray flux, and since the ^{10}Be/^{26}Al at production should be constant throughout the roughly 10,000 year-long period they might have sampled, problems involved with sample depth, exposure aspect, elevations, and ages are likewise eliminated. The calculation of sea-level production rates for these isotopes, however, demands precise knowledge of these factors, most importantly an accurate estimate of exposure age. While the ^{10}Be measurements made by Nishiizumi and others (1986) are certainly of high quality and the samples are applicable to their purposes, if sea-level production rates are to be derived it would be useful to examine these data in the context of more rigorous geological constraints.

3.5 Summary

The dated rocks used in this study provide the best-constrained samples currently available for assessment of ^{10}Be and ^{26}Al buildup in situ in earth surface materials. Measured ^{10}Be buildup in these rocks shows that there is a predictable buildup of ^{10}Be with time, but at a rate lower than that favored in recent publications. The large amount of common Al in rocks and the present detection limit for ^{26}Al by AMS precludes analysis of this isotope at this time.

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TABLE 3-1

^{10}Be PRODUCTION RATE ESTIMATES AND MEASURED ^{10}Be/^{9}Be RATIOS

SAMPLE	PRED. RATIO 1	PRED. RATIO 2	PRED. RATIO 3	MEASURED RATIO
SLR-2*	$9.5\text{x}10^{-14}$	$2.86\text{x}10^{-13}$	$4.76\text{x}10^{-13}$	$5.63\text{X}10^{-13}$
MC84-3#	$1\text{x}10^{-13}$	$3\text{x}10^{-13}$	$4.2\text{x}10^{-13}$	$2\text{x}10^{-13}$

Predicted ratios: (1) using Yokoyama and others' (1977) production rates
(2) using Lal and Arnold's (1985) production rates
(3) using Klein and others' (1986) production rates

SAMPLE	MEASURED RATIO	^{10}Be (atoms/gram)
SLR-7#	$1.8\text{x}10^{-13}$	$1.4\text{x}10^{6}$
C-41#	$0.9\text{x}10^{-13}$	$0.72\text{x}10^{6}$
SG-1A#	$2.3\text{x}10^{-13}$	$1.9\text{x}10^{6}$
C-40#	$1.4\text{x}10^{-13}$	$1.1\text{x}10^{6}$

Analyses performed at: *University of Pennsylvania, February 1986
#ETH Zurich, January 1987

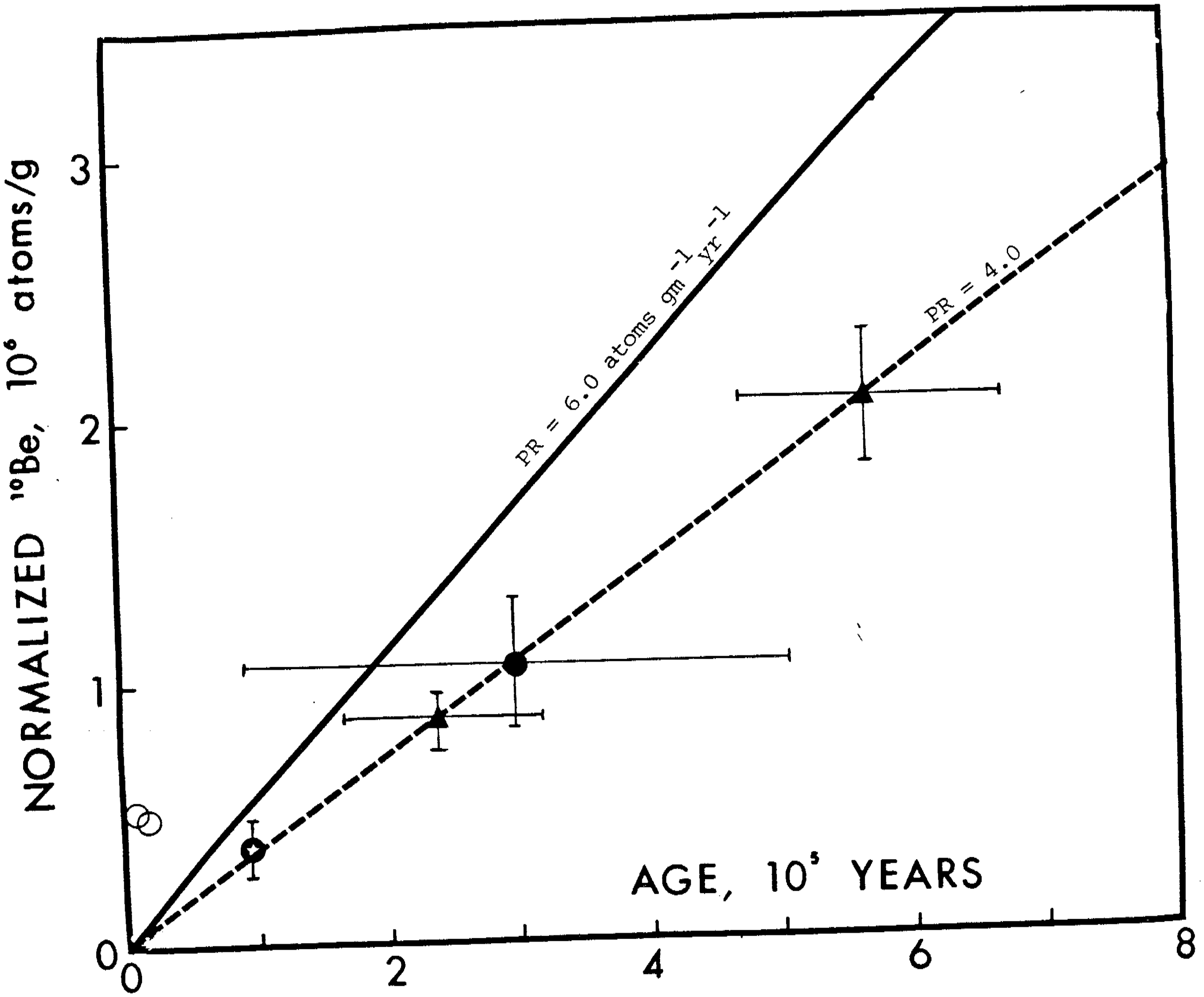

Figure 3-1: Normalized ^{10}Be (10^6 atoms/gram rock) vs. sample age.

Part 4: $^{36}Cl/Cl$ in Young Basalts from the Aden-Afton Basalt Field and Mesilla Park, New Mexico

4.1 Introduction

In a first application of ^{36}Cl buildup dating, it was decided to use this method to date several young volcanic rocks which were previously undateable, or had ages that conflicted with geologic field relations. The ^{36}Cl buildup curve presented in Part 2 is preliminary and requires refinement before it may be applied widely to dating young rocks. It seemed reasonable, however, to use this method to date a suite of rocks which are fairly uniform in composition, which probably have been little affected by heavy seasonal snow accumulation, and for which a fair amount of correlative geologic data is available.

One area well-suited to this application is the region of the Aden-Afton-Santo Tomas basalts in the southern Rio Grande rift, New Mexico. Here, 5 basalt flows extruded upon the La Mesa surface (thought to have stabilized about 0.6-0.7 million years ago; Machette, 1985) have been dated by K-Ar by three different laboratories (Mobil-Geochron, U.S. Geological Survey and University of Arizona). Reported dates range from several hundred thousand to several million years, but the most recent dates at 0.5-0.53 million years (Seager and others, 1984) are considered to be most accurate. There are problems with accepting these dates, however, in that they conflict with data related to soil development (Gile, 1987) and the geomorphology of the region (Hawley and Kottlowski, 1969; Seager and others, 1984).

4.2 Geologic setting

The area of interest lies southwest of Las Cruces, New Mexico, between the Mesilla valley and the Potrillo Mountains (Figure 4-1). This area comprises the central and eastern portions of the Potrillo volcanic field as defined by Hoffer (1971). The central section includes a series of maars (Kilbourne Hole, Hunt's Hole, and others), isolated small cinder and splatter cones, and flows (Aden Crater and associated flows, and the Afton volcanics). The eastern section, called by Hoffer (1971) the Santo Tomas-Black Mountain basalt field, includes four major centers, Santo Tomas, San Miquel (the Finger Flow), Little Black Mountain, and Black Mountain. Although Santo Tomas and Black Mountain each comprise several flows, none of the flows from these different centers is in contact with flows from any other center. They do, however, appear to be closely related to each other in time.

The basalts in this region are of particular importance to the geomorphology of the Rio Grande valley. All of these flows lie upon the La Mesa surface, which stabilized at 600,000-700,000 years ago (Machette, 1985; Seager and others, 1984) based upon radiometric dating of volcanic ash lenses (620,000 and 700,000 years) near the constructional top of formations just below the La Mesa surface. Three of the flows in the eastern section have their sources in cones on the La Mesa surface, but flowed downslope in modern drainage channels almost to the present level of the Rio Grande. Thus the age of extrusion of these flows indicates the interval of time during which the river has cut from the La Mesa surface to its present level.

Some of the first K-Ar dates (Mobil-Geochron, Table 4-1) placed these flows at 100,000-300,000 years ago (Hoffer, 1971), allowing about

200,000-400,000 years for the entrenching of the river. These were later rejected by Seager and others (1984) due to the fact that multiple dates for these same flows determined by the same lab were in the several million-year range (Table 4-1). Later, these same flows were dated by the U.S. Geological Survey and by the University of Arizona (Seager and others, 1984). These dates (Table 4-1) placed all of the central and eastern Potrillo volcanics in the range of 500,000-530,000 years B.P. While this age range allows only 100,000-200,000 years for the river to have cut its present valley, the consistency in the ages determined by two different laboratories led Seager and others (1984) to consider them accurate, and to crowd the late-middle Pleistocene events into a narrow time interval.

Geomorphic data presented by Seager and others (1984), however, cause these ages to be questioned. In the Aden-Afton area, the lowermost of the Afton flows, exposed in Kilbourne Hole, has a thick soil developed on it, which is then overlain by the second Afton flow. This second flow in turn is overlapped to the west by flows from Aden Crater. Both the lowermost Afton Flow and the Aden Crater lava lake were dated at 0.53 million years, which would allow little, if any, time for soil development in the area. Recent work by Gile (1987) on soil development in the central Potrillo area suggests a maximum age of 100,000 years for the lowermost Afton basalt. Somewhat less compelling is the evidence for the age of the youngest eruptions of Aden Crater provided by ^{14}C dating of the remains of a ground sloth, recovered from a lava cave on the cone (Simons and Alexander, 1964), at 11,080±200 years.

4.3 Sampling

Samples were taken from each flow as close as possible to the site(s) previously sampled for K-Ar analysis. In the case of the Finger Flow, Santo Tomas, and the upper Afton flow, Dr. John Hawley, who originally sampled the flows for K-Ar, re-located these sites in the field. At Aden crater and the lower Afton flow the situation was more difficult since these had been sampled by other workers, and since outcrops suitable for ^{36}Cl dating were more difficult to locate. For this reason it is doubtful that the same Aden flow unit was sampled for this study. The lower Afton flow was sampled on a hummock which protrudes above the soil south of Kilbourne Hole. This site may have been covered and exhumed in the period since emplacement, and hence was very likely entirely buried for part of its "exposure" history.

4.4 Preparation and analysis

The samples were prepared by splitting to remove any surface rind and then crushed and sieved to <100 mesh (Murphy, unpublished LANL manual). The ground samples were leached with deionized water to remove pore-water meteoric chloride. After leaching, the rock powders were digested by total fusion with NaOH and dissolved in deionized water. Chloride was precipitated from this solution as AgCl by addition of an excess of $AgNO_3$. Since ^{36}S is an interfering nuclide in AMS analysis of ^{36}Cl, the AgCl was carefully purified by repeated dissolution in NH_4OH and reprecipitation with HNO_3. This procedure is described in detail in Appendix 14.

$^{36}Cl/Cl$ ratios were determined using the TAMS at the Nuclear Structure Research Laboratory at the University of Rochester (Elmore and other, 1979), with long-term reproducibility of approximately 5%. Whole-rock major and minor element analyses were performed by x-ray fluorescence and neutron-activation analysis at the Los Alamos National Laboratory.

4.5 Results and discussion

Measured $^{36}Cl/Cl$ and calculated buildup ages for the samples are shown in Table 4-2. Exposure ages determined using measured ^{36}Cl buildup and the curve calibrated in Part 2 place the Santo Tomas-Finger Flow basalts at 45,000-250,000 years. These dates allow a more reasonable span of time for the Pleistocene erosion of the Rio Grande. Results from the Aden-Afton area are less encouraging; ^{36}Cl buildup suggests ages of 8,236 years for Aden Crater and 10,760 years for the lowermost Afton flow. The Afton date is very likely in error for several reasons: 1) this young age would allow little time for development of the soils overlying the lower Afton flow before extrusion of the younger basalts; 2) Kilbourne Hole, which pierces the lower Afton flow, has been fairly reliably dated at 24,000 years by Gile (1987), suggesting that the lower Afton flow should be much older; and probably most important, 3) the probability that the lower Afton sampling site had been covered would account for the very low ^{36}Cl buildup in this rock. The Aden Crater date is merely equivocal, due to the fact that it is likely that the same "lava lake" unit previously dated was not sampled. If the date measured for the sloth found associated with the crater is accepted as a minimum age for volcanic activity at this site, the ^{36}Cl date may appear somewhat more reasonable.

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TABLE 4-1: UNDATED OR EQUIVOCALLY DATED YOUNG VOLCANIC ROCKS

LOCALITY	USGS QUAD	AGE(MY), ANALYST
San Miguel FF-1	Black Mesa 7.5	0.49+/-0.02 Arizona
		1.91+/-0.1 Mobil&Geochron
		0.232+/-0.8 Mobil&Geochron
		0.154+/-0.119 Mobil&Geochron
Santo Tomas ST-1,2	Black Mesa 7.5	0.55+/-0.03 Arizona
		2.68+/-0.35 Mobil&Geochron
		0.165+/-0.079 Mobil&Geochron
		0.131+/-0.131 Mobil&Geochron
Aden Crater	Aden 15	0.533+/-0.04 Arizona
Afton AF-1	Afton 15	
AF-2	Noria 15	0.053+/-0.03 USGS
		0.52+/-0.1 Mobil&Geochron
		0.144+/-0.077 Mobil&Geochron
		0.106+/-0.086 Mobil&Geochron

TABLE 4-2: DATA FOR UNKNOWN SAMPLES DATED USING 36Cl GEOCHRONOMETER

SAMPLE	LATITUDE (N)	LONGITUDE (W)	ELEV (m)	DEPTH (cm)	S.G. (gm/cm^3)	K_2O (wt.%)	CaO (wt.%)	Cl (ppm)	n ABS$_{(tot)}$ (cm^2/kg)	$^{36}Cl/Cl\times10^{-15}$ (measured)	$^{36}Cl/Cl\times10^{-15}$ (initial)	$^{36}Cl/Cl\times10^{-15}$ (normalized)	CALCULATED AGE (years)
AC-1	32°04'12"	107°03'36"	1356	10	2.50	1.82	9.77	173	7.03	140±5	15	56±2	8,236±217
AF-2	31°56'30"	106°57'48"	1265	10	2.44	1.62	10.93	25	7.21	614±46	11	73±6	10,768±707
ST-1	32°10'12"	106°45'42"	1216	100	2.65	1.87	9.44	376	7.59	405±5	15	920±11	160,253±1,636
ST-2	32°12'48"	106°46'24"	1219	150	2.24	1.77	9.29	298	7.15	434±48	15	1308±145	250,779±22,380
FF-1	32°07'24"	106°45'18"	1219	10	2.68	1.67	9.50	323	6.79	427±44	14	290±30	44,447±3,707

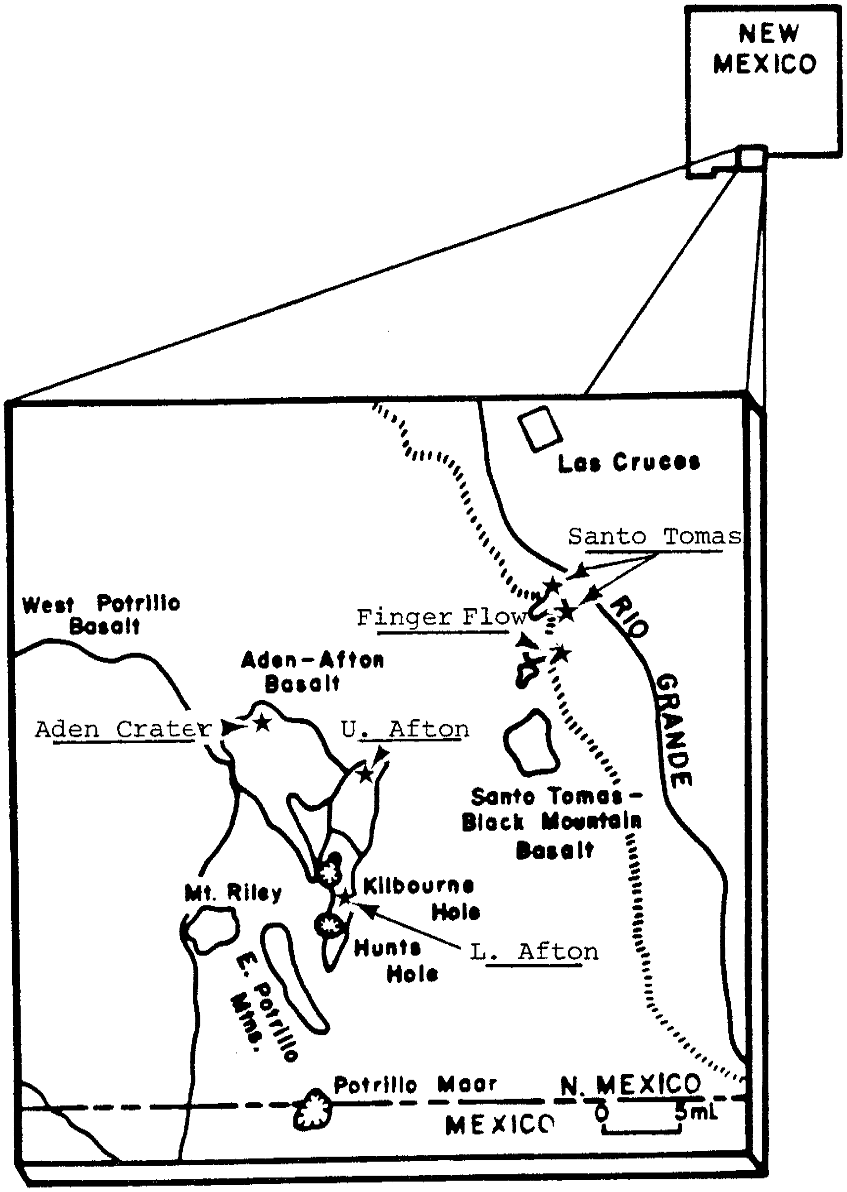


Figure 4-1: Index map of the Potrillo Volcanics

Summary and suggestions for future work

The study reported herein is the first to use AMS in an attempt to experimentally verify whole-rock in situ production rates for ^{36}Cl and ^{10}Be in terrestrial rocks. A major strength of this study is the use of a suite of well-dated volcanic rocks for which exposure histories could be reasonably assumed. In situ buildup of both ^{36}Cl and ^{10}Be is predictable, but production rates determined in this study for these isotopes are somewhat lower than would be predicted from published theoretical rates.

In situ buildup rates for ^{36}Cl will require refinement through the analysis of samples selected specifically to assess the rates of the various production mechanisms for ^{36}Cl before buildup of this isotope may be widely applied to surface-exposure dating. The results reported herein, however, indicate that such dating is feasible, and suggest that ^{10}Be buildup may be useful as well.

Future research should be in several different areas, including:

1) Acquisition of additional samples for calibration work. Specifically, basaltic rocks less than 200,000 years old, and felsic rocks older than about 100,000 years will help to address production ^{36}Cl spallation rates from K vs. Ca. Ideally, these rocks would be from the primary sampling regions, i.e., areas without appreciable snowfall.

2) Sampling through vertical sections of flows to test cosmic-ray attenuation with depth. This might be done best by the use of cores. At the beginning of the study reported herein, the Cl extraction procedure used was not highly efficient. Large volumes (approximately 0.5-1 kg) of rock were required to leach sufficient Cl for analysis; this did not

allow the use of the relatively small samples obtainable by coring.

The total fusion procedure which was used later allows the use of much smaller (a few grams) samples. Short sections of cores of the type commonly used for paleomagnetic work may now be used, and these can provide precise depth control and accurate estimation of overlying rock density. The use of cores will also allow sampling virtually anywhere on the surface of a lava flow, so that areal variation of cosmogenic nuclide buildup may be tested.

3) The leaching procedures used prior to extraction of the elements of interest should be evaluated in more detail than was possible to date. Both total chloride and ^{36}Cl/Cl, or ^{10}Be/^{9}Be, should be measured in both rock powders and leachates following several successive stages of leaching. This will aid in assessing the optimum leaching method for various rock types.

4) Since in situ cosmogenic isotope buildup dating measures surface-exposure time, not dates of closure of an isotopic system, they have potential for broad application beyond simple rock dating. One promising area of application is the dating of glacial moraines; another is in the area of neotectonics.

Rocks previously shielded from cosmic rays below the surface may be suddenly exposed through faulting. Cosmogenic nuclides will begin to accumulate at the time a rock is exposed; assuming that any amount of cosmogenic isotope present in the rock before burial can be estimated or has decayed before exposure, buildup since the time of faulting may be determined. The buildup in this case will date the fault, not the age of the rock. If sufficient previously-shielded rock is exposed by a fault, it may even be possible to determine rates of faulting through the measurement of cosmogenic isotope buildup.

5.1: APPENDIX 1

SITE AND SAMPLE DESCRIPTIONS

SAMPLE: DA-1 ROCK TYPE: basalt LOCAL NAME: Cat Hills

FULL SAMPLE NUMBER: DA830902-1 DATE COLLECTED: 2 September 1983

SITE DESCRIPTION: Site is a shallow roadcut on a farm road 1/2 mile due north of MP7 on the Isleta Grant boundary. Flow rests on sandy Santa Fe Formation, and low spots on upper surface are covered with a thin soil.

SAMPLE DESCRIPTION: Medium grey, amygdaloidal basalt; weathers to buff. Fresh olivine and feldspar phenocrysts are set in a medium-grained groundmass, and amygdales aree filled with calcite, or less commonly, a fibrous zeolite. Surface of the block sampled is coated with caliche that extends along fractures.

ADDITIONAL COMMENTS: Kudo's QB-1 flow.

SAMPLE: DA-2 ROCK TYPE: basalt LOCAL NAME: Cat Hills

FULL SAMPLE NUMBER: DA830902-2 DATE COLLECTED: 2 September 1983

SITE DESCRIPTION: Sample taken from the top of the southernmost prong of the QB-1 flow,about 30 meters north of N.M. Route 6.

SAMPLE DESCRIPTION: Medium grey, amygdaloidal basalt showing flow lineation. Feldspar is most abundant phenocryst with olivine subordinate.

ADDITIONAL COMMENTS: Kudo's QB-1 flow.

SAMPLE: SG-1A,B,C ROCK TYPE: basalt LOCAL NAME: Cerro Verde flow

FULL SAMPLE NUMBER: SG830902-1A, SG830902-1B, SG820902-1C

DATE COLLECTED: 2 September 1983

SITE DESCRIPTION: Southernmost end of "Black Mesa," formed by the Cerro Verde flow, which follows the drainage of the Rio San Jose, where N.M.

Route 6 cuts up through the flow in a 3-5m thick roadcut. The flow lies on sediments of the Santa Fe Formation, mostly cobbles and gravels, but sparse cross-bedded sands; a thin soil lies on top. From top to bottom, the flow is sparsely vesicular for 1 meter or so; dense and crudely jointed for 2 meters; then sparsely vesicular for the bottom meter or so. Caliche coats surfaces near the top, fractures or joints that extend through the section, and the bottom contact. A section was sampled about 50 meters from the southern end of the roadcut: SG-1A is from the top of the flow; SG-1B is from the bottom contact at 3.3 meters; SG-1C is from the dense central section at 2 meters.

SAMPLE DESCRIPTION: SG-1A is a fresh, grey, vesicular glassy basalt with sparse olivine phenocrysts; SG-1B is similar, but with more prominent vesicles, many filled with carbonate; SG-1C is very fresh, grey, medium-grained glassy basalt.

ADDITIONAL COMMENTS: Roadcut is less than 10 years old, hence surface is very fresh. Also known as the "Suwanee" or the "Rio San Jose" flow.

SAMPLE: LG-1A,B ROCK TYPE: basalt LOCAL NAME: Albuquerque Volcanics

FULL SAMPLE NUMBER: LG830902-1A, LG830902-1B

DATE COLLECTED: 2 September 1983

SITE DESCRIPTION: South side of mesa immediately west of Coors Road, 1/2 mile west of Atrisco Drive and immediately north of a small residential landfill. There are two thin flows exposed at the mesa rim, an upper 1/2m thick flow which has well-developed ropy surface features, and a lower 1-2m thick flow which rests upon sandy Santa Fe Formation. LG-1A sample is from the top 25cm of the upper flow, at the point where the unimproved road cuts onto the top of the mesa. LG-1B is from a block adjacent to LG-1A.

SAMPLE DESCRIPTION: Grey, fresh medium-grained basalt with sparse, round vesicles. Feldspar laths are abundant, olivine sparse.

ADDITIONAL COMMENTS: Kelley and Kudo's QB-1 flow.

SAMPLE: CZ-1,2 ROCK TYPE: basalt LOCAL NAME: Carrizozo

FULL SAMPLE NUMBER: CZ830909-1, CZ830909-2

DATE COLLECTED: 9 September 1983

SITE DESCRIPTION: The upper Carrizozo flow was sampled at a small cave about 30 meters north of U.S. 380; the site is in the middle of the flow, across from a small turnout about 1 mile NW from the Valley of Fires State Park entrance. CZ-1 is from the roof of the cave at 4.5 meters depth; CZ-2 is at the entrance to the cave, immediately below (1/2m) the outer ropy, vesicular zone of the flow.

SAMPLE DESCRIPTION: CZ-1 is fresh, grey, medium-grained, micro-vesicular basalt with abundant fresh olivine and plagioclase phenocrysts. CZ-2 is similar, but with larger vesicles.

SAMPLE: BK-1 ROCK TYPE: basalt LOCAL NAME: Broken Back Crater

FULL SAMPLE NUMBER: BK830909-1 DATE COLLECTED: 9 September 1983

SITE DESCRIPTION: NW side of the crater rim, facing SE, in one of the few dense flows that alternate with the cinder layers that form the crater.

SAMPLE DESCRIPTION: Dense, grey basalt with strings of fine vesicles and large fresh olivine phenocrysts. Surface covered with thin brown varnish.

SAMPLE: VV-1 ROCK TYPE: basalt LOCAL NAME: Jornada del Muerto

FULL SAMPLE NUMBER: VV830618-1 DATE COLLECTED: 18 June 1983

SITE DESCRIPTION: Site is on a pressure ridge 0.3 miles west of the ranch road leading north from Harriet Ranch, 0.7 miles north of the ranch. Sample is from a dense zone exposed in the center of a split ridge.

SAMPLE DESCRIPTION: Medium grained grey amygdaloidal basalt; abundant plagioclase laths, fresh olivine, and sparse carbonate in matrix.

SAMPLE: AC-1 ROCK TYPE: basalt LOCAL NAME: Aden Crater

FULL SAMPLE NUMBER: AC831215-1 DATE COLLECTED: 15 December 1983

SITE DESCRIPTION: South side of a broad fissure running E-W across the center of the crater. Sample is from a small rise in this depression and may be related to a small spatter cone in the center of the crater.

SAMPLE DESCRIPTION: Dark grey, vesicular, medium-grained basalt with abundant olivine phenocrysts up to 2mm in size; larger vugs are filled with calcite. Rock has a thin brown varnish.

ADDITIONAL COMMENTS: Damon's UAKA79-130 sample.

SAMPLE: AF-1 ROCK TYPE: basalt LOCAL NAME: Afton volcanics

FULL SAMPLE NUMBER: AF831215-1 DATE COLLECTED: 15 December 1983

SITE DESCRIPTION: Uppermost Afton flow immediately SW of Afton railway crossing. Flow lies upon a thick soil which covers the lower flows; sample is from a large lobe of this flow.

SAMPLE DESCRIPTION: Grey, dense, finely vesicular basalt. Abundant small, fresh olivine and plagioclase, sparse calcite in groundmass.

SAMPLE: AF-2 ROCK TYPE: basalt LOCAL NAME: Afton volcanics

FULL SAMPLE NUMBER: AF831215-2 DATE COLLECTED: 15 December 1983

SITE DESCRIPTION: Lowermost Afton flow, the same that crops out within Kilbourne Hole. This flow is covered with a thick soil; sample is from a knob which projects through the soil about halfway between Kilbourne Hole and Hunt's Hole.

SAMPLE DESCRIPTION: Grey, fine-grained vesicular basalt, weathering to brown, with sparse fresh 2mm olivine phenocrysts.

ADDITIONAL COMMENTS: Mehnert's D2720R flow.

SAMPLE: KH-1,2,3,4 ROCK TYPE: peridotite LOCAL NAME: Kilbourne Hole

FULL SAMPLE NUMBER: KH831215-1, KH831215-2, KH831215-3, KH831215-4

DATE COLLECTED: 15 December 1983

SITE DESCRIPTION: NW side of Kilbourne Hole, facing SE on the rim of the tuff ring. All four peridotite nodules selected from the surface within a 100-meter radius.

SAMPLE DESCRIPTION: All of the nodules have a basaltic rind which is visible on their underside; the upper side of the nodules is coated with caliche. KH-1 is a 10cm-diameter lherzolite, grain size 1-2mm, with a 1cm basalt rind; KH-2 is a 10cm-diameter harzburgite with very sparse green diopside, grain size 1-3mm, 3mm basalt rind; KH-3 is a 12x5cm lherzolite, grain size <1mm, with a 50mm basalt rind; KH-4 is a 10x5x4cm lherzolite, grain size 1mm, 3mm basalt rind. All are crumbly when broken.

SAMPLE: ST-1 ROCK TYPE: basalt LOCAL NAME: Santo Tomas

FULL SAMPLE NUMBER: ST831216-1 DATE COLLECTED: 16 December 1983

SITE DESCRIPTION: Next to lowermost flow from Santo Tomas Mountain to the NW, at SE end of an arroyo due west of the south end of Stahmann Farms airfield. Sample is at 1.5 meters below the top of a scarp exposed by a recent rock fall. Outer surface is coated with caliche which also lines cracks.

SAMPLE DESCRIPTION: Dark grey, dense, medium-grained vesicular basalt with sparse 2-3mm olivine an <1mm plagioclase phenocrysts.

ADDITIONAL COMMENTS: Mehnert's D2719R flow.

SAMPLE: ST-2 ROCK TYPE: basalt LOCAL NAME: Santo Tomas

FULL SAMPLE NUMBER: ST831216-2 DATE COLLECTED: 16 December 1983

SITE DESCRIPTION: Lowermost flow sampled on south side of an arroyo at SW side of the athletic field on the NE side of the mesa. Sample is from 1/2m below the top of the mesa rim; entire section is coated with up to 1cm caliche.

SAMPLE DESCRIPTION: Grey, fine-grained vesicular basalt with abundant 1-2mm olivine phenocrysts.

SAMPLE: FF-1 ROCK TYPE: basalt LOCAL NAME: Finger Flow

FULL SAMPLE NUMBER: FF831216-1 DATE COLLECTED: 16 December 1983

SITE DESCRIPTION: Extreme SE end of flow where it leaves the scarp and into the Rio Grande drainage. Sample is 2 meters from the top of the flow on a face exposed by a recent rockfall.

SAMPLE DESCRIPTION: Dark grey, dense, very glassy basalt, weathering to brown with a thick varnish; abundant fresh 1mm olivine, <1mm plagioclase phenocrysts.

ADDITIONAL COMMENTS: Mehnert's D2725R flow. Also known as the San Miguel flow.

SAMPLE: GR-1 ROCK TYPE: basalt LOCAL NAME: McCarty's flow
FULL SAMPLE NUMBER: GR830910-1 DATE COLLECTED: 10 September 1983
SITE DESCRIPTION: Site is on the south side of the east end of the roadcut where the flow crosses I-40 immediately west of Stuckey's. Sample is from within a fissure, 40-65cm below the top of the flow.
SAMPLE DESCRIPTION: Dark grey, medium-grained vesicular basalt with sparse plagioclase microphenocrysts.

SAMPLE: LA-1 ROCK TYPE: basalt LOCAL NAME: Laguna basalt
FULL SAMPLE NUMBER: LA830910-1 DATE COLLECTED: 10 September 1983
SITE DESCRIPTION: Shallow roadcut at rest stop SE of Laguna pueblo on th south side of I-40. Sample from 80cm below surface along a 2m high cut; upper surface is covered with a thin layer of blown sand.
SAMPLE DESCRIPTION: Fresh, dark grey fine-grained microvesicular basalt with abundant fresh olivine phenocrysts.

SAMPLE: NSCB-1 ROCK TYPE: basalt LOCAL NAME: Bonito flow
FULL SAMPLE NUMBER: NSCB-1 DATE COLLECTED: October 3, 1983
SITE DESCRIPTION: Sample is from top of a small pressure ridge on the NW margin of the Bonito flow, near an aspen scarred by a rock hammer. Its source, Sunset Crater, is to the SE. Tephra fills many of the low spots on the flow, to several meters in places where the soil supports large (6" diameter) trees, but there is little tephra or soil on the high spots of the flow. Most surfaces are weathered and covered with lichen.

SAMPLE DESCRIPTION: Grey, scoriaceous basalt, with sparse phenocrysts of olivine, ranging from moderately fresh core to weathered exterior.
ADDITIONAL COMMENTS: Sample collected by L. David Nealey, USGS Flagstaff.

SAMPLE: SF-1 ROCK TYPE: dacite LOCAL NAME: Sunflower Dome
FULL SAMPLE NUMBER: SF840614-1 DATE COLLECTED: 14 June 1984
SITE DESCRIPTION: Unit sampled is a dacite block lava flow NE of Manzanita Campground, immediately adjacent to the south side of State Rte. 44 (Lassen Park Road). Sample taken from a large block on the upper surface of the dome, facing NW.
SAMPLE DESCRIPTION: Very fresh, glassy grey dacite, in part finely vesicular.
ADDITIONAL COMMENTS: Clynne's LC81-660, LC84-410 Sunflower Flat samples. California snow course 343, New Manzanita Lake. This area has snow from the third week of November through April 1, commonly ranging from 12-18". However, it is in a "warm pocket" that frequently is bare for long periods during the winter.

SAMPLE: DE-1 ROCK TYPE:andesite LOCAL NAME: Lassen Devastated area
FULL SAMPLE NUMBER: DE840614-1 DATE COLLECTED: 14 June 1984
SITE DESCRIPTION: Site is on the east side of the toe of a debris flow from Mt. Lassen to the SW. A thin soil has developed on this flow but bare sections of the flow, probably never covered, show through.
SAMPLE DESCRIPTION: Fresh, grey to black glassy andesite, with prominent dark mafic inclusions and abundant feldspar phenocyrsts.
ADDITIONAL COMMENTS: This is a "hybrid" andesite, as described by

Clynne, a fragment of the May 19, 1915 lava flow entrained in the May 19 debris flow. California snow course 47, Lower Lassen Peak. This area, Emigrant Pass, has snow from the third week of November through mid-May, with a maximum of 10-12' depth (average 6').

SAMPLE: L683-A,B ROCK TYPE: rhyodacite LOCAL NAME: rhyodacite of Reading Peak

FULL SAMPLE NUMBER: LL683-A, LL683-B DATE COLLECTED: 14 June 1984

SITE DESCRIPTION: Samples are from a small quarry about 100 meters NW of Lassen Park Road, on the south side of a flow from Reading peak to the west. L683-A is from 6.5 meters below top of quarry wall; L683-B is from the top of the same wall. Thin soil has developed in places, but much of the upper surface of the flow has never been covered.

SAMPLE DESCRIPTION: Fresh, pale grey rhyodacite with small, sparse phenocrysts; glassy matrix is devitrified.

ADDITIONAL COMMENTS: Clynne's LC81-683 sample. California snow course 47 Lower Lassen Peak. Site is on the east side of Reading Peak, which has snow from the third week of November through the first week of May. Snow depth ranges from 1-2' with an average of 18". This is a warm, southern exposure that tends to melt out during the season while the bowl formed by the quarry collects much more than the average accumulation; indeed, on the sampling date there was 3-4' of snow drifted in the lower quarry.

SAMPLE: L915-A,B ROCK TYPE: dacite LOCAL NAME: Kings Creek flow

FULL SAMPLE NUMBER: LL915-A, LL915-B DATE COLLECTED: 14 June 1984

SITE DESCRIPTION: Samples are from along Kings Creek, taken from a flow which originated from Lassen Peak to the NW. L915-A is from 3 meters below the top of a roadcut on the SW side of Lassen Park Road, SW of Terrace Lake. L915-B is from the top of the same unit NW of Reading Peak, about 50 meters NW of Lassen Park Road.

SAMPLE DESCRIPTION: Fresh, medium-grey glassy dacite (L915-B is a bit less fresh, showing devitrification of glass.

ADDITIONAL COMMENTS: Clynne's LC82-915 sample. A Tioga-age glacier stripped off the pumiceous carapace of this flow throughout this area, giving this flow an effective exposure age of 8,000 years. California snow course 47, Lower Lassen Peak. This area has snow from the third week of November through the third week of June, ranging in depth from 10-20'; snow may remain into July in some years. There was 3-6' of snow on the roadcut when the flow was sampled, but the L915-B site was free of snow.

SAMPLE: L123-1,2,3 ROCK TYPE: andesite LOCAL NAME: andesite of Bluff Falls

FULL SAMPLE NUMBER: LL123-1, LL123-2, LL123-3

DATE COLLECTED: 14 June 1984

SITE DESCRIPTION: Samples were taken about 50 meters west of State Road 89 (Lassen Park Road) in the Bluff Falls quarry, from a vertical face of roughly 30 meters. Sample 1 is from the top of the quarry wall; sample 2, 10 meters below this on the north side of the quarry; sample 3 at approximately the same level as 2, but near to the center of the quarry wall.

SAMPLE DESCRIPTION: Fresh, medium-grey, glassy andesite.

ADDITIONAL COMMENTS: Clynne's LC80-123 sample. California snow course 51, Harkness Flat. This area has snow from the third week of November through the first week of April, ranging in depth from 1-3', but may be bare for several week-long periods during the winter.

SAMPLE: L724-1,2 ROCK TYPE: rhyodacite LOCAL NAME: Loomis rhyodacite
FULL SAMPLE NUMBER: LL724-1, LL724-2 DATE COLLECTED: 15 June 1984
SITE DESCRIPTION: Outcrop is on the NE side of a shallow roadcut at the junction of State Roads 44 and 89, about 100 meters NW of the Lassen park entrance station. Outcrop has about 3-4 meters vertical exposure. Non-glacial soil has developed in the top 50 cm; below this is an inversely-bedded pyroclastic flow with clasts ranging from pebble to boulder size. Sample 1 is from the top of a 1-meter diameter boulder at 3 meters depth in the fresh pyroclastic flow; sample 2 is from the interior of a 50-cm diameter boulder at the base of the soil zone.
SAMPLE DESCRIPTION: Fresh, pale grey pumiceous rhyodacite with abundant fresh biotite phenocrysts.
ADDITIONAL COMMENTS: Clynne's LC81-724 sample. California snow course 343, New Manzanita Lake. Snow in this area lasts from the third week of November through the first week of April, ranging in depth from 18"-6', most commonly average 2'.

SAMPLE: L391 ROCK TYPE: andesite LOCAL NAME: andesite of Viola
FULL SAMPLE NUMBER: LL391-1 DATE COLLECTED: 15 June 1984
SITE DESCRIPTION: Sample from center of a 50-cm block on the top of a block andesite flow along North Fork Bailey Creek; source is a small cone to the NE. The outer 1-2 cm of the blocks is altered, but the core appear fresh. Soil, which supports large (to 10" diameter) trees, fills the low spots on this flow, but tops of most lobes are clear.

SAMPLE DESCRIPTION: Dark grey to black, vesicular andesite with prominent plagioclase phenocrysts. Matrix appears fresh but there is some staining on the plagioclase.

ADDITIONAL COMMENTS: Clynne's LC80-391 sample. California snow course 343, New Manzanita Lake. This area has intermittent snow cover; it is on a southern exposure that normally melts off immediately after storms. Clynne's LC80-391 is from a denser core of this flow at 3-5 meters depth.

SAMPLE: L564 ROCK TYPE: rhyodacite LOCAL NAME: rhyodacite of Manzanita

FULL SAMPLE NUMBER: LL564 DATE COLLECTED: 15 June 1984

SITE DESCRIPTION: Surface of this flow is very rough and hummocky, with thick (<1 meter) soil developed over entire surface; spines of rock project though this in many places. Sample was taken 1 meter below the top of one of these spines in a shallow roadcut.

SAMPLE DESCRIPTION: Fresh, white rhyodacite with abundant dark mafic phenocrysts.

ADDITIONAL COMMENTS: This sample was mis-numbered in the field; it actually corresponds to Clynne's LC80-534. California snow course 343, New Manzanita Lake.

SAMPLE: BL-1 ROCK TYPE: basalt LOCAL NAME: basalt of Butte Lake

FULL SAMPLE NUMBER: BL840616-1 DATE COLLECTED: 16 June 1984

SITE DESCRIPTION: Block lava flow west of Butte lake, the northern end of the "Fantastic Lava Beds"; source is Crater Butte to the SW. Blocks range in size from football- to Volkswagen-size (about 20cm to 3m). Many blocks have a rough, vesicular surface, but most are dense and smooth, with a very thin brown rind. Sample is from the top of a dense, 1-2 meter diameter block in a low spot on the surface of the flow.

SAMPLE DESCRIPTION: Dense, pale-grey glassy basalt with sparse fresh olivine phenocrysts.

ADDITIONAL COMMENTS: California snow course 51, Harkness Flat. Area has snow from the third week of November through the first week of May, with a maximum depth of 4-5'; snow does not usually melt off during winter.

SAMPLE: MC-1 ROCK TYPE: rhyolite LOCAL NAME: Devil's Punch Bowl

FULL SAMPLE NUMBER: MC840629-1 DATE COLLECTED: 29 June 1984

SITE DESCRIPTION: Site is about 2 miles NE of June Lake Junction on U.S. 395. The Punch Bowl is a depression between the two southernmost cones in the main Mono Craters chain. Sample is from the NE side of a small blocky cone at the center of the Punch Bowl.

SAMPLE DESCRIPTION: Grey, pumiceous rhyolite which weathers to brown; abundant white feldspar phenocrysts, sparse black mafic inclusions.

ADDITIONAL COMMENTS: Dalrymple's 6G006 sample. The entire surface surrounding the cones is littered with small black obsidian bombs. California snow course 208, Mammoth.

SAMPLE: SLR-2 ROCK TYPE: rhyolite LOCAL NAME: Devil's Punch Bowl

FULL SAMPLE NUMBER: SLR-2 DATE COLLECTED: 23 October 1983

SITE DESCRIPTION: Sample from near summit of small cone in the Punch Bowl.

SAMPLE DESCRIPTION: Grey to pink rhyolite, weathers to brown. Finely pumiceous texture with abundant 1-2mm quartz, feldspar phenocrysts and sparse, smaller brown biotite.

ADDITIONAL COMMENTS: Dalrymple's 6G006 sample. Sample collected by Fred Phillips and Nancy Jannik. California snow course 208, Mammoth.

SAMPLE: MC-2 ROCK TYPE: rhyolite LOCAL NAME:

FULL SAMPLE NUMBER: MC840629-2 DATE COLLECTED: 29 June 1984

SITE DESCRIPTION: Site is on the NW side of the dome immediately NE of the Punch Bowl. Sample taken from a pinnacle that projects through soil.

SAMPLE DESCRIPTION: Dark grey, pumiceous rhyolite.

ADDITIONAL COMMENTS: Dalrymple's 5G202 sample. California snow course 208, Mammoth.

SAMPLE: SLR-3 ROCK TYPE: rhyolite LOCAL NAME:

FULL SAMPLE NUMBER: SLR-3 DATE COLLECTED: 23 October 1983

SITE DESCRIPTION: Site is on west side of cone immediately NE of the Punch Bowl. Sample taken from a prominent spine on SW side of peak.

SAMPLE DESCRIPTION: Grey pumiceous rhyolite with very abundant 6-8mm quartz and feldspar phenocrysts and subordinate hornblende.

ADDITIONAL COMMENTS: Dalrymple's 5G202 sample. Sample collected by Fred Phillips and Nancy Jannik. California snow course 208, Mammoth.

SAMPLE: MC-3 ROCK TYPE: rhyolite LOCAL NAME:

FULL SAMPLE NUMBER: MC840629-3 DATE COLLECTED: 29 June 1984

SITE DESCRIPTION: Site is on the NE side of the dome immediately SW of the Punch Bowl. Sample taken from spur which projects through soil.

SAMPLE DESCRIPTION: Dark grey pumiceous rhyolite.

ADDITIONAL COMMENTS: Dalrymple's 6G005 sample. California snow course 208, Mammoth.

SAMPLE: MC-4 ROCK TYPE: rhyolite LOCAL NAME:

FULL SAMPLE NUMBER: MC840629-4 DATE COLLECTED: 29 June 1984

SITE DESCRIPTION: SE flank of third cone from north in Mono Craters chain; a depression, much larger than the Punch Bowl, separates the second and third cones.

SAMPLE DESCRIPTION: Grey, very glassy rhyolite from a block in a recent rockfall which shows a brownish outer rind similar to the top surface of the nearby outcrop.

ADDITIONAL COMMENTS: Within 100 meters of Dalrymple's 5G204 sample. If the other depression is the Devil's punchbowl, this one must be his bathtub. California snow course 208, Mammoth.

SAMPLE: SLR-4 ROCK TYPE: obsidian LOCAL NAME: Panum Crater

FULL SAMPLE NUMBER: SLR-4 DATE COLLECTED: 23 October 1983

SITE DESCRIPTION: Site is 100 meters south of highest point on the west side of the central dome.

SAMPLE DESCRIPTION: Grey to black obsidian; very thin hydration rind that rims all fractures.

ADDITIONAL COMMENTS: Sample collected by Fred Phillips and Nancy Jannik. California snow course 208, Mammoth.

SAMPLE: SLR-5 ROCK TYPE: rhyolite LOCAL NAME: Panum Crater

FULL SAMPLE NUMBER: SLR-5 DATE COLLECTED: 23 October 1983

SITE DESCRIPTION: Site is on underside of a 3-meter thick overhang on the south side of the central dome, about 20 meters above the end of the trail.

SAMPLE DESCRIPTION: Pale to medium-grey pumiceous rhyolite, weathers to buff. Outer surface is smooth with tensional gashes and what appears to be a flow lineation of vesicles, which range up to 3-5mm.

ADDITIONAL COMMENTS: Sample collected by Fred Phillips and Nancy Jannik. California snow course 208, Mammoth.

SAMPLE: SLR-6 ROCK TYPE: rhyolite LOCAL NAME: Wilson Butte

FULL SAMPLE NUMBER: SLR-6 DATE COLLECTED: 23 October 1983

SITE DESCRIPTION: Site is on SE side of Wilson Butte. Sample is from southernmost pinnacle immediately adjacent to U.S. 395.

SAMPLE DESCRIPTION: Dark grey, pumiceous rhyolite. Voids are large and texture appears fibrous in part; very sparse large (up to 5mm) quartz phenocrysts.

ADDITIONAL COMMENTS: Sample collected by Fred Phillips and Nancy Jannik. California snow course 208, Mammoth.

SAMPLE: MM-1 ROCK TYPE: basalt LOCAL NAME:

FULL SAMPLE NUMBER: MM840701-1 DATE COLLECTED: 1 July 1984

SITE DESCRIPTION: Basalt flow crops out along stream at Big Springs Campground, immediately north of Owens River Road. Site is on the north side of the stream. Top of flow is well-exposed, with prominent ropy and scoriaceous features; some low spots may have 10 cm of soil. The exposed margin of the flow displays well-developed columns. Top meter of the flow is very vesicular and feldspar and olivine phenocrysts show alteration; below this is a denser zone, but even the fresher part (2-3 meters down) shows some alteration. Lower surface appears smooth, but with some gas explosion tubes. Sample is from 1 meter below top of flow, in the dense zone immediately below the vesicular part. The section sampled was from the interior of the flow, exposed by a recent fall of a small column.

SAMPLE DESCRIPTION: Dense, dark grey basalt; fairly fresh matrix, but olivine and feldspar phenocrysts show brown alteration.

ADDITIONAL COMMENTS: Bailey's sample 73G009. California snow course 208, Mammoth.

SAMPLE: MM-2 ROCK TYPE: basalt LOCAL NAME:

FULL SAMPLE NUMBER: MM840701-2 DATE COLLECTED: 1 July 1984

SITE DESCRIPTION: Site is about 100 meters east of U.S. 395, on the south side of Dry Creek, south of Lookout Mountain. Top of flow has thin soil in spots but mainly shows rough, ropy flow features. Sample is from 1 meter below top of flow.

SAMPLE DESCRIPTION: Dense, reddish basalt, porphyritic with feldspar.

ADDITIONAL COMMENTS: Bailey's sample 73G008. Dry Creek is misnamed, as it was flowing a foot deep on the date of sampling. California snow course 208, Mammoth.

SAMPLE: MM-3 ROCK TYPE: rhyolite LOCAL NAME:

FULL SAMPLE NUMBER: MM840702-3 DATE COLLECTED: 2 July 1984

SITE DESCRIPTION: Site is on the SW side of the top of a dome 2 miles north of Mammoth Lakes. Most of the dome has deep soil, supporting large (12") trees, but several smaller spines project through this. Sample is from a block on one of these spines.

SAMPLE DESCRIPTION: White to buff, crumbly pumiceous rhyolite with abundant large biotite phenocrysts. A brown stain permeates the outer sections of the rock, but interior sections appear fresh.

ADDITIONAL COMMENTS: Bailey's 72G007 sample. "Lichenography" of the site suggests that the spines have had continuous exposure. California snow course 208, Mammoth.

SAMPLE: SLR-7 ROCK TYPE: rhyolite LOCAL NAME:

FULL SAMPLE NUMBER: SLR-7 DATE COLLECTED: 23 October 1983

SITE DESCRIPTION: South side of the top of a dome 2 miles north of Mammoth Lakes. Sample from top of an extrusion spine projecting through thick soil.

SAMPLE DESCRIPTION: Very pale grey to white finely pumiceous rhyolite with brown staining on outer portion; abundant small (<1mm) quartz and hornblende phenocrysts.

ADDITIONAL COMMENTS: Bailey's 72G007 sample. Sample collected by Fred Phillips and Nancy Jannik. California snow course 208, Mammoth.

SAMPLE: MM-4 ROCK TYPE: basalt LOCAL NAME:

FULL SAMPLE NUMBER: MM840702-4 DATE COLLECTED: 2 July 1984

SITE DESCRIPTION: Block lava flow at the top of a hill on logging road which runs north from Route 203, about 1.5 miles north of the Shady Rest Campground and fire station. Area is heavily forested but flow crops out as a bare knob at the crest of the hill.

SAMPLE DESCRIPTION: Dense grey basalt, porphyritic with olivine which is stained brown throughout even the largest blocks.

ADDITIONAL COMMENTS: Bailey's 72G016 sample. California snow course 208, Mammoth.

SAMPLE: MM-5 ROCK TYPE: basalt LOCAL NAME:

FULL SAMPLE NUMBER: MM840702-4 DATE COLLECTED: 2 July 1984

SITE DESCRIPTION: This is the middle flow of three that are covered by the Casa Diablo Till. Outcrop is exposed in a canyon north of Route 203, immediately west of Cas Diablo Hot Springs. Sample is at 2 meters depth in a face exposed by a large recent rock fall. The older basalt is exposed at the bottom of the canyon below the sample site, and Casa Diablo-equivalent lake beds are exposed on the south wall of the canyon.

SAMPLE DESCRIPTION: Dark grey to black scoriaceous basalt which weathers to brown. Small, elongate irregular voids suggest flow lineation. Abundant colorless olivine phenocrysts, rare yellow pyroxene, and plagioclase laths.

ADDITIONAL COMMENTS: California snow course 208, Mammoth.

SAMPLE: MM-6 ROCK TYPE: basalt LOCAL NAME:

FULL SAMPLE NUMBER: MM840702-6 DATE COLLECTED: 2 July 1984

SITE DESCRIPTION: Site is 1/2 mile west of MM-5 site on the top of the north side of the canyon. Basalt pressure ridges and generally rough surface project through thin soil. Sample is from 1 meter depth in a ridge cut by the stream.

SAMPLE DESCRIPTION: Dark grey to black scoriaceous basalt which weathers to brown. Small, elongate irregular voids suggest flow lineation. Abundant colorless olivine phenocrysts, rare yellow pyroxene, and plagioclase laths.

ADDITIONAL COMMENTS: Bailey's 73G014 sample. California snow course 208, Mammoth.

SAMPLE: SLR-8 ROCK TYPE: basalt LOCAL NAME:

FULL SAMPLE NUMBER: SLR-8 DATE COLLECTED: 23 October 1983

SITE DESCRIPTION: Block taken from top of pressure ridge immediately south of U.S. 395, SW of Casa Diablo Hot Springs, 1/2 mile west of sheriff substation.

SAMPLE DESCRIPTION: Dark grey to black scoriaceous basalt which weathers to brown. Small, elongate irregular voids suggest flow lineation. Abundant colorless olivine phenocrysts, rare yellow pyroxene, and altered plagioclase laths. Interior surfaces of void are stained brown and frequently coated with carbonate.

ADDITIONAL COMMENTS: Sample collected by Fred Phillips and Nancy Jannik. California snow course 208, Mammoth.

SAMPLE: C-40 ROCK TYPE: basalt LOCAL NAME:

FULL SAMPLE NUMBER: C840702-40 DATE COLLECTED: 2 July 1984

SITE DESCRIPTION: This flow is immediately above and to the north of the C-41 flow, having the same source in a cinder cone to the NE. Flow is 3-4 meters thick, with a brecciated lower surface, and a vesicular top 1 meter thick. Sample is from the dense central zone, in a rock fall from the roof of a small south-facing cave on the margin of the flow. Sample taken at 2 meters depth, but the outer surface of the flow in indeterminate; all of the fallen material is very fresh, so any exposure other than vertical is probably minimal. Low spots hold a thin soil.

SAMPLE DESCRIPTION: Fresh, sparsely vesicular olivine-bearing basalt.

ADDITIONAL COMMENTS: Sample site is Turrin's MC40 flow.

SAMPLE: C-41 ROCK TYPE: basalt LOCAL NAME:

FULL SAMPLE NUMBER: C840702-41 DATE COLLECTED: 2 July 1984

SITE DESCRIPTION: This flow is the lowest in elevation of several from a breached cinder cone to the NE. Although this flow is covered by the C-40 and other flows for much of its extent, it extends several tens of meters south of the next higher flow, with good surface features exposed. No soil cover, but low spots have a thin cover of aeolian sand. It is 2-3 meters thick, with a brecciated lower surface and a 0.5-1 meter thick vesicular zone at the top. C-41 is from the dense central zone of the flow, 2 meters below the upper surface, in a south-facing crevice exposed by a recent rock fall. Older surfaces in the area have a thick rind of desert varnish, but the freshly-exposed surfaces are clean.

SAMPLE DESCRIPTION: Fresh, sparsely vesicular olivine-bearing basalt with prominent vugs of fresh calcite.

ADDITIONAL COMMENTS: Sample site is on Turrin's MC41 flow.

SAMPLE: AP-1 ROCK TYPE: basalt LOCAL NAME: Ape Cave basalt

FULL SAMPLE NUMBER: AP840619-1 DATE COLLECTED: 19 June 1984

SITE DESCRIPTION: Site is on a knob of basalt 500 meters NE of the Ape Cave entrance, immediately SW of the cone. Some low spots on the surface hold thin soil; outcrop has a 2-5cm weathred rind, but below this rock appears fairly fresh.

SAMPLE DESCRIPTION: Black, vesicular basalt porphyritic with olivine, containing sparse fragments of an older dacite.

SAMPLE: KA-1 ROCK TYPE: andesite LOCAL NAME: Kalama andesite

FULL SAMPLE NUMBER: KA840619-1 DATE COLLECTED: 19 June 1984

SITE DESCRIPTION: Top of a block lava flow SW of Mt. St. Helens, sampled in a shallow roadcut immediately north of Forest Road 81. Area is heavily forested, except for the area cut down by the flow, which is bare of soil.

SAMPLE DESCRIPTION: Grey, glassy andesite porphyritic with grey plagioclase.

SAMPLE: KA-2 ROCK TYPE: dacite LOCAL NAME: Kalama dacite

FULL SAMPLE NUMBER: KA840619-2 DATE COLLECTED: 19 June 1984

SITE DESCRIPTION: Debris-flow deposit SW of Mt. St. Helens on north side of FR 81. Sample from top of a 5-meter dacite block which projects through soil in heavily forested area.

SAMPLE DESCRIPTION: Grey, glassy dacite.

SAMPLE: KB-1 ROCK TYPE: basalt LOCAL NAME: Kalama basalt

FULL SAMPLE NUMBER: KB840619-1 DATE COLLECTED: 19 June 1984

SITE DESCRIPTION: Top surface of debris flow SW of Mt. St. Helens along north side of FR 81. Area heavily forested except for zone cleared by the flow; some thin soil developed, sparsely, on parts of the flow.

SAMPLE DESCRIPTION: Dense, glassy black basalt.

SAMPLE: MSH-80 ROCK TYPE: dacite LOCAL NAME: Mt. St. Helens

FULL SAMPLE NUMBER: MSH-80 DATE COLLECTED: June 1980

SITE DESCRIPTION: 1980-83 dome in crater.

SAMPLE DESCRIPTION: Grey, glassy dacite.

ADDITIONAL COMMENTS: Sample donated by Louis Brown, Carnegie Institution of Washington. Collected by William Zoller.

SAMPLE: MSH-83 ROCK TYPE: dacite LOCAL NAME: Mt. St. Helens

FULL SAMPLE NUMBER: MSH-83 DATE COLLECTED: July 1983

SITE DESCRIPTION: 1983 dome in crater; rock still hot when sampled.

SAMPLE DESCRIPTION: Grey, glassy dacite.

ADDITIONAL COMMENTS: Sample donated by Michael Doukas, USGS Vancouver, WA.

SAMPLE: USU-78 ROCK TYPE: dacite LOCAL NAME: Usu volcano (Japan)

FULL SAMPLE NUMBER: USU-78 DATE COLLECTED: 12 September 1978

HANDSAMPLE DESCRIPTION: Pale grey, glassy dacite.

ADDITIONAL COMMENTS: Sample donated by Louis Brown, Carnegie Institution of Washington. Collected during an eruptive period by Hiromu Okada, Department of Geophysics, Hokkaido University, Japan.

5.2 Appendix 2: Maps of the sample localities

All maps are current U.S. Geological Survey topographic maps unless otherwise noted.

New Mexico

Arizona

California

Washington

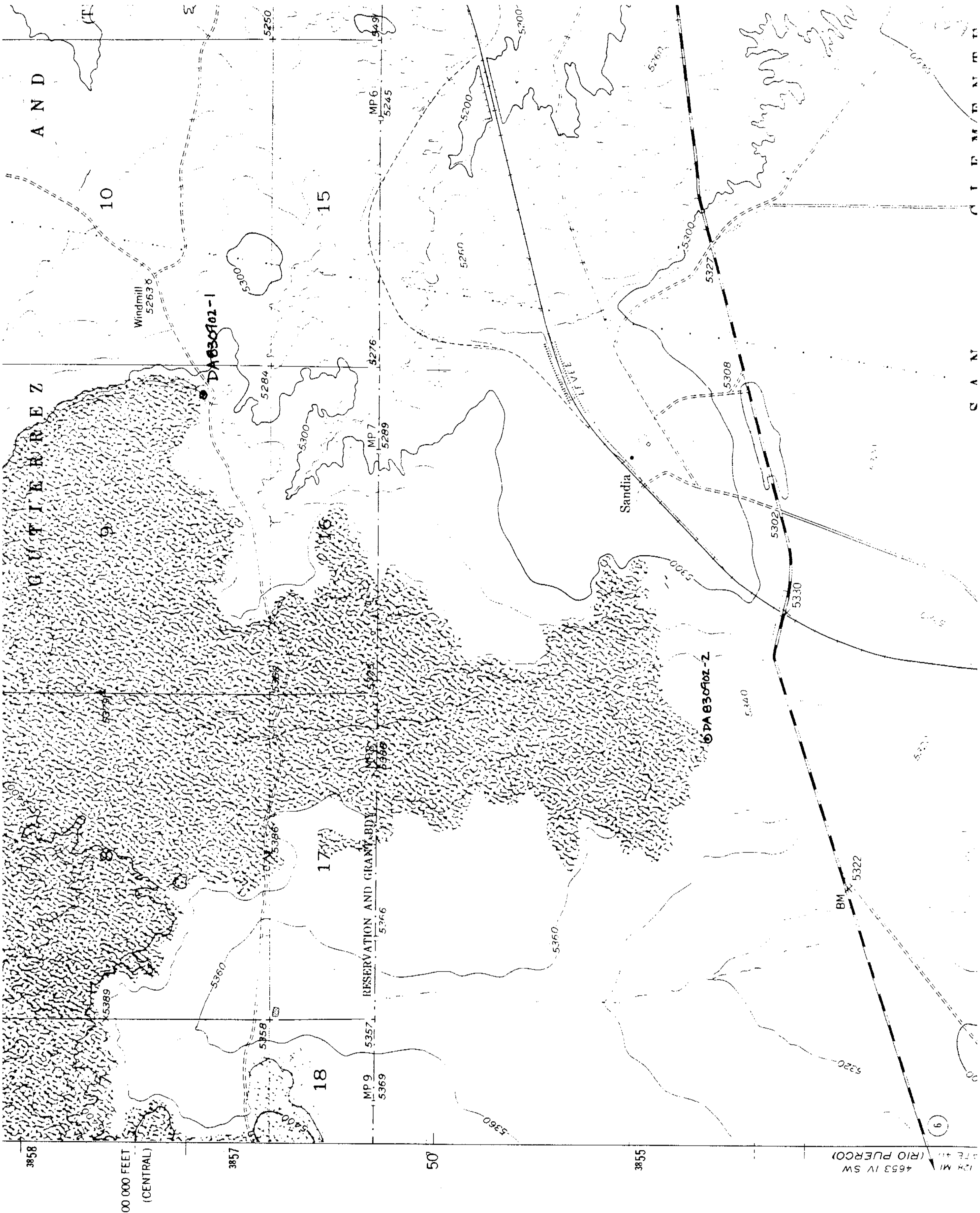
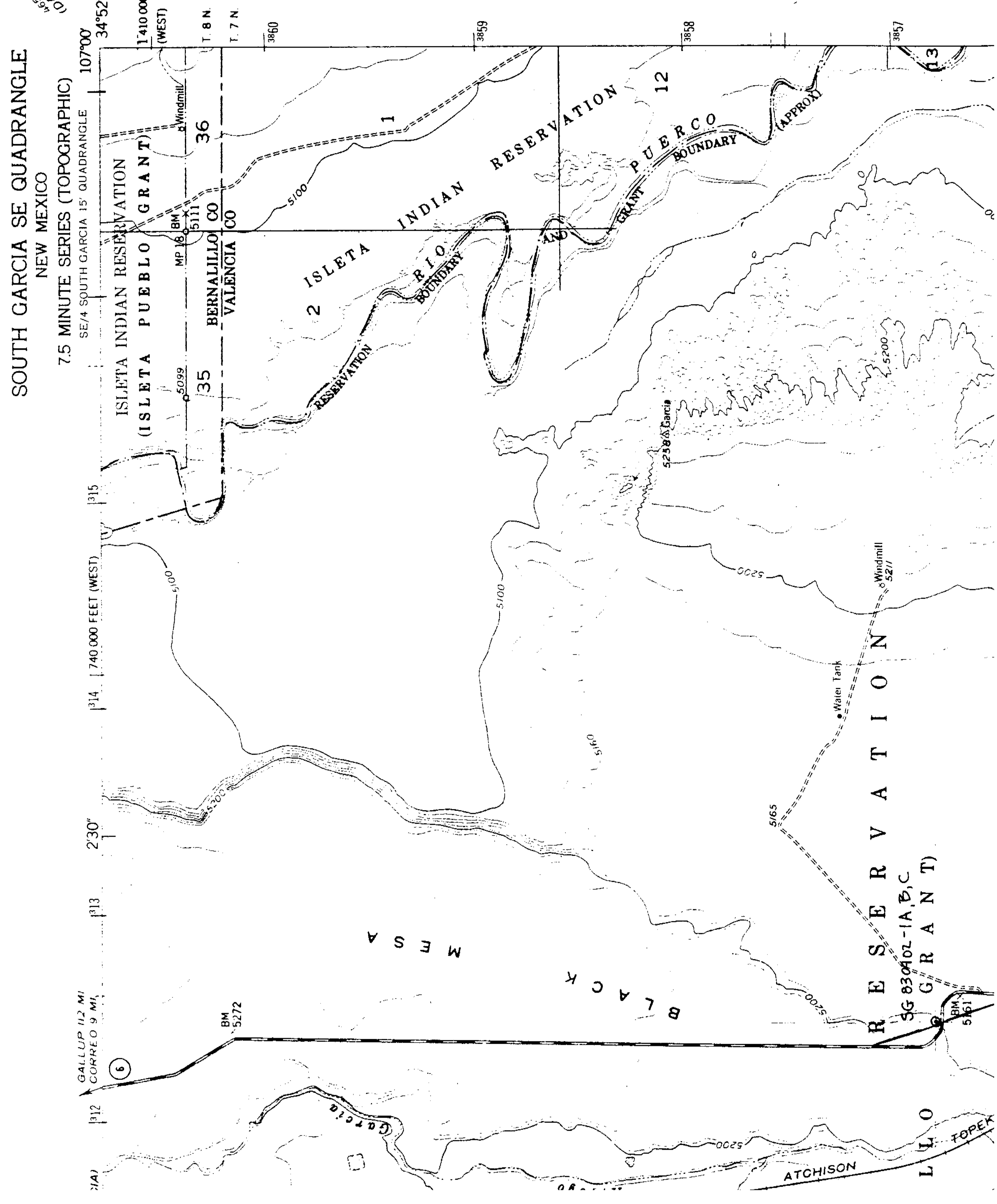
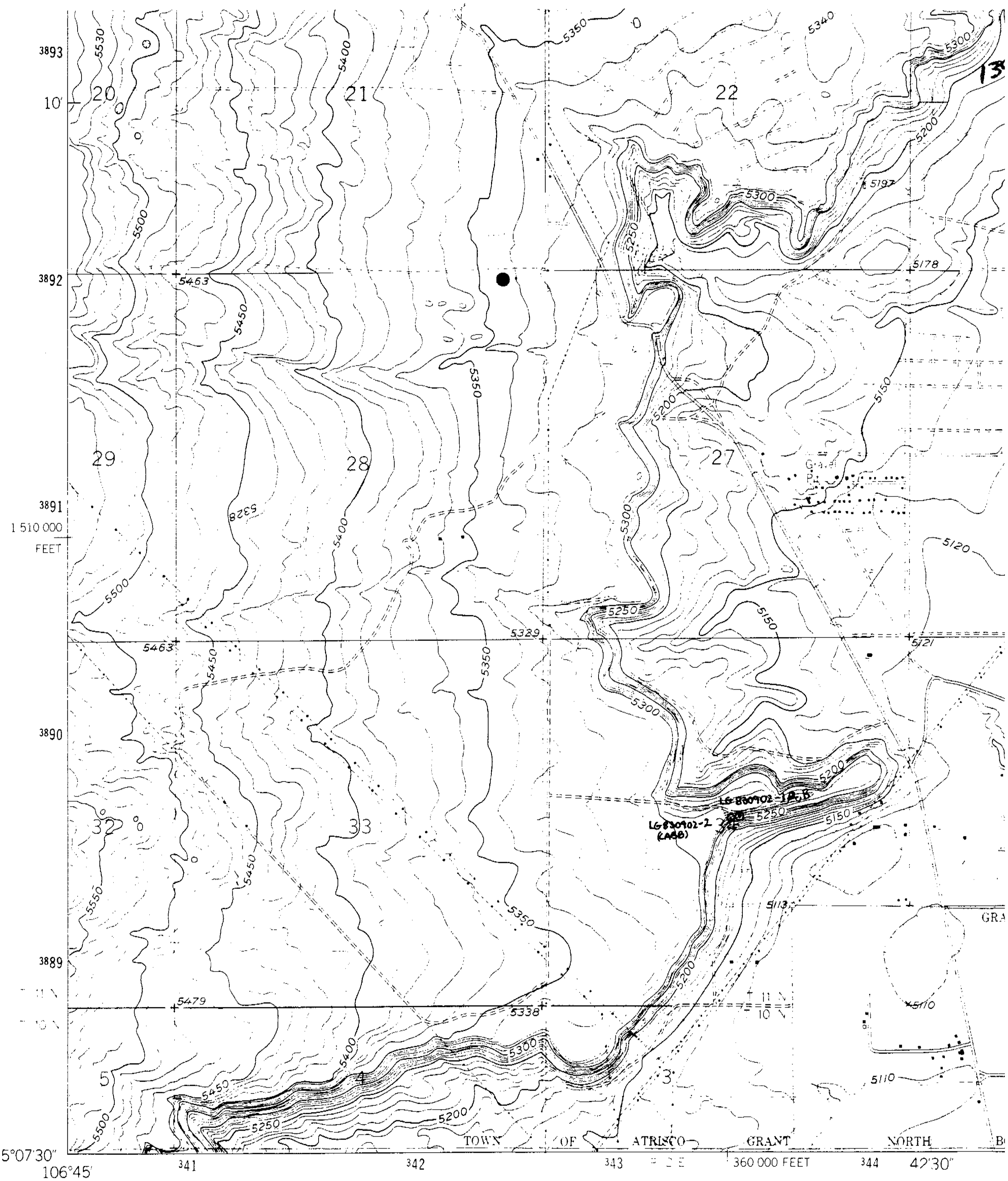


Plate 5.2-1: Portion of the Dalies (NM) sheet showing the location of samples DA-1 and DA-2

138

Plate 5.2-2: Portion of the South Garcia SE (NM) sheet showing the Location of samples SG-1A, SG-1B, and SG-1C.





MESITA NEGRA SE
4654 III SE

Mapped, edited, and published by the Geological Survey

Control by USGS and USC&GS

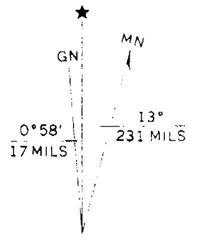
Culture and drainage in part compiled from aerial photographs taken 1959. Topography by planetable surveys 1954. Revised 1960

Polyconic projection. 1927 North American datum
10,000-foot grid based on New Mexico coordinate system, central zone
1000-meter Universal Transverse Mercator grid ticks,
zone 13, shown in blue

Red tint indicates areas in which only landmark buildings are shown

West boundary of Elena Gallegos Grant adjacent to Rio Grande omitted because of insufficient data

Revisions shown in purple compiled from aerial photographs taken 1967 and 1972. This information not field checked



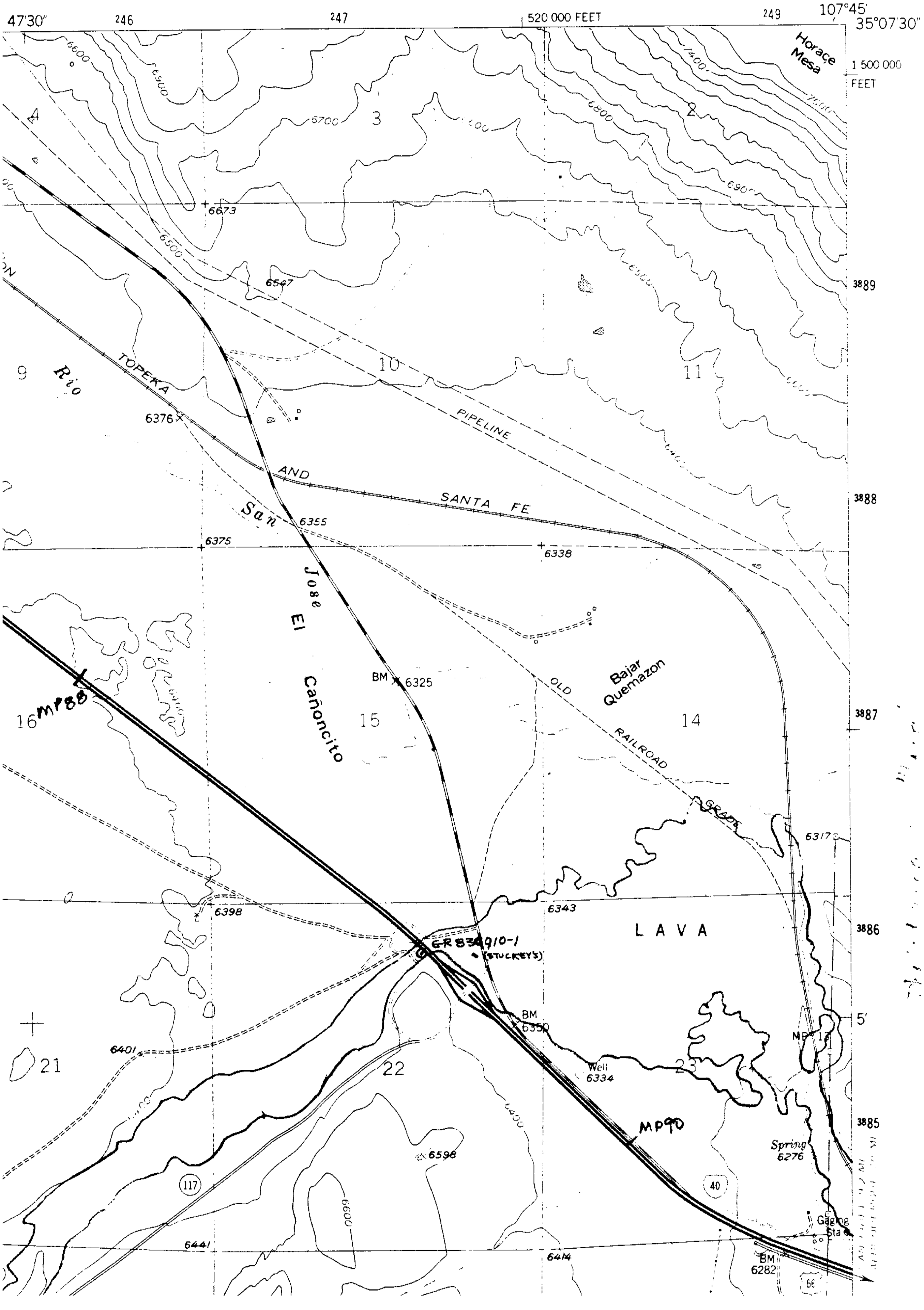
UTM GRID AND 1972 MAGNETIC NORTH
DECLINATION AT CENTER OF SHEET

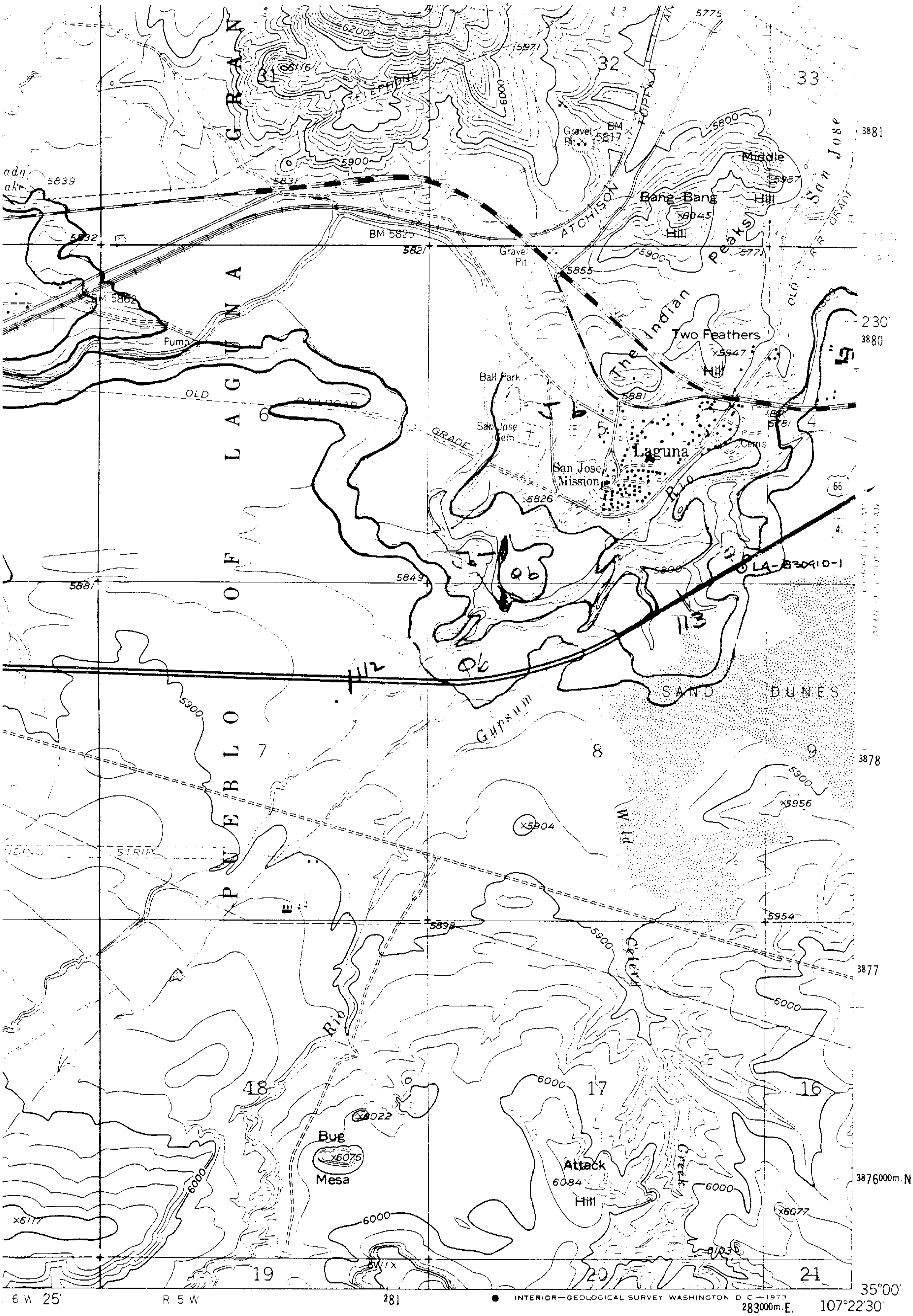
Plate 5.2-3: Portion of the Los Griegos (NM) sheet showing the location of sample LG-1A

Plate 5.2-4: Portion of the Grants SE (NM) sheet showing the location of sample GR-1

GRANTS SE QUADRANGLE
NEW MEXICO–VALENCIA CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)

4454 II NW
(LOBO SPRINGS)





ILE

Plate 5.2-5: Portion of the Laguna (NM) sheet showing the location of sampleLA-1

ROAD CLASSIFICATION

Heavy-duty

Light-duty

(DOUGH M
455

142

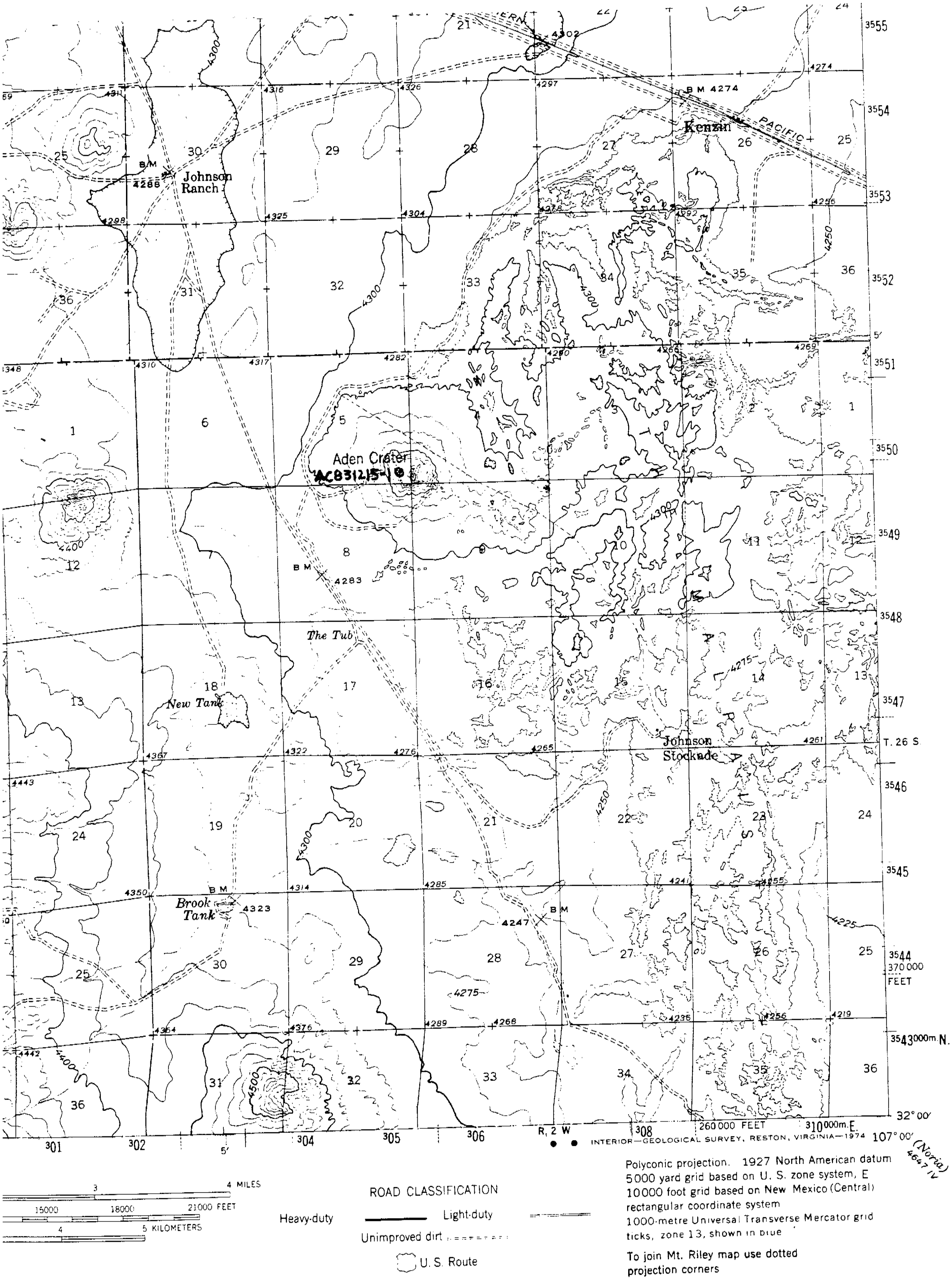


Plate 5.2-6: Portion of the Aden (NM) sheet showing the location of sample AC-1

ADEN, N. MEX.
N3200—W10700/15
1941
AMS 4548 II–SERIES V781

1929

5. OR RESTON, VIRGINIA 22092
AILABLE ON REQUEST

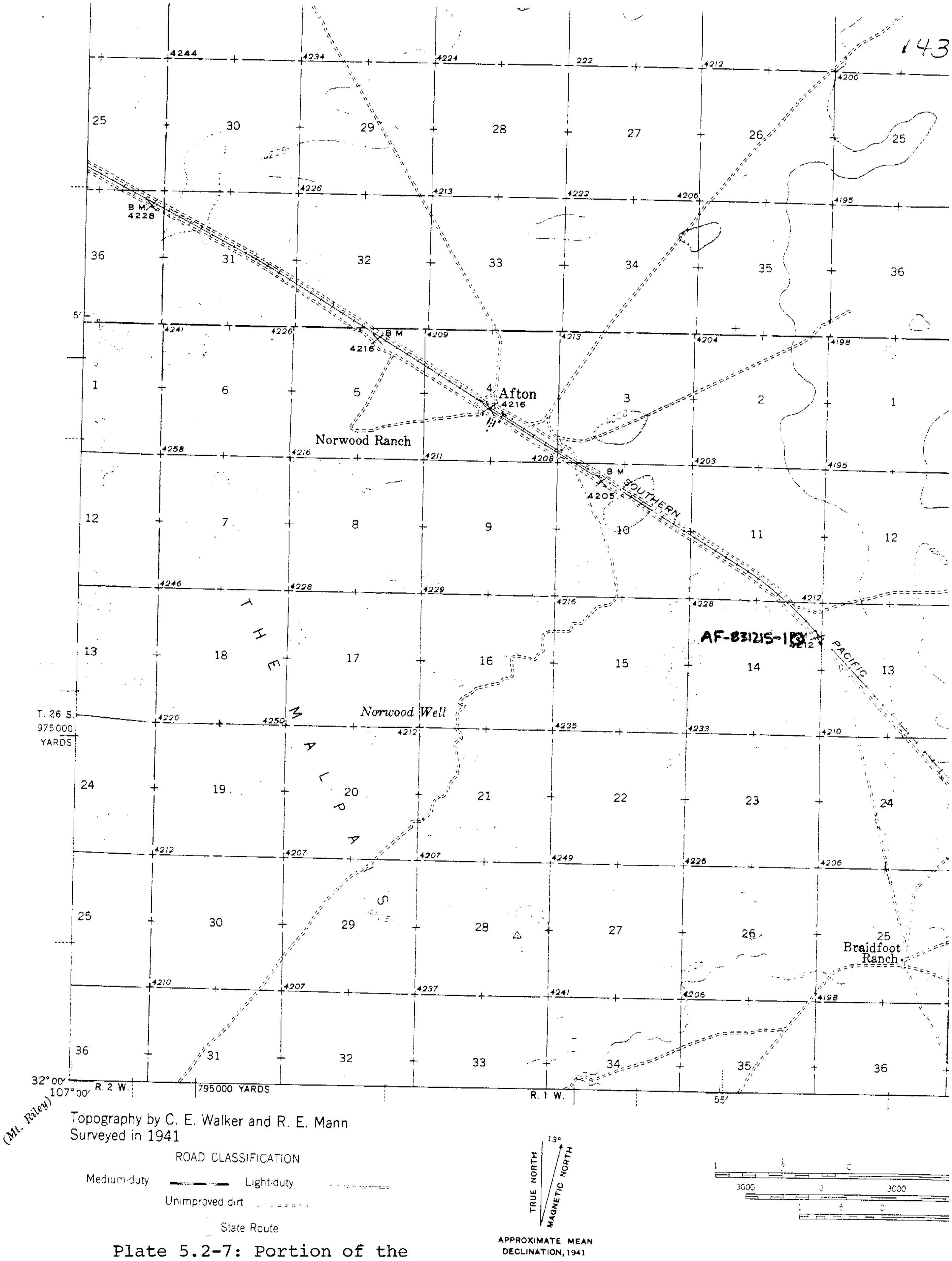
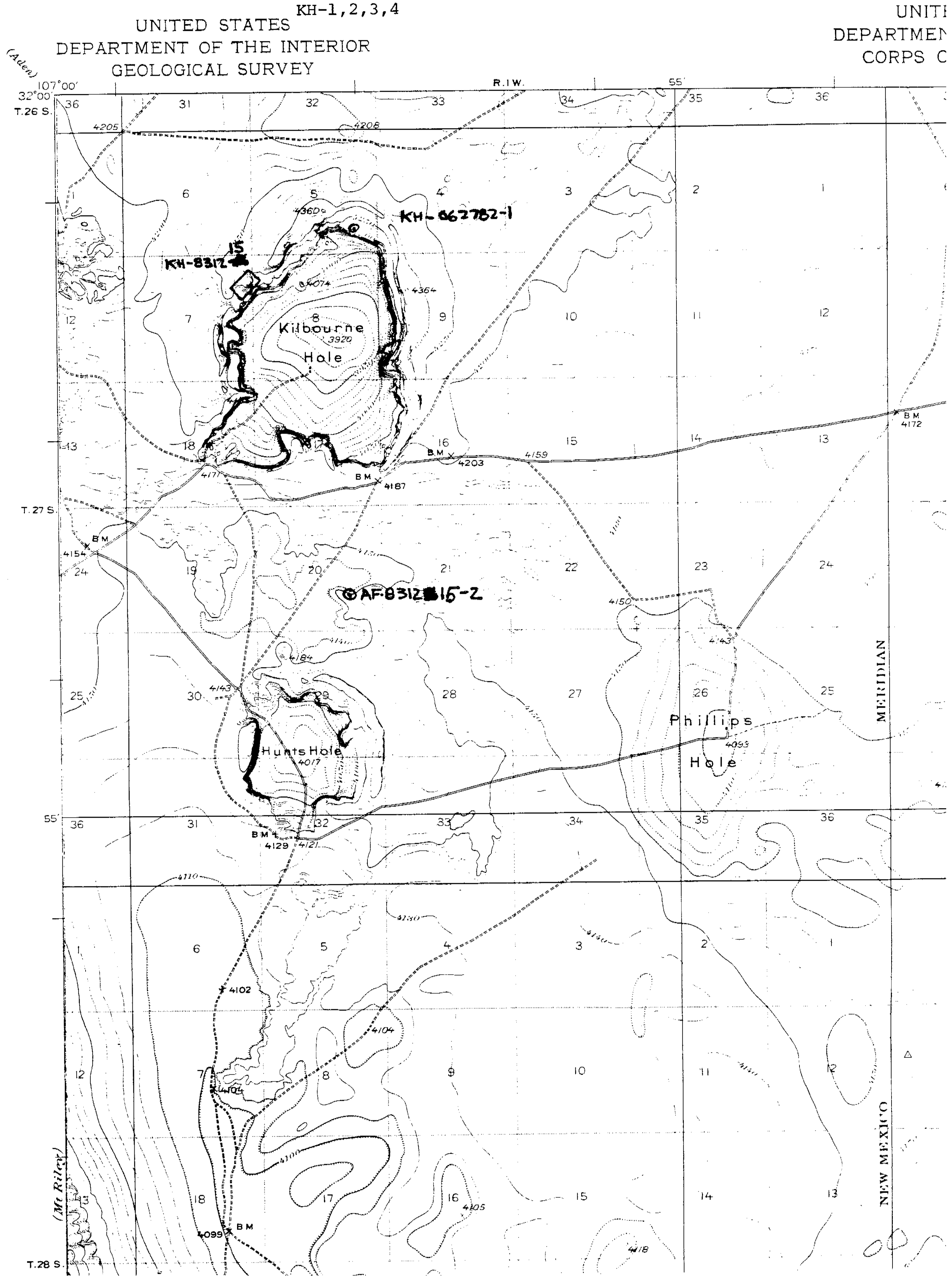


Plate 5.2-7: Portion of the Afton (NM) sheet showing the Location of sample AF-1

Plate 5.2-8: Portion of the Noria (NM) sheet showing the Location of samples AF-2 and KH-1,2,3,4



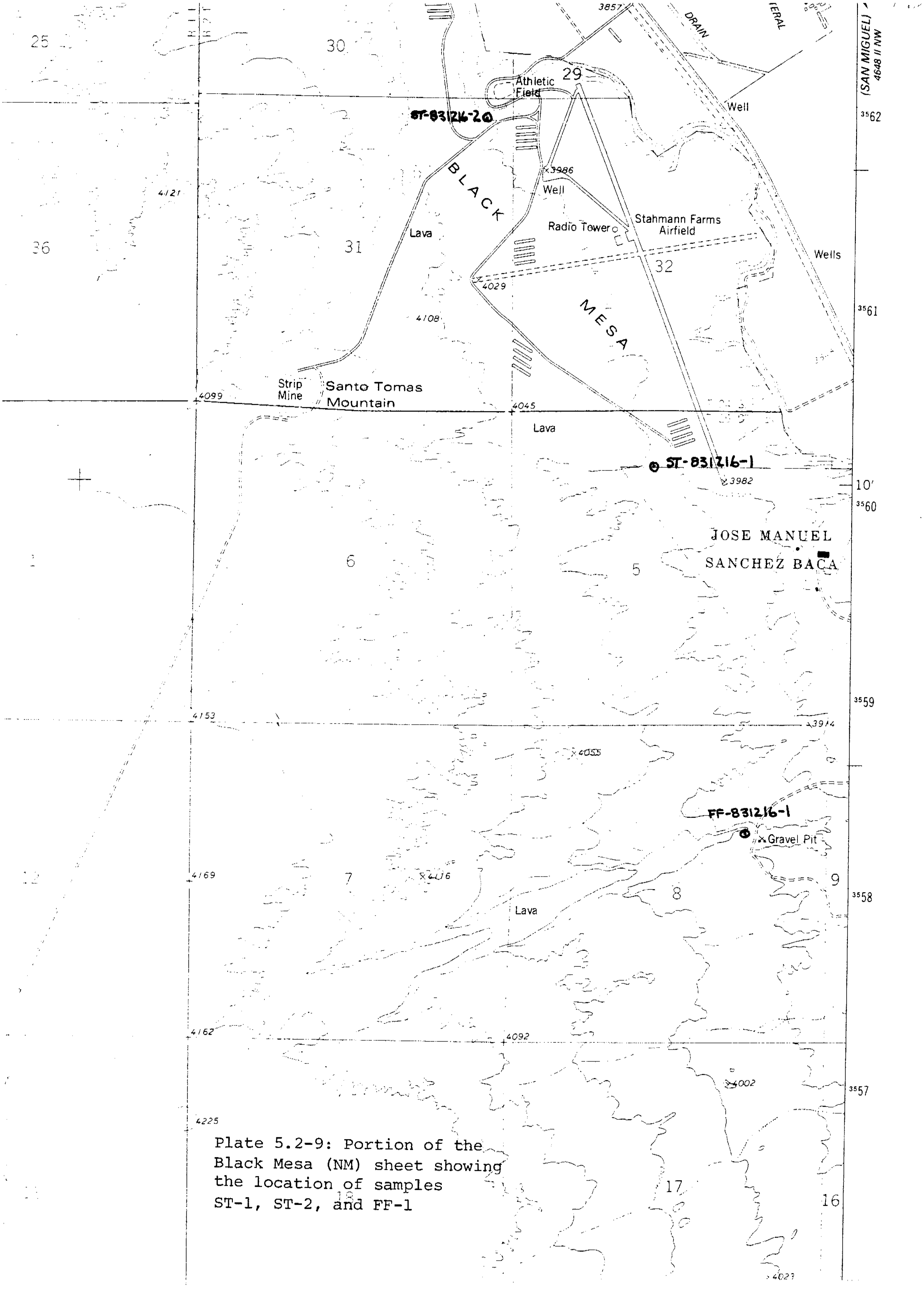
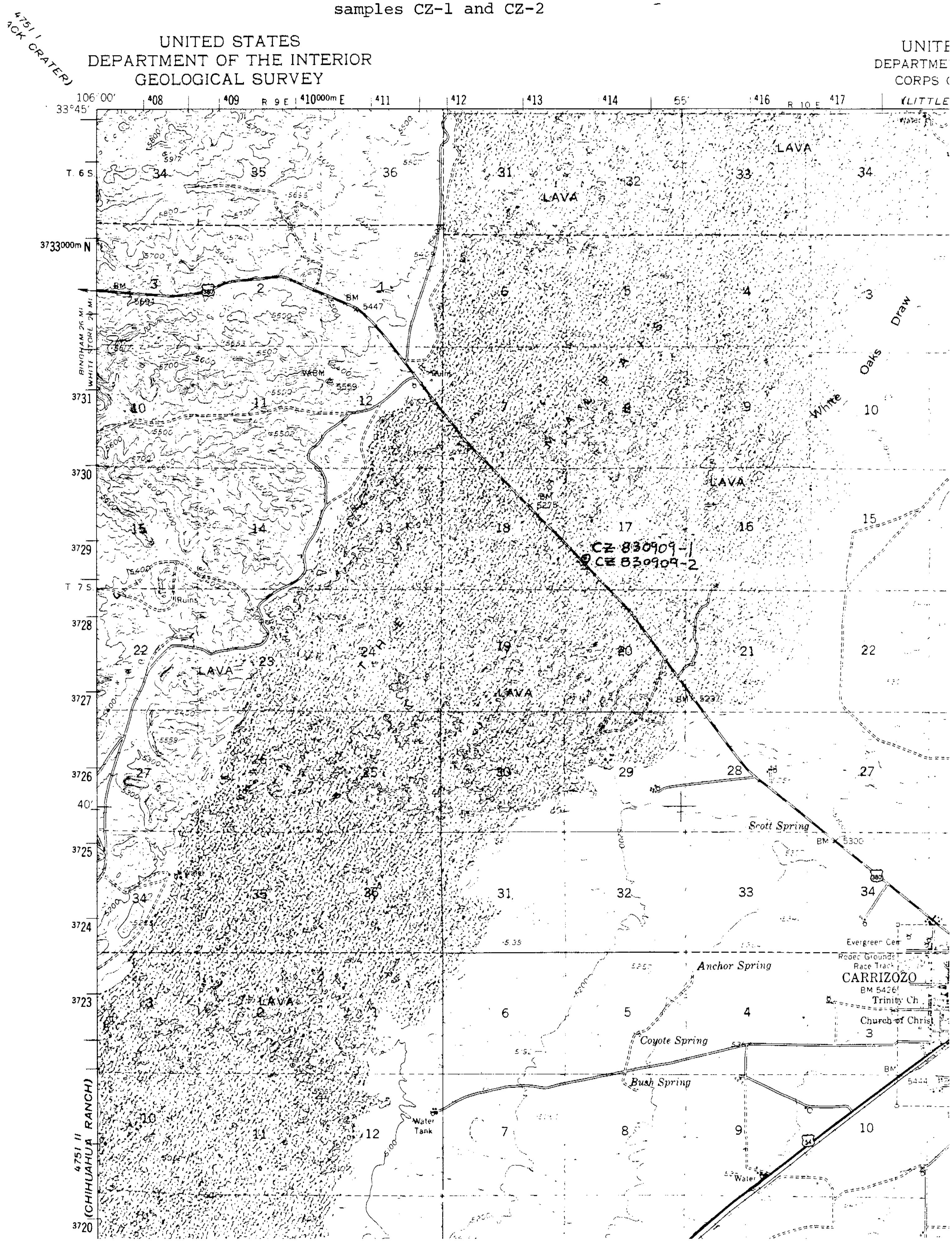


Plate 5.2-9: Portion of the Black Mesa (NM) sheet showing the location of samples ST-1, ST-2, and FF-1

Plate 5.2-10: Portion of the Carrizozo (NM) sheet showing the location of samples CZ-1 and CZ-2



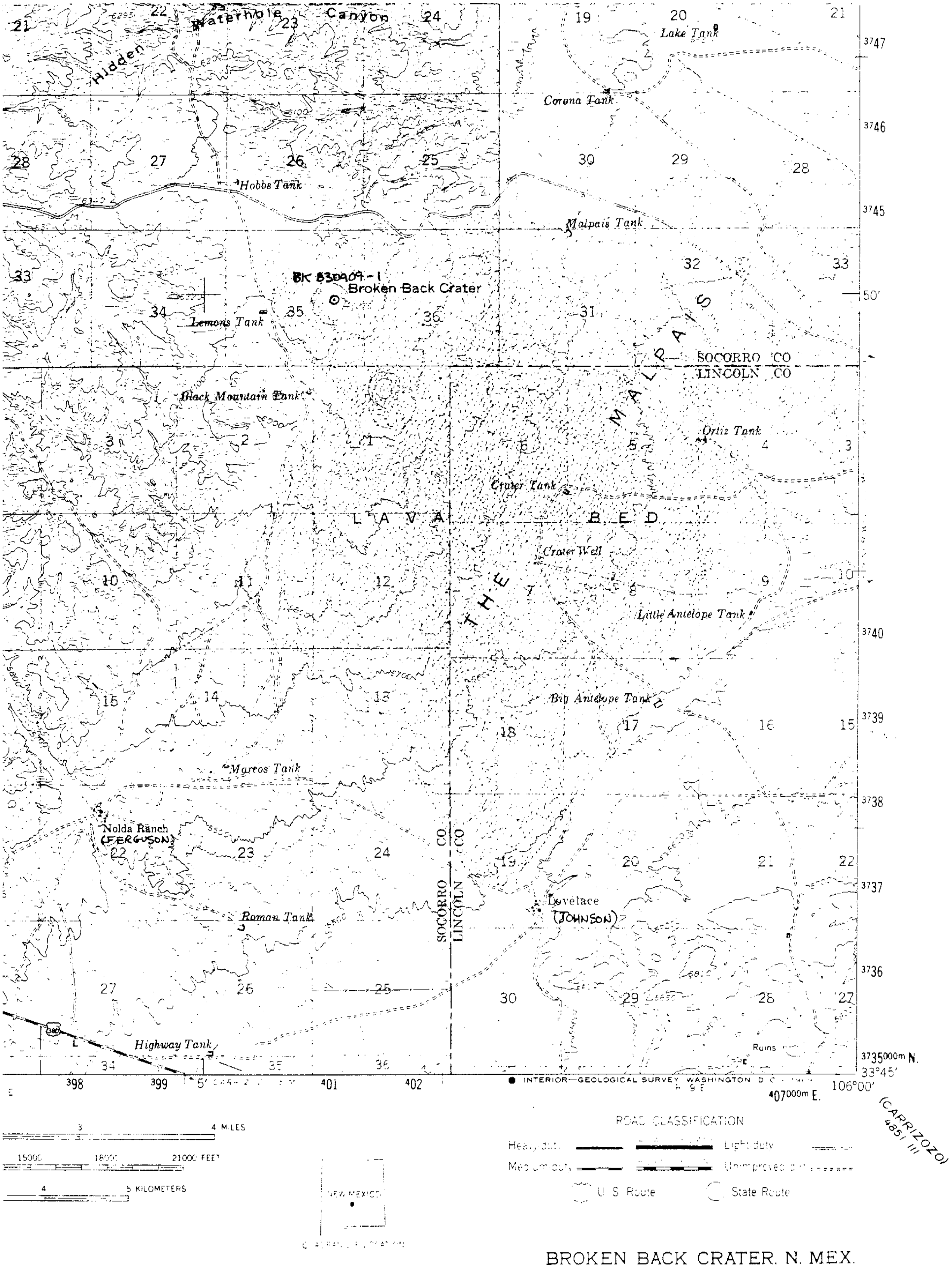
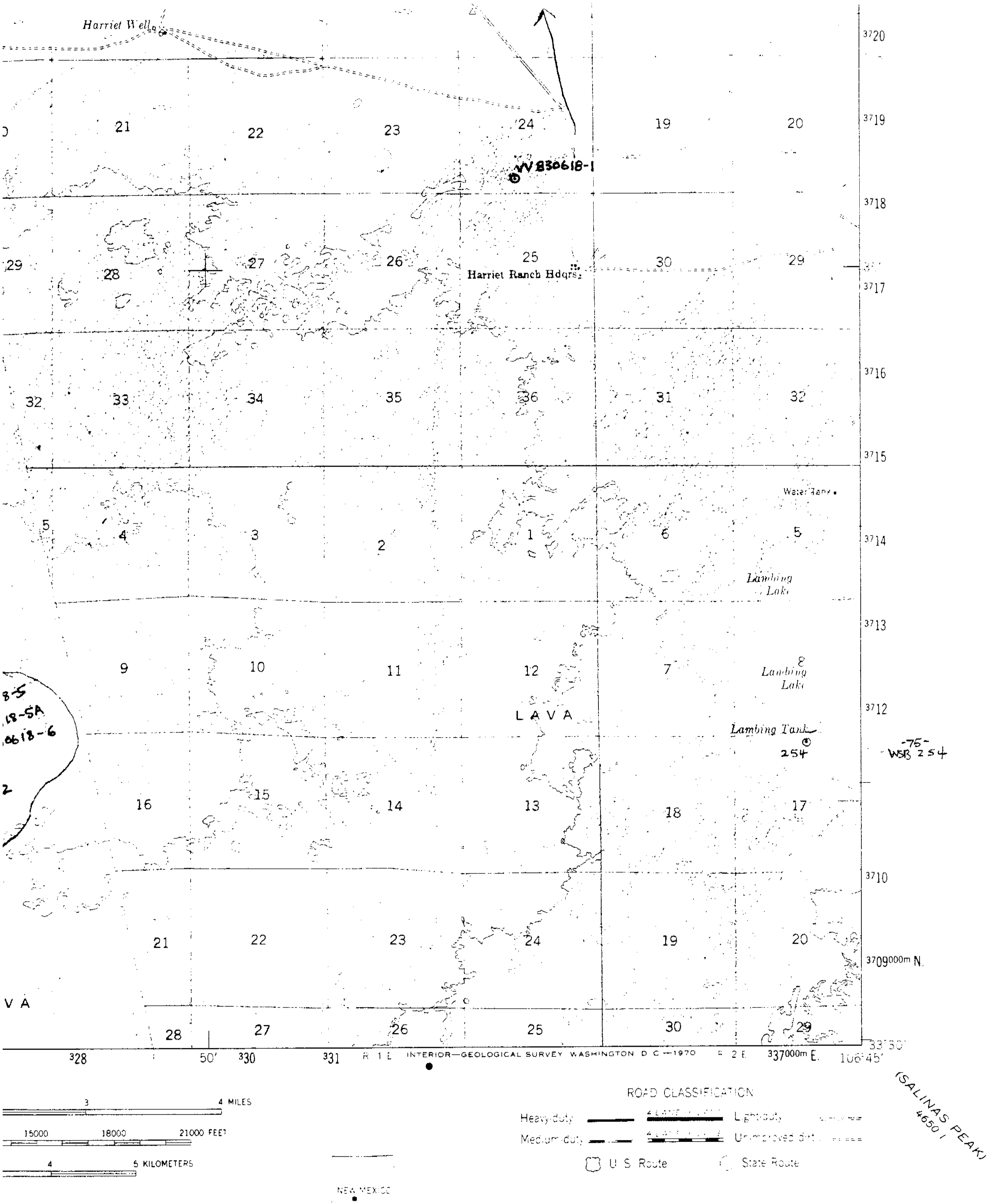


Plate 5.2-11: Portion of the Broken Back Crater (NM) sheet showing the location of sample BK-1



VAL VERDE, N. MEX.
N3330—W10645/15
1948
AMS 4651 III—SERIES V781

TANDARDS
25 OR WASHINGTON, D. C. 20242
AVAILABLE ON REQUEST

Plate 5.2-12: Portion of the Val Verde (NM) sheet showing the location of sample VV-1

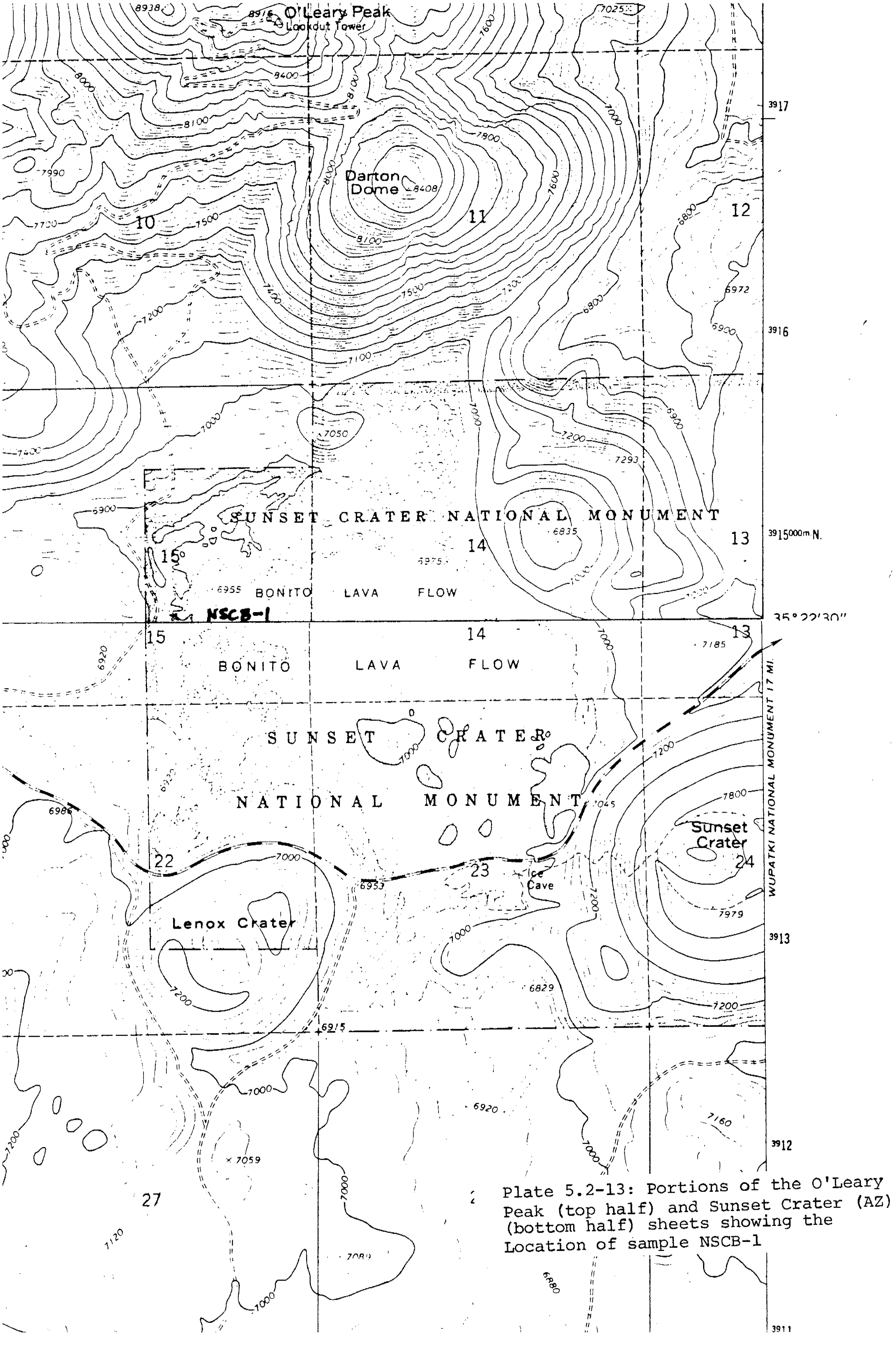


Plate 5.2-13: Portions of the O'Leary Peak (top half) and Sunset Crater (AZ) (bottom half) sheets showing the Location of sample NSCB-1

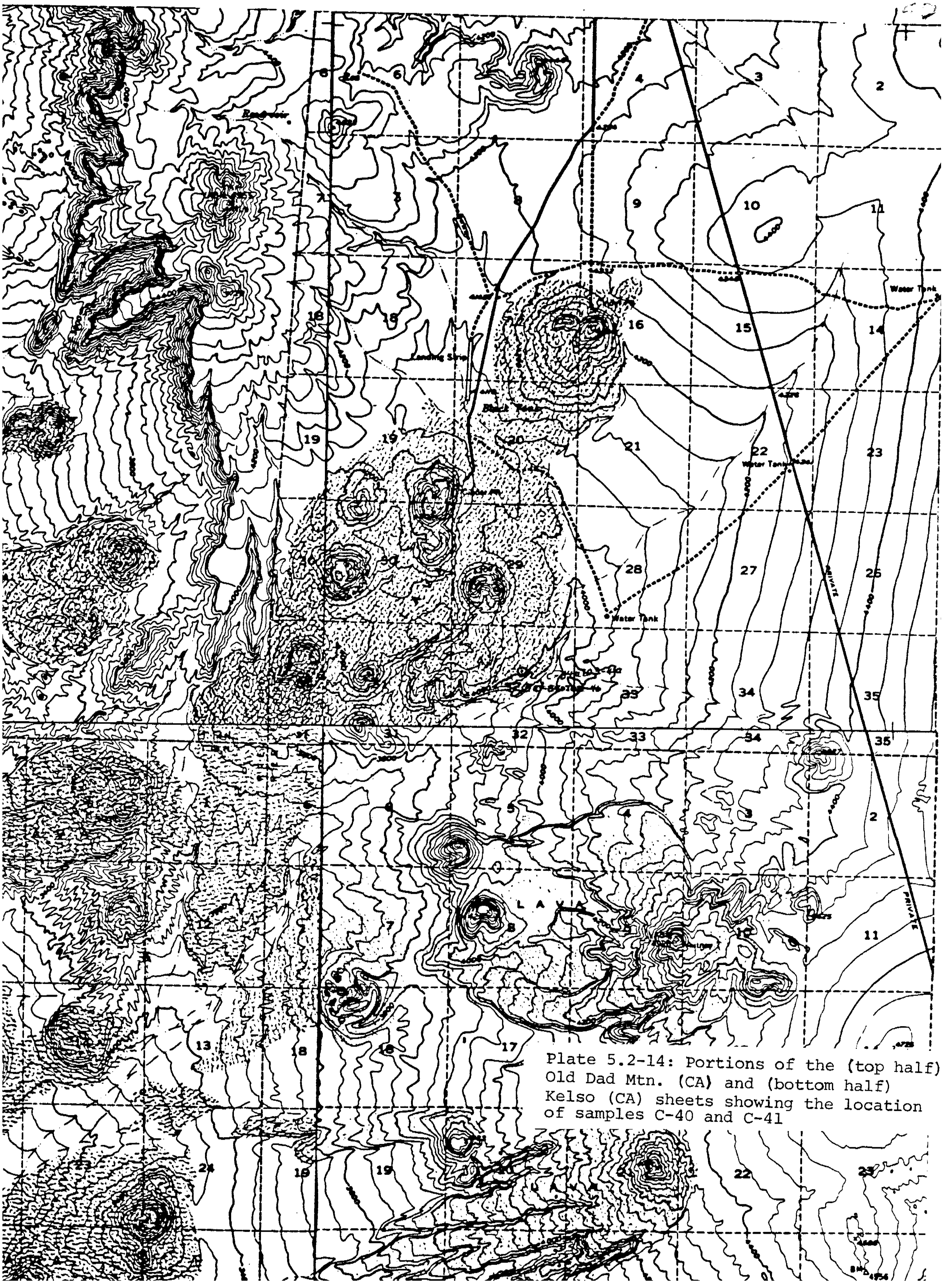
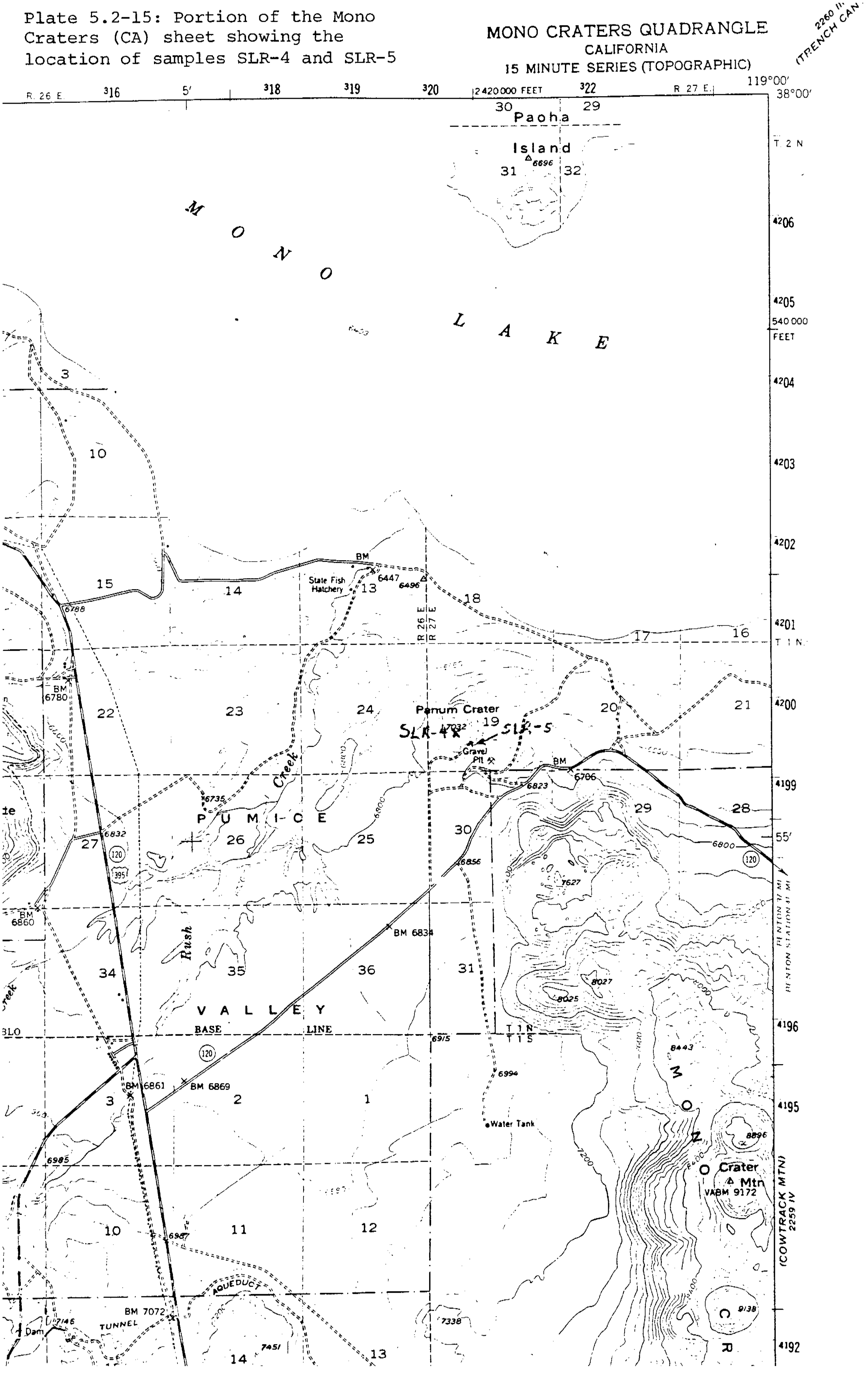


Plate 5.2-14: Portions of the (top half) Old Dad Mtn. (CA) and (bottom half) Kelso (CA) sheets showing the location of samples C-40 and C-41

Plate 5.2-15: Portion of the Mono Craters (CA) sheet showing the location of samples SLR-4 and SLR-5



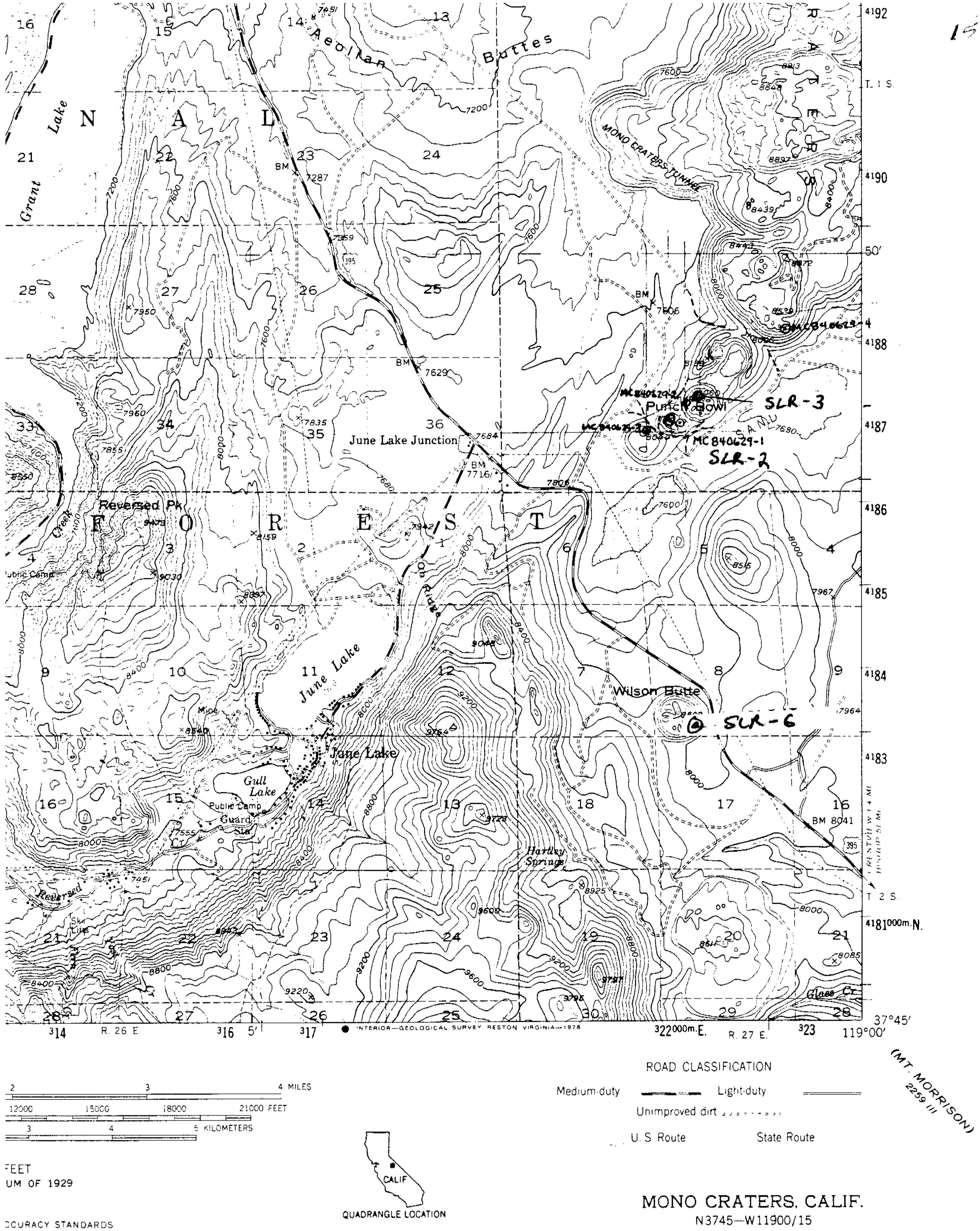
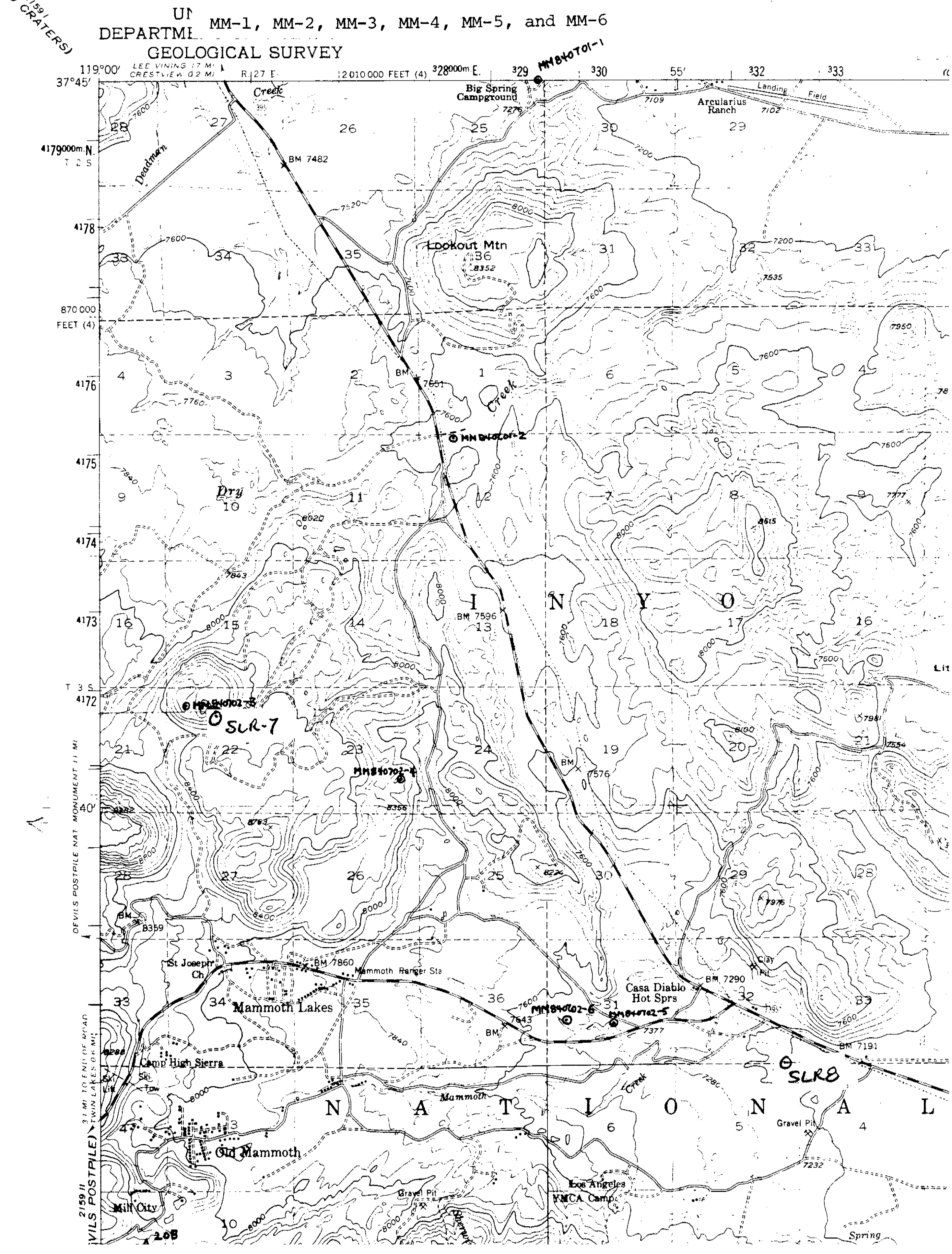


Plate 5.2-16: Portion of the Mono Craters (CA) sheet showing the locations of samples SLR-2, SLR-3, SLR-6, MC-1, MC-2, MC-3, and MC-4

1 15

Plate 5.2-17: Portion of the Mt. Morrison (CA) sheet showing the location of samples SLR-7, SLR-8 MM-1, MM-2, MM-3, MM-4, MM-5, and MM-6



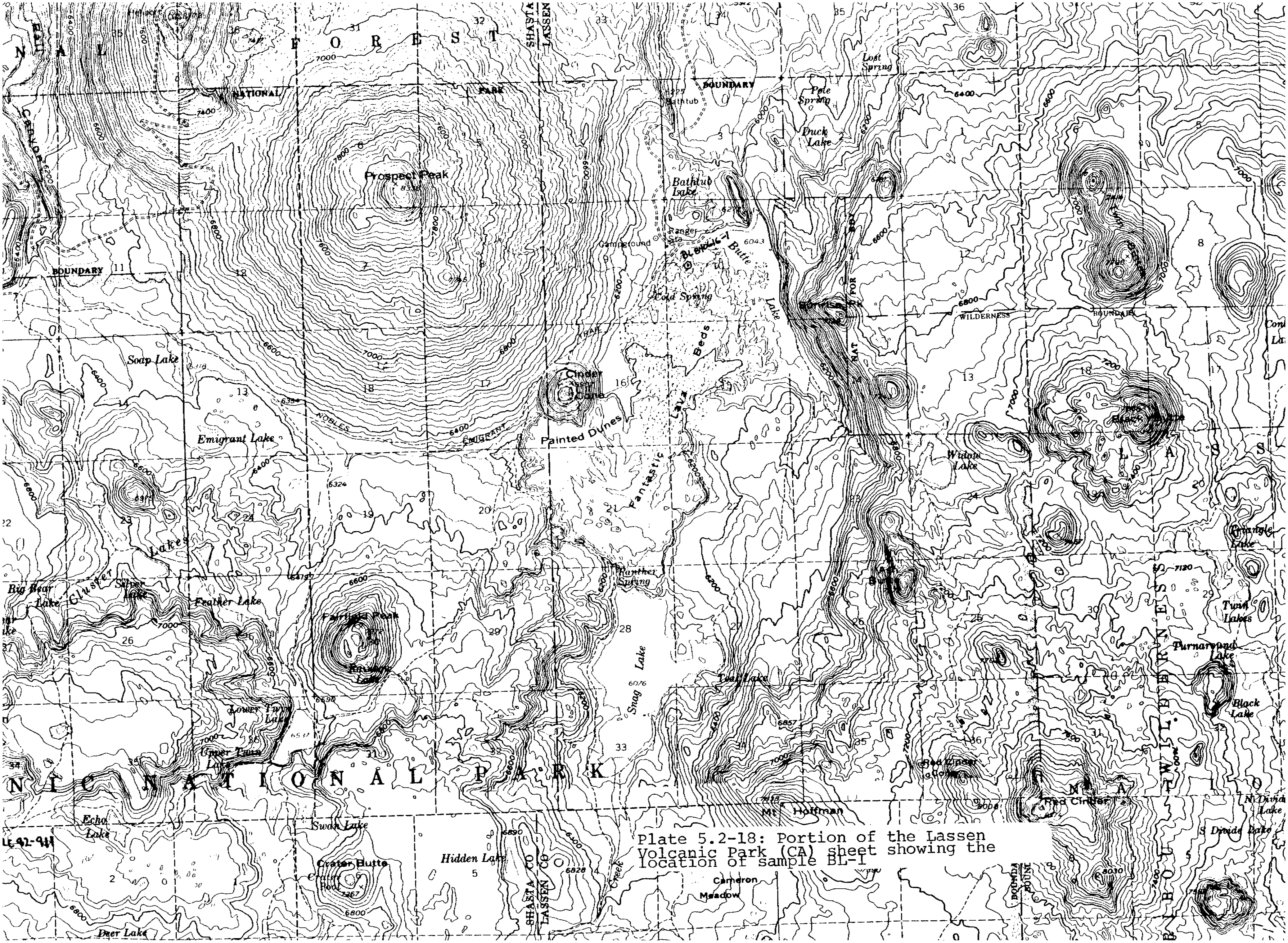


Plate 5.2-18: Portion of the Lassen Volcanic Park (CA) sheet showing the location of sample BL-I

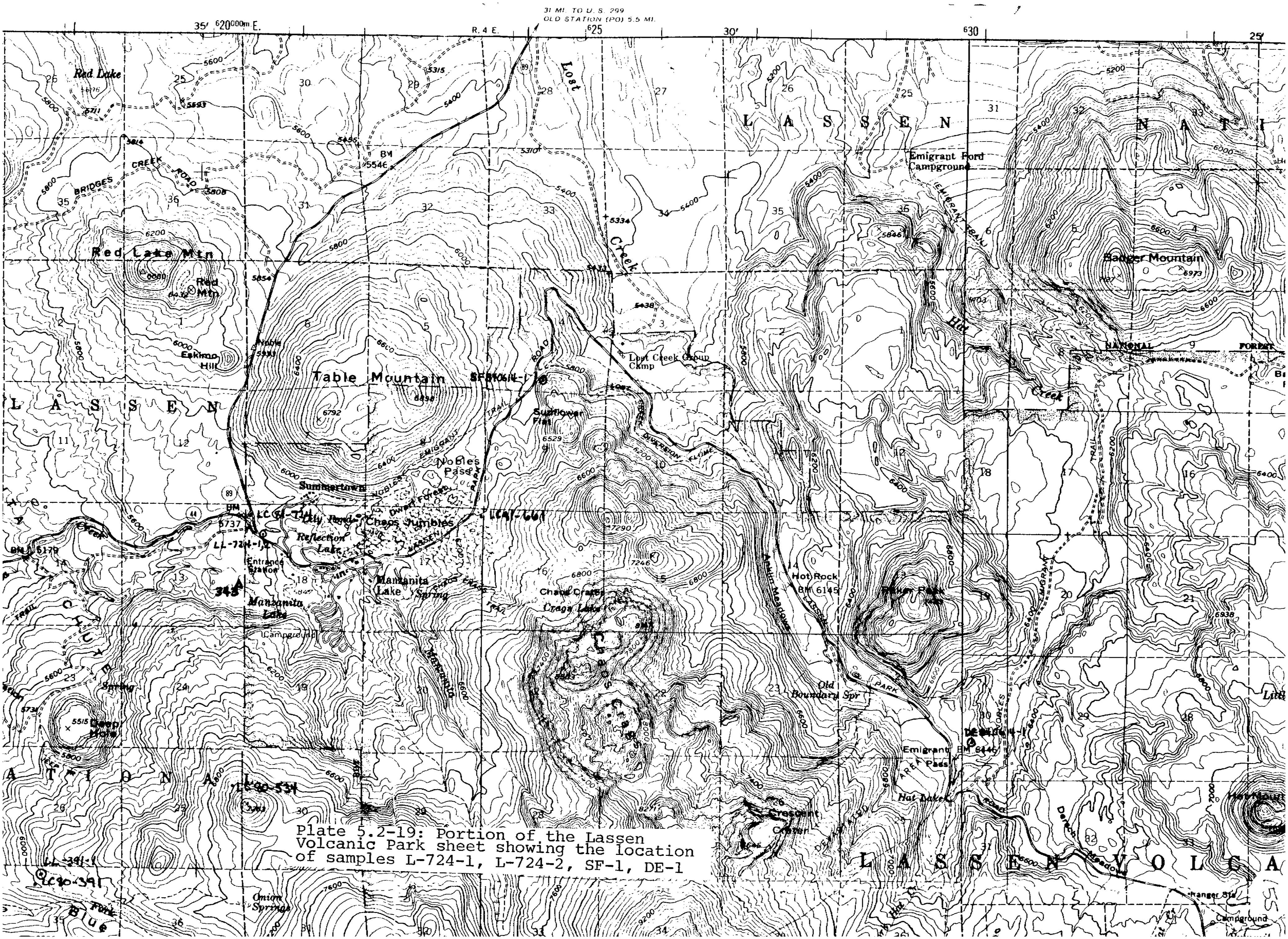


Plate 5.2-19: Portion of the Lassen Volcanic Park sheet showing the location of samples L-724-1, L-724-2, SF-1, DE-1

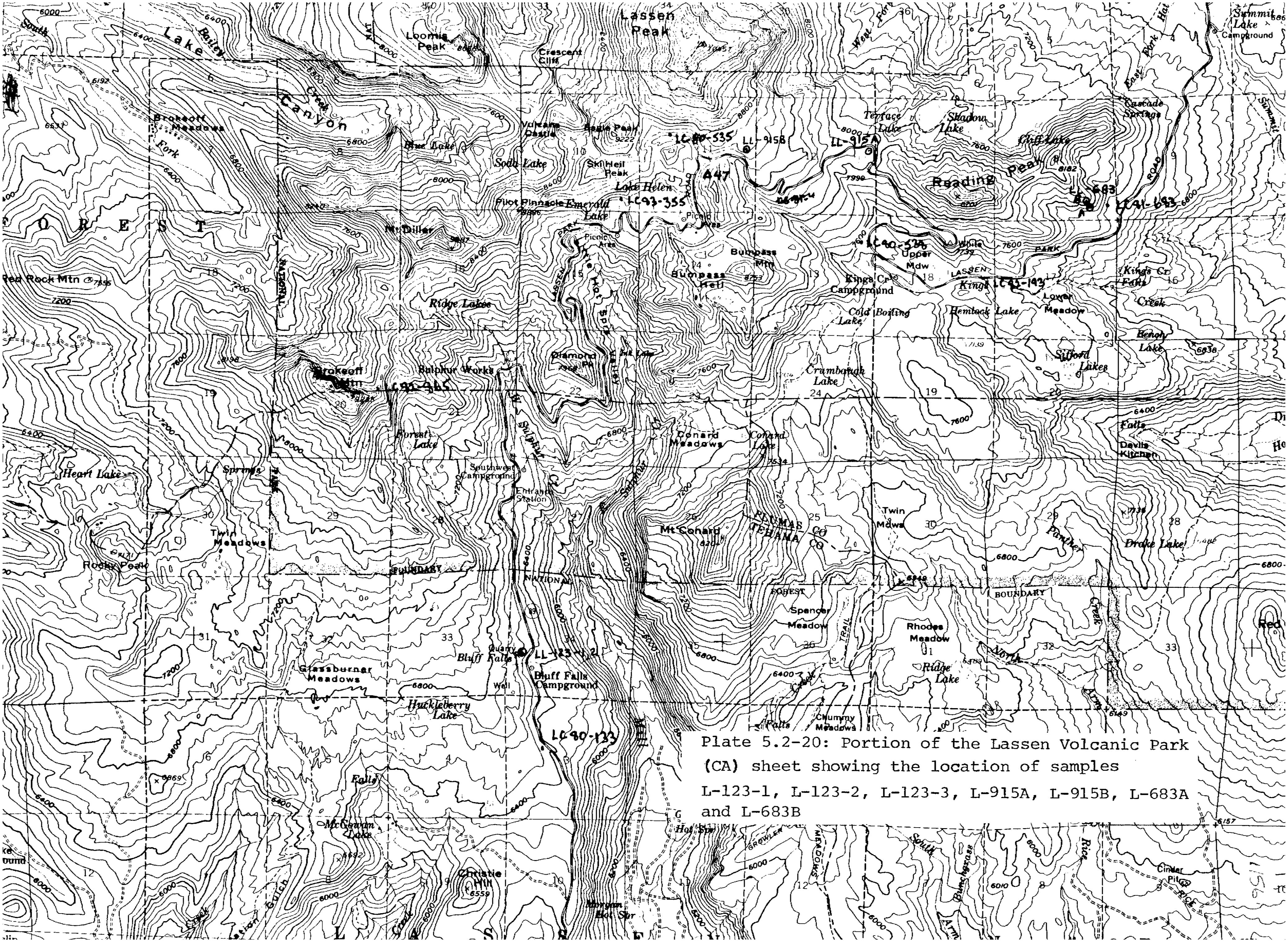
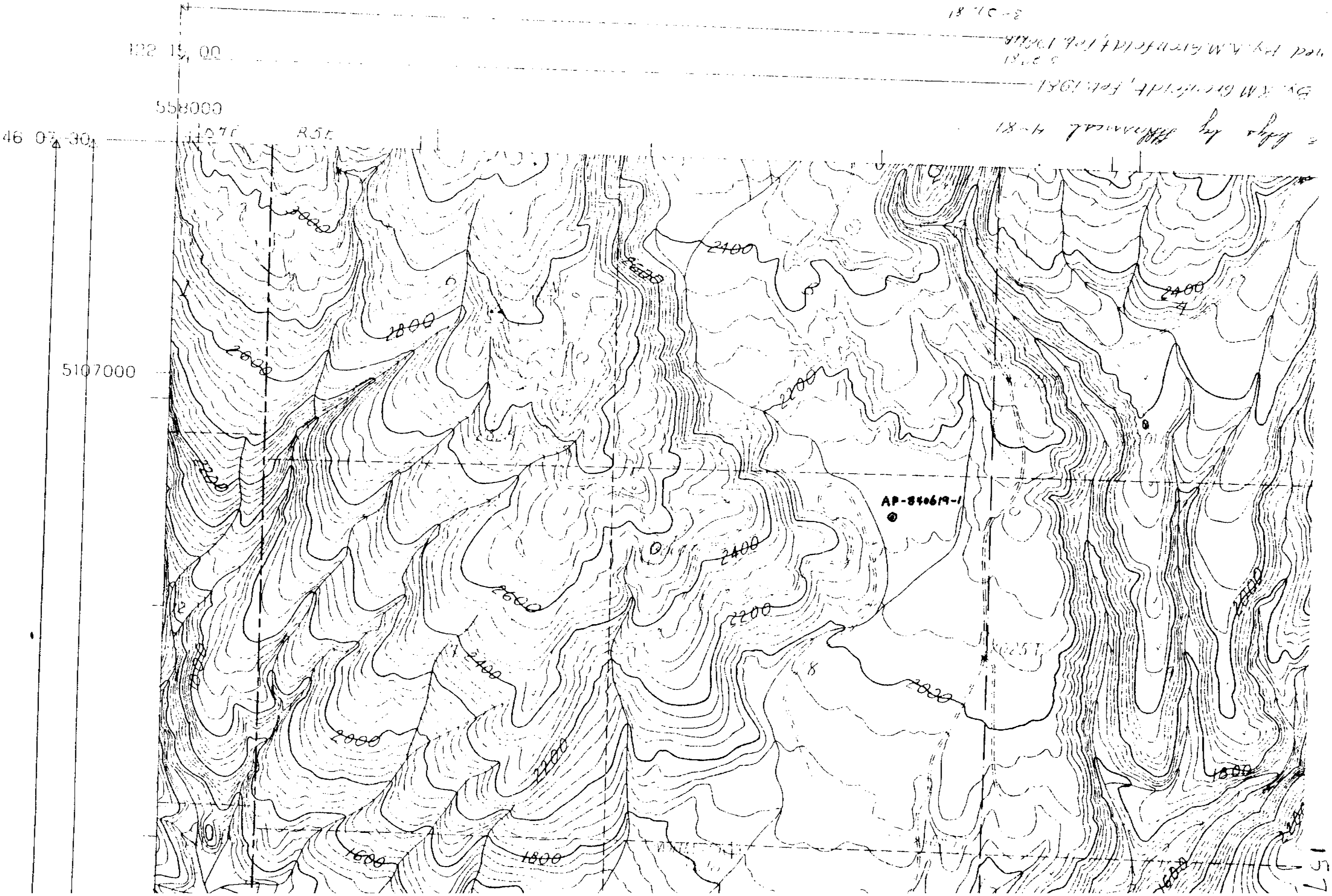


Plate 5.2-20: Portion of the Lassen Volcanic Park (CA) sheet showing the location of samples L-123-1, L-123-2, L-123-3, L-915A, L-915B, L-683A and L-683B

MT ST HELENS SW, WA. C.I.4[illegible] 468 15

Plate 5.2-21: Portion of the Mt. St. Helens SW (WA) sheet (provisional) showing the location of sample AP-1



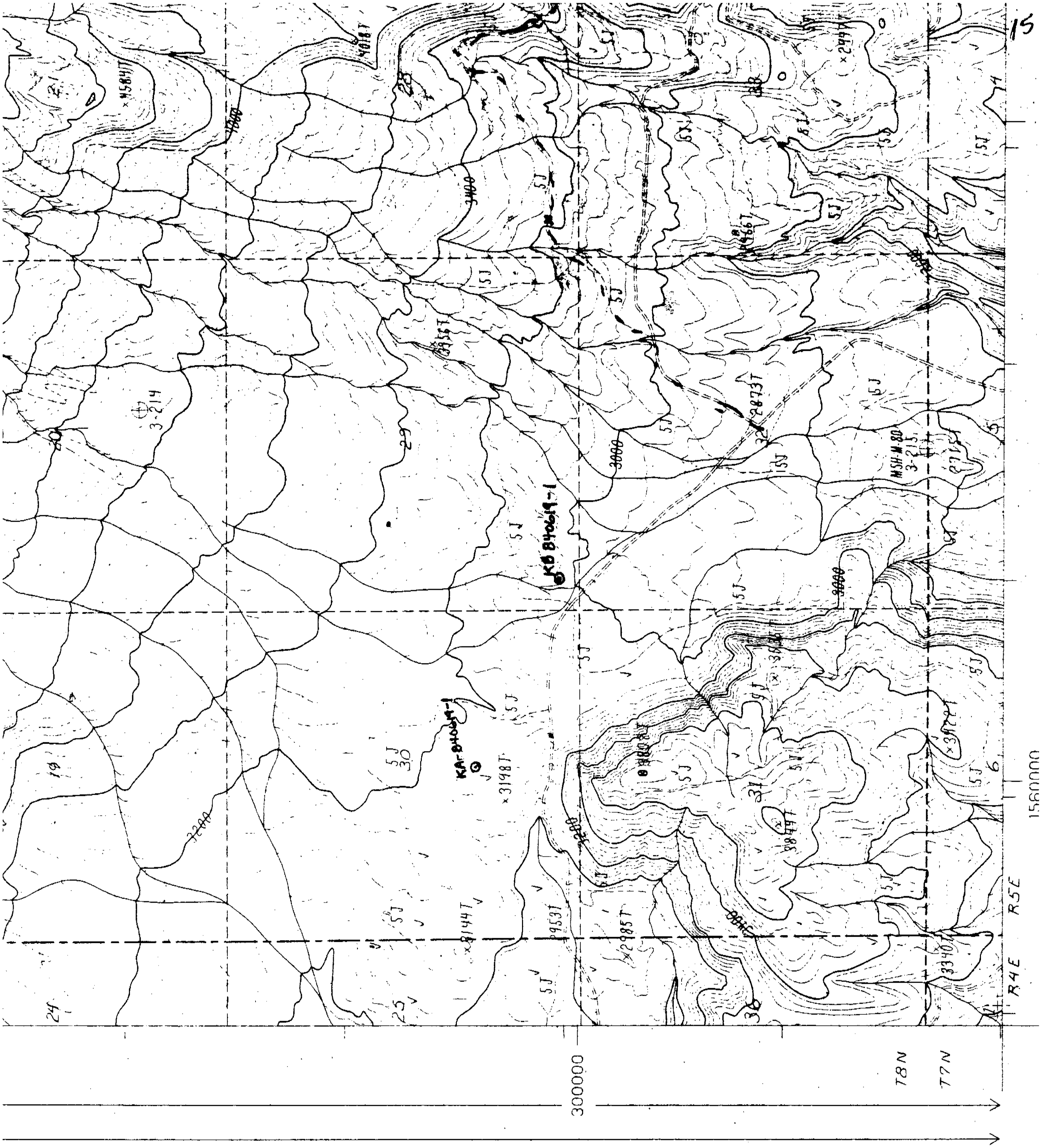


Plate 5.2-22: Portion of the Mt. St. Helens NW (WA) sheet showing the loactions of samples KA-1 and KB-1

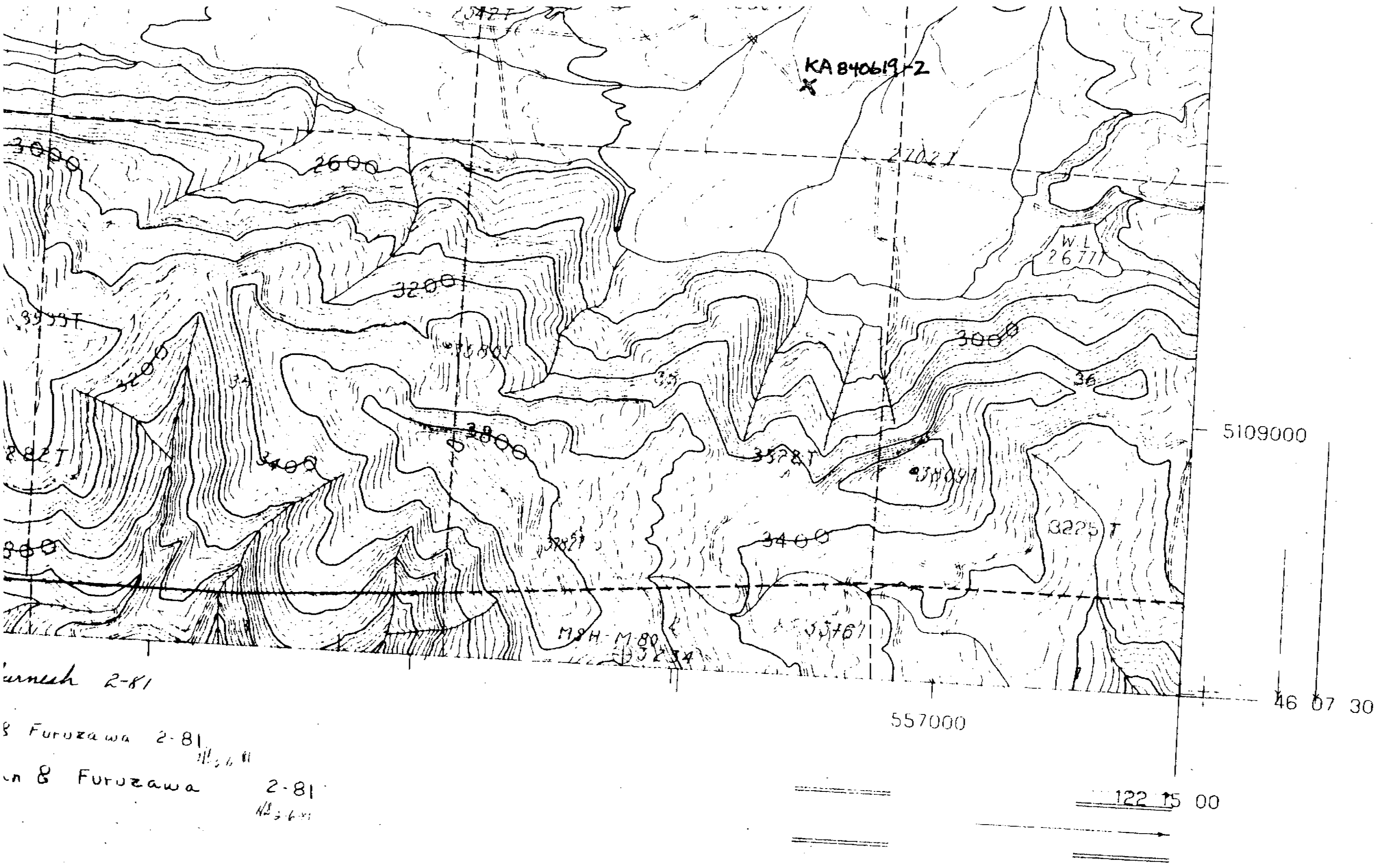


Plate 5. 2-23

COUGAR NE, WA. C. I. 40' 468-10
MSH-M-80 F.H 20000 1980
WASH, S ZONE — 10000 FEET
UTM ZONE 10 — 1000 METERS
LAMB CONF CONIC PROJ
MT ST HELENS PROJ. SCALE 1: 24000

Plate 5.2-23 : Portion of the Cougar NE (WA) sheet showing the location of sample KA-2

Appendix 3 (continued):

PUBLISHED RADIOMETRIC AGES OF ROCKS SAMPLED FOR THE CALIBRATION OF COSMOGENIC ISOTOPE GEOCHRONOMETERS

LOCALITY	SPLE#	USGS QUAD	ROCK TYPE	AGE(MY)	DATED SPLE#, METHOD, REFERENCE
CALIFORNIA (cont')					
LASSEN VOLCANIC FIELD					
Sunflower Dome	SF84-1	Lassen Volcanic Park	dacite	0.036±0.024	LC84-410, U-Th, (10)
Devastated Area	DE84-1	Lassen Volcanic Park	andesite	70 yr	observed, (11)
Butte Lake	BL84-1	Lassen Volcanic Park	basalt	100 yr	observed, (12)
Reading Peak	L-683	Lassen Volcanic Park	dacite	0.212±0.006	LC81-683, whole-rock K-Ar, (10)
Bluff Falls	L-123	Lassen Volcanic Park	andesite	0.462±0.012	LC80-123, whole-rock K-Ar, (10)
Manzanita Creek	L-724	Lassen Volcanic Park	rhyodacite	0.054±0.003	LC81-724, U-Th, (10)
Viola	L-391	Lassen Volcanic Park	andesite	0.304±0.008	LC80-391, whole-rock K-Ar, (10)
Bumpass Mtn.	LC82-193	Lassen Volcanic Park	dacite	0.232±0.008	LC82-193, whole-rock K-Ar, (10)
King's Creek	LC80-538	Lassen Volcanic Park	rhyodacite	0.030±0.009	LC80-538, whole-rock K-Ar, (10)
	L-915	Lassen Volcanic Park	dacite	0.030±0.009	LC82-915, whole-rock K-Ar; ^{14}C, (10)
Manzanita	L-564	Lassen Volcanic Park	rhyodacite	0.055±0.012	LC80-534, U-Th, (10)
Lassen Peak	LC80-535	Lassen Volcanic Park	rhyodacite	7550 yr	LC80-535, 14C, (10)
				0.0088±0.0039	LC80-535, U-Th, (10)
Chaos Crags	LC81-661	Lassen Volcanic Park	rhyodacite	1080±30 yr	LC81-661, 14C, (10)
Twin Meadows	LC82-865	Lassen Volcanic Park	dacite	0.470±0.010	LC82-865, whole-rock K-Ar, (10)
Ski Heil	LC83-355	Lassen Volcanic Park	dacite	0.244±0.010	LC83-355, whole-rock K-Ar, (10)
WASHINGTON					
MT. ST. HELENS					
	MSH-80	Cougar NE *		4 yr	observed
Kalama age rocks					
	KA84-1	Mt. St. Helens NW *	andesite	420±175 yr	14C, (13)
	KA84-2	Cougar NE *	andesite	420±175 yr	14C, (13)
	KB84-1	Mt. St. Helens NW *	basalt	420±175 yr	14C, (13)
Ape Canyon age rocks					
	AP84-1	Mt. St. Helens SW *	basalt	32,400±8,400	14C, (13)

* provisional map

Appendix 3 (continued):

UNDATED OR EQUIVOCALLY DATED YOUNG VOLCANIC ROCKS

LOCALITY	SPLE#	USGS QUAD	ROCK TYPE	AGE(MY)	DATED SPLE#, METHOD, REFERENCE
NEW MEXICO					
COLORADO PLATEAU MARGIN					
McCartys	GR-1	Grants SE 7.5	basalt	900 yr	field relations, (14)
Laguna	LA-1	Laguna 7.5	basalt	0.38±0.25	68-L218, whole-rock K-Ar, (15)
CARRIZOZO AREA					
Broken Back Crater	BK-1	Broken Back Crater 15	basalt		
The malpais	CZ-1, CZ-2	Three Rivers 15	basalt	1000-1500 yr	field relations, (16, 17)
				2000-5000 yr	archeological artifacts, (18)
LAS CRUCES AREA					
San Miguel	FF-1	Black Mesa 7.5	basalt	0.49±0.02	D2725R, whole-rock K-Ar, (19)
				1.91±0.1	D2725R, whole-rock K-Ar, (19)
				0.232±0.8	D2725R, whole-rock K-Ar, (19)
				0.154±0.119	D2725R, whole-rock K-Ar, (19)
Santo Tomas	ST-1,2	Black Mesa 7.5	basalt	0.55±0.03	D2719R, whole-rock K-Ar, (19)
				2.68±0.35	D2719R, whole-rock K-Ar, (19)
				0.165±0.079	D2719R, whole-rock K-Ar, (19)
				0.131±0.131	D2719R, whole-rock K-Ar, (19)
POTRILLO MOUNTAINS AREA					
Aden Crater	AC-1	Aden 15	basalt	0.533±0.04	UAKA-79-130, feldspar K-Ar, (19)
Afton flows	AF-1	Afton 15	basalt		
	AF-2	Noria 15	basalt	0.530±0.03	D2720R, whole-rock K-Ar, (19)
				0.52±0.1	D2720R, whole-rock K-Ar, (19)
				0.144±0.077	D2720R, whole-rock K-Ar, (19)
				0.106±0.086	D2720R, whole-rock K-Ar, (19)
Kilbourne Hole	KH-1	Noria 15	peridotite		
CALIFORNIA					
LONG VALLEY	SLR-8, MM84-5	Mt. Morrison 15	basalt	62,000<>126,000 yr	glacial stratigrpahy, (20)

5.3.1: APPENDIX 3: PUBLISHED RADIOMETRIC AGES OF ROCKS SAMPLED FOR THE CALIBRATION OF COSMOGENIC ISOTOPE GEOCHRONOMETERS

LOCALITY	SPLE#	USGS QUAD	ROCK TYPE	AGE(MY)	DATED SPLE#, METHOD, REFERENCE
NEW MEXICO					
ALBUQUERQUE BASIN					
Albuquerque volcanics	LG-1	Los Griegos 7.5	basalt	0.19±0.04	DKA2324, whole-rock K-Ar, (1)
Cat Hills	DA-1, DA-2	Dalies 7.5	basalt	0.14±0.038	Qbl, feldspar K-Ar, (2)
COLORADO PLATEAU MARGIN					
Cerro Verde	SG-1	South Garcia 7.5	basalt	0.32±0.22	DKA3064, whole-rock K-Ar, (1)
				0.278±0.302	UAKA86-64, feldspar K-Ar, (3)
JORNADA DEL MUERTO					
The malpais	VV-1	Val Verde 15	basalt	0.76±0.1	DKA3063, whole-rock K-Ar, (1)
ARIZONA					
SAN FRANCISCO VOLCANIC FIELD					
Sunset Crater	NSCB-1	O'Leary Peak 7.5	basalt	1066yr	dendrochronology, (4)
CALIFORNIA					
MONO CRATERS					
Punch Bowl	SLR-2, MC84-1	Mono Craters 15	rhyolite	11,500±2,900yr	6G006, sanidine K-Ar, (5)
				9,000±1,800yr	6G006, sanidine K-Ar, (5)
				10,900±4,200yr	6G006, sanidine K-Ar, (5)
	SLR-3, MC84-2	Mono Craters 15	rhyolite	6,800±1,400yr	5G202, sanidine K-Ar, (5)
				6,100±1,200yr	5G202, sanidine K-Ar, (5)
	MC84-3	Mono Craters 15	rhyolite	8,700±1,400yr	6G005, sanidine K-Ar, (5)
	MC84-4	Mono Craters 15	rhyolite	6,900±1,600yr	5G204, sanidine K-Ar, (5)
				6,300±1,400yr	5G204, sanidine K-Ar, (5)
Panum Crater	SLR-4, SLR-5	Mono Craters 15	obsidian	1,300yr	hydration-rind dating, (6)
Wilson Butte	SLR-6	Mono Craters 15	obsidian	2,500yr	hydration-rind dating, (6)
LONG VALLEY					
	MM84-1	Mt. Morrison 15	basalt	0.104±0.011	73G009, whole-rock K-Ar, (7)
	MM84-2	Mt. Morrison 15	basalt	0.145±0.015	73G008, whole-rock K-Ar, (7)
	SLR-7, MM84-3	Mt. Morrison 15	rhyolite	0.106±0.003	72G007, sanidine K-Ar, (7)
	MM84-4	Mt. Morrison 15	basalt	0.151±0.027	72G016, whole-rock K-Ar, (7)
	MM84-6	Mt. Morrison 15	basalt	0.062±0.013	73G014, whole-rock K-Ar, (7)
CIMA VOLCANIC FIELD					
	C84-40	Old Dad Mtn. 15	basalt	0.67±0.13	MC-40, feldspar K-Ar, (8,9)
				0.48±0.114	UAKA86-62, feldspar K-Ar, (3)
	C84-41	Old Dad Mtn. 15	basalt	0.27±0.10	MC-41, feldspar K-Ar, (8,9)
				0.227±0.1	UAKA86-63, feldspar K-Ar, (3)

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5.4 APPENDIX 4: WHOLE-ROCK MAJOR-ELEMENT DATA IN WEIGHT PERCENT

DATA FOR ROCKS COLLECTED IN NEW MEXICO

SAMPLE	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	TOTAL	n=	Rock Type
DA-1	50.04	1.91	16.56	11.17	0.17	6.84	9.21	3.37	1.06	0.40	100.73	2	basalt
DA-2	49.43	1.85	16.30	11.62	0.17	6.57	9.33	3.03	0.97	0.49	99.76	1	basalt
SG-1A	50.59	1.51	15.14	12.41	0.16	8.55	8.49	2.77	0.76	0.23	100.61	1	basalt
SG-1B	50.42	1.48	15.34	12.07	0.16	8.48	8.59	2.70	0.78	0.22	100.24	2	basalt
SG-1C	50.19	1.59	15.26	12.33	0.17	8.55	8.50	2.79	0.75	0.21	100.34	1	basalt
LG-1A	50.05	1.53	15.43	11.46	0.16	8.48	9.57	2.63	0.53	0.21	100.05	1	basalt
GR-1	51.15	1.51	15.23	12.02	0.16	8.09	9.13	2.70	0.73	0.21	100.93	1	basalt
LA-1	50.15	1.31	14.94	12.77	0.17	8.80	8.80	2.74	0.57	0.18	100.43	1	basalt
CZ-1	50.72	1.58	16.63	10.60	0.15	6.73	8.04	3.72	1.45	0.35	99.97	1	basalt
CZ-2	51.01	1.67	15.98	11.15	0.15	6.55	8.23	3.68	1.44	0.34	100.20	1	basalt
AC-1	45.91	2.19	15.33	11.12	0.17	9.54	9.77	3.23	1.82	0.55	99.63	2	basalt
AF-1	45.38	2.01	14.55	12.25	0.18	10.88	10.95	2.93	1.54	0.50	101.17	1	basalt
AF-2	45.25	2.17	15.21	11.86	0.18	9.75	10.93	2.91	1.62	0.53	100.41	3	basalt
FF-1	47.09	2.06	16.47	11.38	0.17	8.42	9.50	3.47	1.67	0.55	100.78	1	basalt
ST-1	47.28	2.11	16.62	10.48	0.16	7.63	9.44	3.51	1.87	0.57	99.67	1	basalt
ST-2	47.21	2.08	16.18	11.24	0.17	8.71	9.29	3.53	1.77	0.57	100.75	1	basalt
VV-1	50.54	1.65	16.39	10.54	0.16	6.52	8.47	3.45	1.69	0.42	99.83	1	basalt
KH-3	44.78	0.34	3.31	9.71	0.14	40.09	3.04	0.01	0.03	0.02	101.47	2	peridotite
ERROR(±)	0.31	0.02	0.40	0.46	0.01	0.44	0.06	0.04	0.20	0.10			

DATA FOR ROCKS COLLECTED IN ARIZONA

SAMPLE	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	TOTAL	n=	Rock Type
NSCB-1	48.16	1.71	16.49	11.85	0.17	7.99	9.96	3.19	0.84	0.49	100.85	1	basalt
ERROR(±)	0.31	0.02	0.40	0.46	0.01	0.44	0.06	0.04	0.20	0.10			

Appendix 4 (continued):

WHOLE-ROCK MAJOR-ELEMENT DATA IN WEIGHT PERCENT

DATA FOR ROCKS COLLECTED AT MONO CRATERS AND LONG VALLEY CALIFORNIA

SAMPLE	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	TOTAL	n=	Rock Type
MC-1	74.42	0.06	12.32	1.28	0.05	0.03	0.56	3.64	4.51	0.00	96.87	1	rhyolite
MC-2	74.63	0.07	12.41	1.35	0.04	0.03	0.57	3.62	4.65	0.00	97.37	2	rhyolite
MC-3	75.34	0.07	12.48	1.23	0.05	0.03	0.57	3.81	4.69	0.01	98.28	2	rhyolite
MC-4	75.25	0.06	12.51	1.28	0.04	0.04	0.56	3.75	4.55	0.00	98.04	3	rhyolite
SLR-2	76.24	0.26	12.66	1.28	0.05	0.04	0.56	3.80	4.62	0.00	99.51	1	rhyolite
SLR-3	75.68	0.11	12.58	1.15	0.05	0.04	0.57	3.89	4.61	0.00	98.68	1	rhyolite
SLR-4	77.93	0.14	12.66	1.24	0.04	0.02	0.57	3.92	4.67	0.00	101.19	1	obsidian
SLR-5	77.32	0.26	12.72	1.18	0.04	0.02	0.57	3.94	4.66	0.00	100.71	1	rhyolite
SLR-6	75.81	0.17	12.62	1.11	0.04	0.04	0.56	3.87	4.63	0.00	98.85	1	rhyolite
SLR-7	74.86	0.22	12.77	1.25	0.05	0.20	0.76	3.62	4.54	0.04	98.31	1	rhyolite
SLR-8	52.44	1.37	20.06	7.67	0.10	4.11	7.96	3.47	1.52	0.79	99.49	1	basalt
MM-1	49.61	1.86	18.21	9.18	0.14	5.60	8.90	3.38	1.63	0.58	98.91	2	basalt
MM-2	54.24	1.29	18.21	7.65	0.11	3.94	7.08	4.07	1.89	0.42	98.90	2	basalt
MM-3	74.48	0.15	12.65	1.21	0.05	0.19	0.77	3.56	4.63	0.02	97.71	2	rhyolite
MM-4	52.28	1.65	17.91	9.18	0.14	5.18	8.08	4.12	1.64	0.46	100.64	2	basalt
MM-5	51.06	1.38	17.39	8.66	0.12	7.03	8.75	4.08	1.32	0.36	100.15	2	basalt
MM-6	50.41	1.97	17.39	10.29	0.14	4.73	7.95	4.63	1.79	0.56	99.86	2	basalt
ERROR(±)	0.31	0.02	0.40	0.46	0.01	0.44	0.06	0.04	0.20	0.10			

DATA FOR ROCKS COLLECTED IN THE CIMA VOLCANIC FIELD, CALIFORNIA

SAMPLE	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	TOTAL	n=	Rock Type
C-40	47.20	2.74	16.47	11.25	0.18	6.76	8.55	4.16	1.89	0.62	99.82	2	basalt
C-41	48.27	2.71	16.96	10.71	0.17	6.57	8.09	3.93	2.02	0.69	100.12	2	basalt

Appendix 4 (continued):

WHOLE-ROCK MAJOR-ELEMENT DATA IN WEIGHT PERCENT

DATA FOR ROCKS COLLECTED IN LASSEN VOLCANIC NATIONAL PARK

SAMPLE	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	TOTAL	n=	Rock Type
SF-1	68.71	0.35	15.61	2.68	0.05	1.24	3.08	4.11	2.77	0.08	98.68	3	dacite
DE-1	63.13	0.56	16.78	4.82	0.08	2.91	5.24	3.44	2.14	0.13	99.23	2	andesite
BL-1	55.84	0.80	16.27	6.80	0.12	7.14	7.53	3.45	1.46	0.17	99.58	1	basalt
L683-A	66.68	0.43	15.77	3.58	0.07	1.72	3.77	3.46	2.54	0.09	98.11	3	dacite
L683-B	66.35	0.42	16.08	3.37	0.07	1.65	3.90	3.94	2.50	0.09	98.37	3	dacite
L915-A	69.83	0.38	15.23	2.61	0.06	1.24	3.06	3.64	2.83	0.10	98.98	2	dacite
L915-B	69.74	0.39	15.33	3.20	0.06	1.35	3.02	3.70	2.75	0.10	99.64	3	dacite
L123-1	58.39	0.74	17.35	6.32	0.10	3.87	7.04	3.26	1.74	0.14	98.95	1	andesite
L123-1	58.74	0.72	17.56	6.22	0.11	3.90	7.08	3.18	1.53	0.16	99.20	2	andesite
L123-3	58.54	0.74	17.99	6.82	0.11	3.95	7.29	3.34	1.53	0.16	100.47	2	andesite
L724-1	68.56	0.36	15.12	2.48	0.06	1.11	2.79	4.11	2.70	0.09	97.38	3	rhyodacite
L724-2	66.91	0.40	15.75	2.80	0.06	1.25	2.95	4.02	2.49	0.10	96.73	3	rhyodacite
L391	57.79	1.04	17.22	5.97	0.10	2.96	6.64	4.78	2.10	0.31	98.91	2	andesite
L564	68.17	0.46	15.71	2.67	0.06	1.02	2.57	4.01	3.03	0.10	97.80	3	rhyodacite
ERROR(±)	0.31	0.02	0.40	0.46	0.01	0.44	0.06	0.04	0.20	0.10			

Appendix 4 (continued):

DATA FOR ROCKS COLLECTED AT MT. ST. HELENS WASHINGTON

SAMPLE	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	TOTAL	n=	Rock Type
AP-1	50.17	1.63	16.72	11.38	0.17	6.63	9,78	3.25	0.52	0.19	100.44	2	basalt
KA-1	63.48	0.90	17.11	5.52	0.08	1.77	4.86	4.67	1.51	0.18	100.08	1	andesite
KA-2	63.81	0.75	17.09	5.01	0.08	2.27	5.00	4.11	1.46	0.16	99.74	3	andesite
KB-1	54.11	1.53	17.34	8.94	0.13	5.02	7.76	3.72	1.03	0.23	99.81	2	basalt
MSH-80	62.32	0.98	16.49	6.62	0.10	1.99	5.04	4.37	1.48	0.19	99.58	1	dacite
MSH-83	62.93	0.71	18.28	5.11	0.08	2.27	5.45	4.21	1.26	0.14	100.44	2	dacite
ERROR(±)	0.31	0.02	0.40	0.46	0.01	0.44	0.06	0.04	0.20	0.10			

DATA FOR ROCKS COLLECTED AT USU JAPAN

SAMPLE	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	TOTAL	n=	Rock Type
USU-78	70.47	0.50	15.24	4.13	0.16	0.95	3.92	4.47	0.94	0.17	100.95	1	dacite
ERROR(±)	0.31	0.02	0.40	0.46	0.01	0.44	0.06	0.04	0.20	0.10			

5.5 APPENDIX 5: WHOLE-ROCK MINOR-ELEMENT DATA IN PARTS PER MILLION

DATA FOR ROCKS COLLECTED IN NEW MEXICO

SAMPLE	Cl	B	Co	Hf	Rb	Th	U	Sc	La	Ce	Nd	Sm	Eu	Gd	Tb	Yb	Lu
DA-1	<25	1.3	42.23	4.03	n.d.	2.24	0.35	25.85	20.2	40.4	19.6	4.53	1.65	5.18	n.d.	2.55	n.d.
SG-1A	58	4.1	56.70	3.22	n.d.	1.70	0.58	24.17	11.5	19.4	20.9	3.58	1.23	4.62	n.d.	2.06	n.d.
SG-1B	<25	4.2	55.17	3.33	n.d.	1.90	0.54	25.87	11.6	26.2	20.9	3.42	1.33	4.55	n.d.	2.47	n.d.
SG-1C	<25	4.0	55.25	3.42	n.d.	1.74	0.57	25.27	13.7	21.9	20.9	3.94	1.34	4.83	n.d.	2.40	n.d.
LG-1A	<25	1.3	56.85	2.67	n.d.	1.23	0.44	25.50	10.1	23.2	12.6	3.18	1.26	4.05	n.d.	2.16	n.d.
CZ-2	198	n.d.	44.4	4.16	31.6	3.32	1.05	21.8	24.4	52.3	24.9	5.85	1.89	5.23	0.76	2.56	0.393
AC-1	173	n.d.	52.0	5.28	46.0	5.09	1.26	39.1	25.4	82.6	36.3	7.01	2.27	6.23	0.88	2.68	0.382
AF-1	109	n.d.	63.0	5.00	41.4	3.97	1.08	36.0	34.2	81.3	<25	6.67	2.56	6.23	1.03	2.54	0.399
AF-2	<25	n.d.	48.4	4.61	32.4	3.37	1.09	31.3	27.1	53.5	26.6	5.83	1.71	6.86	0.81	2.44	0.402
FF-1	323	n.d.	50.2	5.27	36.8	4.61	1.13	26.1	40.4	84.3	42.0	7.23	2.36	4.48	1.09	3.60	0.404
ST-1	376	n.d.	58.6	8.09	65.9	6.28	1.30	29.9	44.6	112.6	41.0	7.86	2.75	9.21	1.65	3.20	0.556
ST-2	298	n.d.	47.2	5.65	44.4	5.05	1.32	24.5	43.1	88.3	28.0	8.08	2.42	7.22	1.12	2.97	0.487
%ERROR(±)	9	10	5	6	12	5	5	5	5	5	15	5	5	15	12	9	12

DATA FOR ROCKS COLLECTED IN ARIZONA

SAMPLE	Cl	B	Co	Hf	Rb	Th	U	Sc	La	Ce	Nd	Sm	Eu	Gd	Tb	Yb	Lu
NSCB-1	33	1.9	50.03	3.26	n.d.	2.82	1.05	n.d.	25.1	30.3	60.1	24.70	5.60	1.87	5.02	n.d.	2.24
%ERROR(±)	9	10	5	6	12	5	5	5	5	5	15	5	5	15	12	9	12

Appendix 5 (continued):

WHOLE-ROCK MINOR-ELEMENT DATA IN PARTS PER MILLION

DATA FOR ROCKS COLLECTED AT MONO CRATERS AND LONG VALLEY CALIFORNIA

SAMPLE	Cl	B	Co	Hf	Rb	Th	U	Sc	La	Ce	Nd	Sm	Eu	Gd	Tb	Yb	Lu
MC-1	475	31.5	4.90	4.80	n.d.	19.8	6.25	1.76	23.8	55.4	24.0	4.9	0.14	4.19	n.d.	3.15	n.d.
MC-2	484	33.2	6.51	5.06	n.d.	20.4	6.24	1.76	22.1	50.3	17.4	4.7	0.12	4.68	n.d.	3.41	n.d.
MC-3	502	22.5	0.44	5.34	223	22.6	6.26	1.86	26.8	57.5	32.9	3.7	0.19	4.15	0.78	3.78	0.470
MC-4	493	24.0	0.64	8.40	289	31.1	6.48	2.21	29.7	84.8	51.9	4.6	0.25	4.10	1.33	3.69	0.676
SLR-2	428	31.5	4.90	4.80	n.d.	19.8	6.23	1.76	23.8	55.4	20.4	4.9	0.14	4.19	n.d.	3.15	n.d.
SLR-3	401	33.2	6.51	5.06	n.d.	20.4	6.20	1.72	22.1	50.3	17.4	4.7	0.12	4.68	n.d.	3.41	n.d.
SLR-4	432	32.9	14.03	4.81	n.d.	21.5	6.31	1.95	23.8	55.4	18.5	4.98	0.17	4.68	n.d.	3.25	n.d.
SLR-5	600	75.8	13.00	4.89	n.d.	20.5	6.20	1.85	24.1	54.8	22.8	4.85	0.14	5.31	n.d.	3.42	n.d.
SLR-6	477	34.3	8.32	4.74	n.d.	21.0	6.25	1.88	22.3	52.2	20.4	5.00	0.15	4.21	n.d.	3.41	n.d.
SLR-7	221	53.9	7.31	5.16	209	20.5	6.41	1.45	25.8	56.2	17.5	3.84	0.30	3.49	0.55	2.40	0.390
MM-3	171	53.9	1.50	5.29	203	21.0	6.29	1.45	27.1	54.5	20.1	3.56	0.29	3.49	0.57	2.43	0.386
%ERROR(±)	9	10	5	6	12	5	5	5	5	5	15	5	5	15	12	9	12

DATA FOR ROCKS COLLECTED IN THE CIMA VOLCANIC FIELD, CALIFORNIA

SAMPLE	Cl	B	Co	Hf	Rb	Th	U	Sc	La	Ce	Nd	Sm	Eu	Gd	Tb	Yb	Lu
C-40	400	n.d.	43	7.28	46.6	5.00	1.21	20.0	43.6	85.9	46	8.82	2.74	7.72	1.18	3.22	0.414
C-41	380	n.d.	58.9	11.6	61.5	7.66	1.31	23.3	47.5	124.1	61	9.43	3.3	10.96	1.90	2.53	0.550
%ERROR(±)	9	10	5	6	12	5	5	5	5	5	15	5	5	15	12	9	12

Appendix 5 (continued):

WHOLE-ROCK MINOR-ELEMENT DATA IN PARTS PER MILLION

DATA FOR ROCKS COLLECTED IN LASSEN VOLCANIC NATIONAL PARK

SAMPLE	Cl	B	Co	Hf	Rb	Th	U	Sc	La	Ce	Nd	Sm	Eu	Gd	Tb	Yb	Lu
L683-A	<25	n.d.	9.1	3.6	70	8.9	2.90	8.11	21	38	13	2.3	0.68	3.0	0.38	1.4	0.210
L915-A	256	n.d.	6.1	3.5	68	11.1	3.37	5.70	24.4	39.8	14.3	2.83	0.65	2.52	0.29	1.28	0.198
L123-1	287	n.d.	20.6	3.3	37	4.6	1.4	20.5	18	32	26	3.1	0.92	3.9	0.55	1.8	0.28
L724-2	399	18.4	4.4	4.0	79	11.7	3.4	4.54	27	44	19	2.5	0.66	3.2	0.30	1.5	0.23
L391	146	n.d.	16.8	4.0	39	4.7	1.4	18.3	23	43	25	4.4	1.23	3.6	0.53	1.8	0.32
%ERROR(±)	9	10	5	6	12	5	5	5	5	5	15	5	5	15	12	9	12

DATA FOR ROCKS COLLECTED AT MT. ST. HELENS WASHINGTON

SAMPLE	Cl	B	Co	Hf	Rb	Th	U	Sc	La	Ce	Nd	Sm	Eu	Gd	Tb	Yb	Lu
MSH-83	293	10	13	n.d.	n.d.	4	0.99	10	13	24	13	2.45	<2	2.6	n.d.	1	n.d.
%ERROR(±)	9	10	5	6	12	5	5	5	5	5	15	5	5	15	12	9	12

5.6 APPENDIX 6: TOTAL CHLORIDE CONTENT OF ANALYSED ROCKS BY XRF

DATA FOR SAMPLES COLLECTED IN NEW MEXICO

SAMPLE	ppm Cl UNLEACHED	ppm Cl LEACHED
DA-1	218	<25
DA-2	22	<25
SG-1A	129	54
SG-1B	90	11
SG-1C	66	<25
LG-1A	58	<25
CZ-1	137	<25
CZ-2	328	197
GR-1	59	<25
LA-1	135	<25
AC-1	332	157
AF-1	275	93
AF-2	306	<25
ST-1	564	361
ST-2	525	279
FF-1	1155	305
VV-1	<25	<25

Appendix 6 (continued):

DATA FOR SAMPLES COLLECTED IN CALIFORNIA

SAMPLE	ppm Cl UNLEACHED	ppm Cl LEACHED
SLR-2	554	462
SLR-3	609	436
SLR-4	620	466
SLR-5	973	604
SLR-6	598	509
SLR-7	305	219
SLR-8	333	<25
MC-1	529	475
MC-2	517	512
MC-3	1019	505
MC-4	619	525
MM-1	181	43
MM-2	96	<25
MM-3	179	175
MM-4	<25	<25
MM-5	233	<25
MM-6	<25	<25
C-40	546	391
C-41	569	369
L724-1	531	508
L724-2	531	434
L683-A	<25	<25
L683-B	135	87

Appendix 6 (continued):
DATA FOR SAMPLES COLLECTED IN CALIFORNIA (continued)

SAMPLE	ppm Cl UNLEACHED	ppm Cl LEACHED
L391	216	190
L915-A	494	297
L915-B	362	232
SF-1	345	276
DE-1	87	<25
L564	267	257
L123-1	501	263
L123-2	262	101
L123-3	611	97
BL-1	303	251

TOTAL CHLORIDE CONTENT OF ANALYSED ROCKS BY XRF

DATA FOR SAMPLES COLLECTED IN WASHINGTON

SAMPLE	ppm Cl UNLEACHED	ppm Cl LEACHED
MSH-80	487	301
MSH-83	533	293
KA-1	251	89
KA-2	73	64
KB-1	125	79
AP-1	<25	<25

5.7 APPENDIX 7: REPRESENTATIVE WHOLE-ROCK COMPOSITIONS

ROCK TYPE	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	Cl	B	Li	Sm	Gd
Syenite	58.58	0.84	16.64	6.51	0.17	1.87	3.53	5.24	4.95	429	20	20	9.5	5.8
Trachyte	61.21	0.70	16.96	5.53	0.15	0.93	2.34	5.47	4.98	128	6	20	11	7.4
Granite	71.30	0.31	14.32	3.03	0.05	0.71	1.84	3.68	4.07	202	12	35	8.3	7.6
Rhyolite	72.82	0.28	13.27	2.71	0.06	0.39	1.14	3.55	4.30	328	25	50	8.5	7.3
Granodiorite	66.09	0.54	15.73	4.41	0.08	1.74	3.83	3.75	2.73	219	25	30	8.5	7.4
Rhyodacite	65.55	0.60	15.04	4.38	0.09	2.09	3.62	3.67	3.00	264	16	30	6.2	6.8
Dacite	65.01	0.58	15.91	4.98	0.09	1.78	4.32	3.79	2.17	213	16	30	6.2	6.8
Diorite	57.48	0.95	16.67	7.96	0.12	3.71	6.58	3.54	1.76	335	15	25	8.3	7.6
Andesite	57.94	0.87	17.02	7.75	0.14	3.33	6.79	3.48	1.62	166	25	15	6.2	6.8
Gabbro	50.14	1.12	15.48	11.47	0.12	7.59	9.58	2.39	0.93	186	10	15	2.5	3.0
Diabase	50.14	1.49	15.02	11.80	0.16	6.40	8.90	2.91	0.99	227	10	15	5.0	5.5
Basalt	49.20	1.84	15.74	11.70	0.20	6.73	9.47	2.91	1.10	129	5	15	6.8	6.2
Peridotite	42.26	0.63	1.82	10.91	0.41	31.24	5.05	0.49	0.34	156	5	2	1.0	1.0

N.B. Oxides in weight %, from LeMaitre, R.W., 1976, The chemical variability of some common igneous rocks; Journal of Petrology, v. 17, p. 589-637. All Fe expressed as Fe_2O_3. Elements in ppm from Wedepohl, K.H., (ed.), 1978, Handbook of Geochemistry; Berlin, Springer-Verlag.

5.8 APPENDIX 8: THERMAL-NEUTRON ABSORPTION CROSS-SECTIONS BY ELEMENT AND TOTAL FOR REPRESENTATIVE WHOLE-ROCK COMPOSITIONS

ROCK TYPE	Si	Ti	Al	Fe	Mn	Mg	Ca	Na	K	Cl	B	Li	Sm	Gd	other*	TOTAL
Syenite	0.937	0.386	0.466	1.237	0.167	0.022	0.162	0.052	1.227	0.240	0.840	0.124	0.228	1.102	0.124	7.424
Trachyte	0.979	0.322	0.475	1.051	0.147	0.011	0.108	0.055	1.345	0.072	0.242	0.124	0.264	1.406	0.112	6.713
Granite	1.141	0.143	0.401	0.576	0.049	0.009	0.085	0.037	1.099	0.113	0.504	0.217	0.199	1.444	0.102	6.119
Rhyolite	1.165	0.129	0.372	0.515	0.059	0.005	0.052	0.036	1.161	0.184	1.050	0.310	0.204	1.387	0.113	6.742
Granod.	1.057	0.248	0.440	0.838	0.078	0.021	0.176	0.038	0.737	0.123	1.050	0.186	0.204	1.406	0.112	6.714
Rhyod.	1.049	0.276	0.421	0.832	0.088	0.025	0.167	0.037	0.810	0.148	0.672	0.186	0.149	1.292	0.105	6.257
Dacite	1.041	0.267	0.445	0.946	0.088	0.021	0.199	0.038	0.586	0.119	0.672	0.186	0.149	1.292	0.103	6.152
Diorite	0.920	0.437	0.467	1.512	0.118	0.045	0.303	0.035	0.475	0.188	0.630	0.155	0.199	1.444	0.118	7.046
Andesite	0.927	0.400	0.477	1.473	0.137	0.040	0.312	0.035	0.437	0.093	1.050	0.093	0.149	1.292	0.118	7.033
Gabbro	0.802	0.515	0.433	2.179	0.118	0.091	0.441	0.024	0.251	0.104	0.420	0.093	0.060	0.570	0.104	6.205
Diabase	0.802	0.685	0.421	2.242	0.157	0.077	0.409	0.029	0.267	0.127	0.420	0.093	0.120	1.045	0.117	7.011
Basalt	0.787	0.846	0.441	2.223	0.196	0.081	0.436	0.029	0.297	0.072	0.210	0.093	0.163	1.178	0.120	7.172
Perid.	0.676	0.290	0.051	2.073	0.402	0.375	0.232	0.005	0.092	0.087	0.210	0.012	0.024	0.190	0.080	4.799

* see discussion Section 2.5

5.9 APPENDIX 9: THERMAL-NEUTRON ABSORPTION CROSS-SECTIONS BY ELEMENT AND TOTAL

DATA FOR ROCKS COLLECTED IN NEW MEXICO

SAMPLE	Si	Ti	Al	Fe	Mn	Mg	Ca	Na	K	Cl	B	Li	Sm	Gd	others*	TOTAL
DA-1	0.801	0.879	0.464	2.122	0.167	0.082	0.424	0.034	0.029	0.014	0.550	0.155	0.109	0.984	0.116	6.93
SG-1A	0.809	0.695	0.424	2.358	0.157	0.103	0.391	0.028	0.021	0.032	0.172	0.155	0.086	0.878	0.107	6.42
SG-1B	0.807	0.681	0.430	2.293	0.157	0.102	0.395	0.027	0.021	0.014	0.176	0.155	0.082	0.865	0.106	6.31
SG-1C	0.803	0.731	0.427	2.343	0.167	0.103	0.391	0.028	0.020	0.014	0.168	0.155	0.095	0.918	0.108	6.47
CZ-1	0.812	0.727	0.466	2.014	0.147	0.081	0.370	0.037	0.039	0.014	0.210	0.155	0.140	0.994	0.106	6.22
CZ-2	0.816	0.768	0.447	2.119	0.147	0.079	0.379	0.037	0.039	0.111	0.210	0.155	0.140	0.994	0.110	6.55
AC-1	0.735	1.007	0.429	2.113	0.167	0.114	0.449	0.032	0.049	0.097	0.210	0.155	0.168	1.184	0.118	7.03
AF-1	0.726	0.925	0.404	2.238	0.176	0.131	0.504	0.029	0.042	0.061	0.210	0.155	0.160	0.994	0.116	6.96
AF-2	0.724	0.998	0.426	2.253	0.176	0.117	0.503	0.029	0.044	0.014	0.210	0.155	0.140	1.303	0.121	7.21
FF-1	0.753	0.948	0.461	2.162	0.167	0.101	0.437	0.035	0.045	0.181	0.210	0.155	0.174	0.851	0.114	6.79
ST-1	0.756	0.971	0.465	1.991	0.157	0.092	0.434	0.035	0.050	0.211	0.210	0.155	0.189	1.750	0.127	7.59
ST-2	0.755	0.957	0.453	2.136	0.167	0.105	0.427	0.035	0.048	0.167	0.210	0.155	0.194	1.372	0.120	7.15

DATA FOR ROCKS COLLECTED IN THE CIMA VOLCANIC FIELD, CALIFORNIA

SAMPLE	Si	Ti	Al	Fe	Mn	Mg	Ca	Na	K	Cl	B	Li	Sm	Gd	others*	TOTAL
C-40	0.755	1.260	0.461	2.138	0.176	0.081	0.393	0.042	0.051	0.224	0.210	0.155	0.212	1.467	0.130	7.75
C-41	0.772	1.247	0.475	2.035	0.167	0.079	0.372	0.039	0.055	0.213	0.210	0.155	0.226	2.082	0.138	8.27

DATA FOR ROCKS COLLECTED AT MT. ST. HELENS WASHINGTON

SAMPLE	Si	Ti	Al	Fe	Mn	Mg	Ca	Na	K	Cl	B	Li	Sm	Gd	others*	TOTAL
MSH-83	1.007	0.327	0.512	0.971	0.078	0.027	0.251	0.042	0.034	0.164	0.630	0.136	0.113	0.804	0.084	5.04

* see discussion in Section 2.5

Appendix 9 (continued):

THERMAL-NEUTRON ABSORPTION CROSS-SECTIONS BY ELEMENT AND TOTAL

DATA FOR ROCKS COLLECTED AT MONO CRATERS AND LONG VALLEY CALIFORNIA

SAMPLE	Si	Ti	Al	Fe	Mn	Mg	Ca	Na	K	Cl	B	Li	Sm	Gd	others*	TOTAL
MC-1	1.191	0.028	0.345	0.243	0.049	--	0.026	0.036	0.122	0.266	1.323	0.117	0.796	0.186	0.080	4.81
MC-2	1.194	0.032	0.347	0.257	0.039	--	0.026	0.036	0.126	0.271	1.394	0.113	0.889	0.186	0.083	4.99
MC-3	1.205	0.032	0.349	0.234	0.049	--	0.026	0.038	0.127	0.281	0.937	0.186	0.118	0.946	0.077	4.61
MC-4	1.204	0.028	0.350	0.243	0.039	--	0.026	0.038	0.123	0.276	1.008	0.140	1.372	0.186	0.086	5.12
SLR-2	1.220	0.120	0.354	0.243	0.049	--	0.026	0.038	0.125	0.240	1.323	0.186	0.117	0.796	0.082	4.92
SLR-3	1.211	0.051	0.352	0.219	0.049	--	0.026	0.039	0.124	0.225	1.394	0.186	0.113	0.889	0.083	4.96
SLR-4	1.247	0.064	0.354	0.236	0.039	--	0.026	0.039	0.126	0.242	1.382	0.186	0.120	0.889	0.084	5.03
SLR-6	1.213	0.078	0.353	0.211	0.039	--	0.026	0.039	0.125	0.267	1.441	0.120	0.800	0.186	0.083	4.98
SLR-7	1.198	0.101	0.358	0.238	0.049	0.002	0.026	0.036	0.123	0.124	2.264	0.186	0.092	0.663	0.093	5.55
MM-2	0.868	0.593	0.510	1.454	0.108	0.047	0.326	0.041	0.051	0.063	0.210	0.155	0.095	0.095	0.093	5.56
MM-3	1.192	0.069	0.354	0.230	0.049	0.002	0.035	0.036	0.125	0.096	2.264	0.085	0.663	0.155	0.091	5.45

DATA FOR ROCKS COLLECTED IN LASSEN VOLCANIC NATIONAL PARK

SAMPLE	Si	Ti	Al	Fe	Mn	Mg	Ca	Na	K	Cl	B	Li	Sm	Gd	others*	TOTAL
L683-A	1.067	0.198	0.442	0.680	0.069	0.021	0.173	0.035	0.069	0.014	0.630	0.186	0.055	0.570	0.071	4.28
L915-A	1.117	0.175	0.426	0.496	0.059	0.015	0.141	0.036	0.076	0.143	0.630	0.186	0.068	0.479	0.069	4.12
L915-B	1.116	0.179	0.429	0.608	0.059	0.016	0.139	0.037	0.074	0.106	0.630	0.068	0.479	0.186	0.070	4.20
L123-1	0.934	0.340	0.486	1.201	0.098	0.046	0.324	0.033	0.047	0.161	1.050	0.186	0.074	0.741	0.097	5.82
L724-1	1.097	0.166	0.423	0.471	0.059	0.013	0.128	0.041	0.073	0.258	0.777	0.186	0.060	0.608	0.074	4.43
L724-2	1.071	0.184	0.441	0.532	0.059	0.015	0.136	0.040	0.067	0.223	0.777	0.060	0.608	0.186	0.075	4.47
L391	0.925	0.478	0.482	1.134	0.098	0.036	0.305	0.048	0.057	0.082	1.050	0.186	0.106	0.684	0.096	5.77
SF-1	1.099	0.161	0.437	0.509	0.049	0.015	0.142	0.041	0.075	0.167	0.630	0.068	0.479	0.186	0.069	4.11

5.10 Appendix 10: California Snow Course Data*

Snow Course	Number	Latitude(N)	Longitude(W)	Elevation(m)	Aspect	Exposure	Sample Points	Record Began	Average April 1 Water Content(cm)
New Manzanita Lake	343	$40^{o}32.0'$	$121^{o}33.7'$	1798	north	open timber	10	1950	20.6 cm
Lower Lassen Peak	47	$40^{o}28.1'$	$121^{o}30.4'$	2514	northwest	open meadow	10	1930	204.0 cm
Harkness Flat	51	$40^{o}25.1'$	$121^{o}16.2'$	1889	west	open meadow	10	1930	74.7 cm
Mammoth	208	$37^{o}37.2'$	$118^{o}59.2'$	2529	northeast	open meadow	8	1928	50.8 cm

*Data from: 1986 California Snow Survey Measurement Schedule, State of California Department of Water Resources, Sacramento.

Snow course 343 data used in normalization of ^{36}Cl/Cl for samples SF-1, L724-1, L724-2, L391.
Snow course 47, samples L683-A, L915-A, L915-B.
Snow course 208, samples MC-1, MC-2, MC-3, MC-4, SLR-2, SLR-3, SLR-4, SLR-6, SLR-7, MM-2, MM-3.

5.11 APPENDIX 11: ELEVATION AND LATITUDE CORRECTIONS FOR COSMIC-RAY FLUX

5.11.1: ELEVATION CORRECTION FACTORS

ELEVATION(m)	PR RELATIVE TO 3840m*	PR RELATIVE TO SEA LEVEL
0	0.09	1.00
500	0.13	1.44
1000	0.18	2.00
1500	0.25	2.78
2000	0.35	3.89
2500	0.47	5.22
3000	0.63	7.00
3500	0.83	9.22
3840	1.00	11.11
4000	1.08	12.00
5000	1.76	19.56
6000	2.80	31.11
7000	4.20	46.67
8000	6.00	66.67

*Data from Yokoyama, Y; Reyss, J-L.; and Guichard, F., 1977, Production of radionuclides by cosmic rays at mountain altitudes; Earth and Planetary Sciences Letters, v. 36, p 44-50. These data were recalculated relative to sea level and the equation of the attenuation curve with depth in the atmosphere was determined to be roughly exponential between 0-8000 meters elevation:

$$\text{PR factor} = 1.07e^{(6.2\text{x}10^{-4}[\text{elevation}])}$$

GEOMAGNETIC LATITUDE FACTORS FOR WESTERN NORTH AMERICA

GEOMAGNETIC LATITUDE	RELATIVE PRODUCTION RATE*
58	1.49
52	1.39
47	1.23
44	1.09
38	0.86
32	0.70
28	0.56
20	0.45

*Data from Yokoyama and others, 1977. These data are given by continent. The equation of the attenuation curve with latitude was determined to be roughly linear between 24°-54° (N) geomagnetic latitude:

$$\text{PR factor} = 0.035(^{\circ}\text{geomagnetic latitude}) - 0.43$$

5.12 APPENDIX 12: NORMALIZATION DATA FOR SAMPLES COLLECTED IN NEW MEXICO

SAMPLE	LATITUDE (N)	LONGITUDE (W)	GEOM.LAT. (N)	L	ELEV (m)	E	DEPTH (cm)	S.G. (gm/cm^3)	D	K_2O (wt.%)	CaO (wt.%)	Cl (ppm)	n $ABS_{(tot)}$ (cm^2/kg)	nf(tot) (/ppmCl)
SG-1A	34°50'18"	107°03'06"	43.69°	1.10	1585	2.86	20	2.46	0.77	0.76	8.49	58	6.42	86.0
SG-1B	34°50'18"	107°03'06"	43.69°	1.10	1585	2.86	330	2.33	0.01	0.78	8.59	25	6.31	87.5
SG-1C	34°50'18"	107°03'06"	43.69°	1.10	1585	2.86	200	2.59	0.08	0.75	8.50	25	6.48	85.3

NORMALIZATION DATA FOR SAMPLES COLLECTED IN THE CIMA VOLCANIC FIELD CALIFORNIA

SAMPLE	LATITUDE (N)	LONGITUDE (W)	GEOM.LAT. (N)	L	ELEV (m)	E	DEPTH (cm)	S.G. (gm/cm^3)	D	K_2O (wt.%)	CaO (wt.%)	Cl (ppm)	n $ABS_{(tot)}$ (cm^2/kg)	nf(tot) (/ppmCl)
C84-40	34°15'30"	115°43'00"	42.52°	1.06	1219	2.28	200	2.32	0.09	1.89	8.55	400	7.71	71.6
C84-41	35°15'30"	115°43'00"	42.52°	1.06	1201	2.25	200	2.69	0.06	2.02	8.09	380	8.22	67.2

NORMALIZATION DATA FOR SAMPLES COLLECTED IN THE LASSEN VOLCANIC FIELD CALIFORNIA

SAMPLE	LATITUDE (N)	LONGITUDE (W)	GEOM.LAT. (N)	L	ELEV (m)	E	DEPTH (cm)	S.G. (gm/cm^3)	D	K_2O (wt.%)	CaO (wt.%)	Cl (ppm)	n $ABS_{(tot)}$ (cm^2/kg)	nf(tot) (/ppmCl)
L724-1	40°32'24"	121°34'24"	48.81°	1.28	1768	3.20	300	1.60	0.08	2.70	2.79	399	4.43	124.6
L724-2	40°32'24"	121°34'24"	48.81°	1.28	1768	3.20	100	1.68	0.41	2.49	2.95	399	4.47	123.4
L683-A	40°28'12"	121°26'30"	48.65°	1.27	2316	4.50	650	2.39	0.01	2.54	3.77	25	4.28	129.0
L391	40°30'00"	121°36'30"	48.78°	1.28	1853	3.38	150	2.34	0.16	2.10	6.64	146	5.77	95.7
L915-A	40°28'30"	121°30'12"	48.65°	1.27	2633	5.47	300	2.36	0.03	2.83	3.06	256	4.12	134.0
L915-B	40°28'30"	121°30'12"	48.65°	1.27	2633	5.47	0	2.50	1.00	2.75	3.02	189	4.20	131.4
SF-1	40°33'30"	121°32'00"	48.83°	1.28	1853	3.38	0	2.07	1.00	2.77	3.08	299	4.11	134.3

NORMALIZATION DATA FOR SAMPLES COLLECTED AT MT. ST. HELENS WASHINGTON

SAMPLE	LATITUDE (N)	LONGITUDE (W)	GEOM.LAT. (N)	L	ELEV (m)	E	DEPTH (cm)	S.G. (gm/cm^3)	D	K_2O (wt.%)	CaO (wt.%)	Cl (ppm)	n $ABS_{(tot)}$ (cm^2/kg)	nf(tot) (/ppmCl)
MSH-83	46°12'00"	122°11'30"	54.48°	1.48	1755	3.18	0	2.15	1.00	1.26	5.45	293	5.04	109.5

Appendix 12 (continued):

NORMALIZATION DATA FOR SAMPLES COLLECTED AT MONO CRATERS AND LONG VALLEY CALIFORNIA

SAMPLE	LATITUDE (N)	LONGITUDE (W)	GEOM.LAT. (N)	L	ELEV (m)	E	DEPTH (cm)	S.G. (gm/cm^3)	D	K$_2$0 (wt.%)	CaO (wt.%)	Cl (ppm)	n ABS$_{(tot)}$ (cm^2/kg)	nf(tot) (/ppmCl)
MC-1	37^{o}48'54"	119^{o}01'30"	46.10^o	1.18	2365	4.64	10	1.39	0.93	4.51	0.56	475	4.81	114.8
MC-2	37^{o}49'00"	119^{o}02'48"	46.10^o	1.18	2457	4.91	0	1.94	1.00	4.65	0.57	484	4.99	110.6
MC-3	37^{o}48'48"	119^{o}01'18"	46.10^o	1.18	2460	4.92	20	1.89	0.82	4.69	0.57	502	4.61	119.7
MC-4	37^{o}49'30"	119^{o}00'48"	46.10^o	1.18	2536	5.16	0	2.25	1.00	4.55	0.56	493	5.12	107.8
SLR-2	37^{o}48'54"	119^{o}01'30"	46.10^o	1.18	2365	4.64	10	1.71	0.91	4.62	0.56	428	4.92	112.2
SLR-3	37^{o}49'00"	119^{o}02'48"	46.10^o	1.18	2457	4.91	10	1.56	0.92	4.61	0.57	401	4.96	111.3
SLR-4	37^{o}55'36"	119^{o}02'48"	46.19^o	1.19	2143	4.04	10	2.35	0.88	4.67	0.57	432	5.03	109.7
SLR-6	37^{o}46'54"	119^{o}01'24"	46.04^o	1.18	2594	5.34	10	1.66	0.92	4.63	0.56	477	4.98	110.8
SLR-7	37^{o}40'36"	118^{o}59'06"	45.94^o	1.18	2682	5.64	10	1.81	0.91	4.54	0.76	221	5.55	99.5
MM-2	37^{o}42'30"	118o56'48"	45.34^o	1.16	2305	4.47	100	2.62	0.25	1.89	7.08	113	5.56	99.3
MM-3	37^{o}40'36"	118^{o}59'06"	45.34^o	1.16	2682	5.64	0	1.88	1.00	4.63	0.77	171	5.45	101.3

NORMALIZATION DATA FOR UNKNOWN SAMPLES DATED USING 36CL GEOCHRONOMETER

SAMPLE	LATITUDE (N)	LONGITUDE (W)	GEOM.LAT. (N)	L	ELEV (m)	E	DEPTH (cm)	S.G. (gm/cm^3)	D	K$_2$0 (wt.%)	CAO (wt.%)	CL (ppm)	n ABS$_{(tot)}$ (cm^2/kg)	nf(tot) (/ppmcl)
AC-1	32^{o}04'12"	107^{o}03'36"	40.94^o	1.00	1356	2.48	10	2.50	0.80	1.82	9.77	173	7.03	78.5
AF-2	31^{o}56'30"	106^{o}57'48"	40.78^o	1.00	1265	2.34	10	2.44	0.88	1.62	10.93	25	7.21	76.6
ST-1	32^{o}10'12"	106^{o}45'42"	41.05^o	1.01	1216	2.27	100	2.65	0.25	1.87	9.44	376	7.59	72.7
ST-2	32^{o}12'48"	106^{o}46'24"	41.08^o	1.01	1219	2.28	150	2.24	0.17	1.77	9.29	298	7.15	77.2
FF-1	32^{o}07'24"	106^{o}45'18"	40.99^o	1.00	1219	2.28	20	2.68	0.75	1.67	9.50	323	6.79	81.3
CZ-1	33^{o}44'12"	105^{o}55'54"	42.72^o	1.07	1608	2.90	450	2.60	0.01	1.45	8.04	25	6.22	88.7
CZ-2	33^{o}42'12"	105^{o}55'54"	42.72^o	1.07	1608	2.90	170	2.26	0.11	1.44	8.23	198	7.42	84.3

5.13 APPENDIX 13: ^{36}Cl/Cl FOR SAMPLES COLLECTED IN NEW MEXICO

SAMPLE	^{36}Cl/Clx10^{-15} (measured)
SG-1A	6770±62
SG-1B	137±8

DATA FOR SAMPLES COLLECTED AT MONO CRATERS AND LONG VALLEY CALIFORNIA

SAMPLE	^{36}Cl/Clx10^{-15} (measured)
SLR-2	182±23
SLR-3	70±5
SLR-4	20±2
SLR-6	46±5
SLR-7	3900±200
MC-1	95±9
MC-2	90±20
MC-3	46±9
MC-4	118±5
MM-2	1248±123
MM-3	695±192

DATA FOR SAMPLES COLLECTED IN THE CIMA VOLCANIC FIELD CALIFORNIA

SAMPLE	^{36}Cl/Clx10^{-15} (measured)
C84-40	350±35
C84-41	155±55

Appendix 13 (continued):

DATA FOR SAMPLES COLLECTED AT MT. ST. HELENS WASHINGTON

SAMPLE	^{36}Cl/Cl x10^{-15} (measured)
MSH-83	15±1

DATA FOR SAMPLES COLLECTED IN LASSEN VOLCANIC FIELD

SAMPLE	^{36}Cl/Cl x10^{-15} (measured)
L724-1	149±12
L724-2	280±5
L683-A	83±8
L391	685±34
L915-A	25±4
L915-B	291±29
SF-1	153±12

DATA FOR UNKNOWN SAMPLES DATED USING 36Cl GEOCHRONOMETER

SAMPLE	^{36}Cl/Cl x10^{-15} (measured)
AC-1	140±5
AF-2	614±46
ST-1	405±5
ST-2	434±48
FF-1	427±44
CZ-1	40±6
CZ-2	68±6

5.14 Appendix 14: Cl extraction and purification for silicate rock samples

N.B. Care must be taken during these processes to avoid contamination with extraneous Cl. All equipment should be cleaned thoroughly before use, by the following steps:

(1) DD water
(2) dilute HNO_3
(3) DD water
(4) dilute NH_4OH
(5) DD water (2x)

Wear plastic gloves throughout these procedures; it is best to use the disposable type, changing them for each new sample and/or step.

Filtration steps should be done using 0.45 micron millipore filters and the appropriate filtration funnel. Save the blue paper filter separators for use in the final drying step. Filter large volumes of solution directly into clean filtration flasks; smaller volumes should be filtered into test tubes placed within the flask so that the neck of the funnel extends into the test tube.

A) Leach out pore-water chloride:

(1) Wash 100 g 100-150 mesh rock powder in 1000 ml DD water by mixing thoroughly in blender
(2) Pour into 1000 ml beaker, cover, and allow to settle for 48 hrs.
(3) When supernatant is clear (or nearly so), decant. If Cl analysis of leachate is desired, place supernatant in 1000 ml plastic bottles; otherwise discard.

(4) Dry rock powder at 110° C overnight

(5) Remove dry rock powder and grind gently to homogenize

B) Determine minimum sample size:

(1) Estimate $^{36}Cl/Cl$ for sample by using the age equation and an approximate age

(2) Grams sample required = $0.4/((\text{ppm Cl}\times10^{-6})(^{36}\text{Cl/Cl}\times10^{15}))$

(3) Since recovery is typically 50-60%, double the result in (2) to get minimum sample size (typically 30-40 g)

C) NaOH fusion:

(1) Prepare 100 ml nickel crucible by washing, rinsing with DD water, leaching for 1 hr in 10% HNO_3, rinsing in DD water, and drying.

(2) Accurately weigh ultrapure NaOH, 6x sample weight, into the crucible

(3) Place crucible on clay dish and fuse NaOH at 565° C for 15 min. to drive off water

(4) Remove crucible from furnace and allow to cool until NaOH is solid

(5) Accurately weigh rock powder (weight determined in (B), above) onto weighing paper or into a sample boat, and pour carefully on top of NaOH cake

(6) Replace crucible on clay dish and fuse at 565° C for 30 min.; swirl crucible to ensure mixture of rock powder and flux; fuse an additional 30 minutes

(7) Remove crucible, cover, and allow to cool

(8) Remove cake from crucible and store in suitable container

(9) Repeat until necessary amount of rock powder is fused

Notes:

(I) Carbonate flux may also be used. If so, use the following procedure:

Reagents: KNO_3

$KNaCO_3$, as a 1:1 molar mixture of KCO_3 and $NaCO_3$:

$$KNO_3 = 1.3(NaCO_3)$$

(1) Accurately weigh rock powder into a clean cardboard ice cream container or beaker

(2) Add $KNaCO_3$, 5x sample weight, and mix thoroughly

(3) Add KNO_3, 1/5 sample weight, and mix thoroughly

(4) Place 30-35 g of the mixture in a 100 ml Pt crucible

(5) Place crucible on clay dish and fuse mixture in a muffle furnace at 1000° C for 30-40 min, or until entire mass is fused

(6) Remove crucible, cover, and allow to cool

(7) Remove cake from crucible and store in suitable container

(8) Repeat (4-7) until all of mixture is fused

(II) It is also possible to extract the fusion cake directly into DD water. This may be done in one of several ways:

(1) If the melt is *very* fluid, it may be poured *carefully* from the crucible into the water (CAUTION: hot melt will boil water violently), or

(2) When the crucible is removed from the furnace, swirl the melt around the inside of the crucible so that it thinly coats the entire inside. Allow to cool slightly, and then carefully place the crucible into the water

N.B. If this latter method is used, be sure that the outside of the crucible is clean.

D) Chloride extraction:

N.B. During the acidification of carbonate flux solutions, a large volume of CO_2 is generated. Acid must be added slowly or the solution will "boil" over.

(1) Dissolve fusion cake(s) in 1000 ml hot DD water+10 ml ethanol, stirring

(2) Decant supernatant and discard ppt, unfused rock powder, etc.; if solution is not clear, filter or spin to remove particulates before proceeding

(3) Acidify to pH 2-3 with HNO_3, stirring

N.B. The dissolved fusion cakes create an extremely basic solution (pH approx. 12), so that acidification will require a large (typically 80-100 ml) volume of HNO_3. The addition of strong acid causes a violent reaction and should be done dropwise. The general course of the reaction is:

(a) No change to pH 9

(b) At pH 9, colloidal ppt forms and persists

(c) pH decreases slowly to about 7 (with evolution of CO_2 in carbonate)

(d) CO_2 evolves rapidly in carbonate solution at pH 7

(e) Solution may clear as pH drops to 1-2 (CO_2 production subsides)

(4) Spin to remove colloidal material or ppt before proceeding

(5) Add an excess of 0.1N $AgNO_3$ to precipitate AgCl (use approx. 2x the amount necessary to ppt all Cl in solution)

(6) Cover and allow to sit in a dark place overnight (solution may be heated at 60-70^{0} C to increase flocculation)

(7) If storage is necessary, spin to concentrate AgCl, decant all but enough supernatant to cover AgCl, and place in dark bottle

E) Purification of AgCl:

Reagent: $Ba(NO_3)_2$

(1) Place several grams of $Ba(CO_3)_2$ in a flask

(2) Add enough HNO_3 to partially dissolve the $Ba(CO_3)_2$, leaving some in solid form on the bottom of the flask

(3) Cover flask for storage

N.B. When using this solution, draw off liquid from the top.

(1) Filter or spin solution, discard filtrate/supernatant

(2) Wash AgCl in 50 ml DD water, discard wash water

(3) Repeat (2)

(4) Dissolve AgCl with 10 ml NH_4OH

(5) Add 14 ml 1:1 HNO_3; place in ice water for 30 min. to ppt AgCl

(6) Spin, discard supernatant

(7) Dissolve AgCl with 50 ml NH_4OH

(8) Add 1 ml $Ba(NO_3)_2$, cover, and allow to sit in a dark place overnight

(9) Spin or filter; save supernatant/filtrate, discard ppt

(10) Dilute solution with 30 ml DD water; add HNO_3 dropwise until AgCl begins to ppt; place on ice for 30 min.

(11) Spin, discard supernatant

(12) Repeat 10-11

(13) Wash with 50 ml DD water

(14) Spin, discard supernatant

(15) Repeat 13-14

(16) If there is a large amount (>300 mg) of AgCl, transfer to a small crucible (if using glass centrifuge tubes, leave in tube) and dry overnight at 65° C; if amount is smaller, filter AgCl, remove filter and place on a crumpled blue filter separator and dry AgCl on filter overnight

(15) Place AgCl (or AgCl and filter) in a dark bottle or a small bottle covered with aluminum foil for storage

N.B. If large amounts of sulfide are probable, repeat 10-11 as necessary.

5.15 Appendix 15: Be and Al extraction for silicate rock samples

N.B. The following is carried out under an aluminum enclosure within a fume hood; this attempts to isolate the samples from turbulent room air and thus reduce the amount of atmospheric B and Be which may contaminate the samples.

1) Accurately weigh 10.0 g rock powder into 200 ml teflon beaker
2) Add spike of 1-2 mg ^{9}Be in solution (beryl No. 3, 0.6 mg/ml, use 2-4 ml)
3) (a) Suspend rock powder in 30 ml 1:5 $HCLO_4$
   (b) Add 70 ml 1:1 HF/HNO_3
   (c) Cover partially and evaporate at 60-80^{o} for 48 hrs.; after all nitrate has been expelled, evaporate syrupy ppt. on higher heat.
4) Repeat (3) until all rock powder is digested
5) Convert to chloride by adding 100 ml 4N HCl and evaporating to dryness
6) Add 200 ml 2N HCl and heat mildly until all ppt. is dissolved
   (If ppt. does not dissolve completely, return to (3) and repeat as necessary)
7) (a) Titrate supernatant with NH_4OH to pH 9; let stand for 5-10 min. to ppt. Al, Be, Fe, Ti
   (b) Spin
   (c) Draw off supernatant and discard
8) Add 200 ml 2N HBr and heat mildly until all ppt. is dissolved
9) (a) Titrate with NH_4OH to pH 4.2 to ppt. Fe, Ti
   (b) Spin (3000-5000 rpm for 5-10 min. as necessary)

(c) Draw off supernatant and save; discard ppt.

10) (a) Titrate supernatant with NH_4OH to pH 9; let stand for 5-10 min. to ppt. Al, Be
    (b) Spin
    (c) Draw off supernatant and discard

11) (a) Wash with 100 ml NH_4OH; agitate to disperse ppt.
    (b) Spin
    (c) Draw off supernatant and discard

12) Repeat (11)

13) N.B. Procedure must be carried through to end without standing from here.
    (a) Add enough 1:10 HF to bring solution to pH 5 (brown color disappears; Be complexes with ammonium fluoride); let stand for 5-10 min. to ppt. Al
    (b) Spin
    (c) Draw off supernatant; retain both supernatant and ppt.
    (d) For Al go to (25)

14) Evaporate supernatant to dryness

15) Dissolve in 1:20 HF

16) a) Titrate with NH_4OH to pH 8; let stand for 5-10 min. to ppt. Fe
    b) Spin; draw off supernatant and save; discard ppt.

17) Evaporate supernatant to dryness; be certain of dryness before proceeding (bake in ventilated oven at 200^oC overnight)

18) Add enough 1:5 $HClO_4$ to cover and evaporate to dryness

19) Repeat (18)

20) Convert to chloride by adding 2N HCl (approx. 2x volume of ppt.) and evaporating to dryness

21) a) Dissolve ppt. in 50 ml 1:3 HCl
    b) Add 10 ml chromatography grade methyl alcohol (forms boric acid, methyl esters)
    c) Evaporate to dryness at 65°C to boil off B complexes
22) Dissolve in 2N HCl
23) Do (6), (7) to ppt. Be as BeOH
24) Place ppt. in ceramic cup and bake overnight at 550° C to drive off water and leave BeO

For Al:

25) Do (9), (10) to wash fluoride from ppt.
26) Cover with 4N HCl and evaporate to dryness
27) Repeat (21)
28) Dissolve in 4N HCl
29) Load onto anion exchange column and begin collecting immediately
30) Wash through with 30 ml 4N HCl

To prepare anion exchange column:

1) Sieve Bio-Rad AG-1X8 resin to 100-200 mesh
2) Wash with DD water
3) Wash with 4N HCl
4) Load column with 15-20 ml of resin/acid slurry
5) Allow to settle then drain

To wash Fe from column, wash with 100 ml 1N HCl; column can be reused.

5.16 APPENDIX 16: PROGRAMS FOR ^{36}Cl DATA REDUCTION

5.16.1 The following programs were written for use on the HP-25C calculator, but may be modified for use on any HP calculator. These programs include some redundant steps that enable one to follow the course of the calculations and extract data which may be useful elsewhere. Likewise, some steps may be omitted for certain cases; for instance, when calculating the sea-level buildup curve, steps 20-29 of the predicted ratio program may be omitted, as they deal with elevation, latitude, and depth corrections.

5.16.2 MINIMUM SAMPLE SIZE FOR Cl EXTRACTION

```
01 X
02 RCL 1
03 X
04 RCL 2
05 X<>Y
06 DIVIDE
07 GTO 00
```

Registers:

1) 10^{-6}
2) 0.4

To Run:

1) Enter ppm Cl
2) Enter predicted ^{36}Cl/Cl
   R/S
3) Read minimum sample
   weight in grams

5.16.3 COSMIC-RAY ATTENUATION WITH DEPTH BELOW SURFACE

```
01 ENTER
02 R/S
03 X
04 ENTER
05 RCL 1
06 X
07 g e^x
08 GTO 00
```

Registers:

1) atten. coefficient
   = -5.25×10^{-3}

To Run:

1) Enter rock density
   in gm/cm^3
2) Enter depth in cm
   R/S
3) Read attenuation
   factor (dimensionless)

5.16.4 PREDICTED RATIOS:

```
01 RCL 3
02 X
03 ENTER
04 R/S
05 RCL 4
06 X
07 +
08 ENTER
09 R/S
10 STO 2
11 R/S
12 X
13 +
14 ENTER
15 RCL 2
16 RCL 7
17 X
18 DIVIDE
19 ENTER
20 R/S
21 X
22 ENTER
23 R/S
24 X
25 ENTER
26 R/S
27 X
28 ENTER
29 R/S
30 RCL 5
31 X
32 g e^X
33 RCL 1
34 X<>Y
35 -
36 X
37 GTO 00
```

Registers:

1) 1
2) ppm Cl
3) $PR_K = 2670$
4) $PR_{Ca} = 710$
5) $-( ) = -2.3 \times 10^{-6}$
7) Abundance of Cl x ( )
   $= 3.9 \times 10^{13}$

To Run:

1) Enter wt% K_2O
   R/S
2) Enter wt% CaO
   R/S
3) Enter ppm Cl
   R/S
4) Enter   nf
   R/S
5) Enter elev. correct.
   R/S
6) Enter depth correct.
   R/S
7) Enter lat. correct.
   R/S
8) Enter age
   R/S
9) Read $^{36}Cl/Cl$

5.16.5 NORMALIZATION:

```
01 RCL 3
02 X
03 ENTER
04 R/S
05 RCL 4
06 X
07 +
08 ENTER
09 R/S
10 STO 6
11 R/S
12 X
13 +
14 ENTER
15 R/S
16 RCL 2
17 X<>Y
18 DIVIDE
19 ENTER
20 RCL 6
21 RCL 1
22 DIVIDE
23 X
24 R/S
25 DIVIDE
26 R/S
27 DIVIDE
28 R/S
29 DIVIDE
30 R/S
31 X
32 R/S
33 GTO 00
```

Registers:

1) $Cl_{ref} = 165$
2) $^{36}Cl_{ref} = 23190$
3) $PR_K = 2670$
4) $PR_{Ca} = 710$

To Run:

1) Enter wt% K_2O
R/S
2) Enter wt% CaO
R/S
3) Enter ppm Cl
R/S
4) Enter nf
R/S
R/S
5) Enter elev. correct.
R/S
6) Enter lat. correct.
R/S
7) Enter depth correct.
R/S
8) Enter measured ratio
R/S
9) Read normalized ratio