CNWRA 95-003

A CRITICAL REVIEW OF DATA IN THE CNWRA VOLCANISM GEOGRAPHIC INFORMATION SYSTEM (GIS) DATABASE

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Nuclear Regulatory Commission
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ABSTRACT

The purpose of this critical review of existing data in the Center for Nuclear Waste Regulatory Analyses (CNWRA) volcanism Geographic Information System (GIS) database is to consider the data in regard to their accuracy and sufficiency for developing and assessing four classes of models. These models are contemplated for addressing the ability to determine frequency and nature of past volcanic events in the Yucca Mountain Region (YMR) and to assess the probability and consequences of future volcanism in that region. The four classes of models include nonparametric and parametric probability models, geochemical evolution (petrogenetic) models, and tectonic models. Acceptable models must be developed for the four classes to permit evaluation of spatial and temporal patterns of analog volcanic fields in the western Great Basin and to apply information about patterns from these fields to the YMR.

Although Quaternary volcano locations are relatively well known for many western Great Basin volcanic fields, ages of the volcanoes often are poorly constrained. This poor chronological constraint is a major concern. Other key problems are: (i) there is little information available to relate individual flows with source vents, and (ii) a significant amount of the published geochemical and geochronological data cannot be related to specific volcanoes in a field. These constraints limit the utility of western Great Basin volcanic fields for rigorously developing and assessing some volcanism models of potential importance.

It appears that both parametric and nonparametric models can be treated with the data in the volcanism GIS database, if reasonable bounding assumptions are established for geochronological data. Because geochemical (petrogenetic) modeling is relatively complex and subjective, it will be difficult to completely develop such models for the YMR within fiscal year 1995. However, these models are extremely valuable for constraining volcanism probability models and should be developed to the extent possible using the database. Limited spatial and temporal data from many areas of interest, as reflected by data currently included on the volcanism and tectonics GIS databases, restrict the ability to distinguish between existing regional-scale magmato-tectonic models or to develop reasonable alternative models. At the scale of the YMR, data in the volcanism and tectonics GIS databases are also insufficient to construct reasonable alternative magmato-tectonic models at the present time. The main constraints for development of magmato-tectonic models are the lack of temporal data on faulting to adequately determine slip history and strain rates and the lack of substantive information on subsurface geometry of fault-dike interactions—both of which are needed to realistically assess temporal and spatial associations of faulting and volcanism.

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The authors wish to thank K. Spivey, P. Hunka, and B. Henderson for providing much of the technical support for development of the volcanism GIS database. Thanks are also due R. Manteufel, L. McKague, B. Sagar, and R. Brient for their valuable technical, programmatic, and quality assurance reviews of this report. The authors greatly appreciate the able assistance of Ms. Esther Cantu, Ms. Barbara Long, Ms. Cathy Garcia, Ms. Bonnie Caudle, and Southwest Research Institute Publications Services in the timely preparation of the report.

QUALITY OF DATA AND SOFTWARE

DATA: Data contained in the CNWRA Volcanism Geographic Information System (GIS) database were taken mainly from the following sources which are extensively referenced in the report on the database by Connor and Hill (1994): peer-reviewed publications and U.S. Geological Survey (USGS) reports, geological maps produced by staff of Federal and State agencies, and academic theses and geological maps. While the data from these sources may not have been collected under formal Quality Assurance (QA) programs, the use of standard scientific practice in collection and analysis of the geological information and the process of peer review of the results assure the data are acceptable for incorporation into the GIS database. Based on this concept, theses and maps produced by university students are deemed acceptable sources of data because standard practices are used in generation of the information, and the work is generally subjected to rigorous review by the student's thesis advisor and committee. Original data generated by staff at CNWRA are also included in the GIS database and meet the QA requirements for data as specified in the CNWRA QA Manual.

SOFTWARE: Arc/Info software (Version 6.1.1) from Environmental Systems Research Institute, Inc. of Redlands, California, is the GIS software being used for construction of the volcanism database. This commercially available software is not controlled under the CNWRA Technical Operating Procedure, "Configuration Management of Scientific and Engineering Computer Codes" (TOP-018), because the original source code has not been modified. However, data manipulation software used with the GIS is controlled under TOP-018.

1 INTRODUCTION

The Volcanism Geographic Information System (GIS) database, developed by staff at the Center for Nuclear Waste Regulatory Analyses (CNWRA), was previously described in a report prepared by Connor and Hill (1994). The GIS database was developed for the Nuclear Regulatory Commission (NRC) primarily for use as a tool for analysis of volcanic fields in the Basin and Range and nearby regions that were considered to be possible natural analogs for volcanism in the Yucca Mountain Region (YMR). This analysis is being conducted as part of the Volcanic Systems of the Basin and Range research project (Stirewalt et al., 1994). Locations of appropriate analog fields were determined, in part, based on information derived from review of pertinent literature on volcanic-magmatic and tectonic history of the Basin and Range (Stirewalt et al., 1992).

The focus on collection of data from possibly analogous volcanic fields in a tectonic setting broadly similar to that of the YMR was adopted because the approach was viewed as reasonable for acquiring information useful in testing conceptual models for development of volcanic fields in the western Great Basin. Analysis of analogous fields in this region provides a context in which to evaluate the characteristics of Plio-Quaternary volcanism of the YMR and the relationship of that volcanism with tectonism. Consequently, a primary application of the GIS database is aiding CNWRA and NRC staff in assessment of models of volcanism for the western Great Basin and, specifically, for the volcanic field of the YMR.

The critical review of existing data in the CNWRA volcanism GIS database is an effort under Task 3 of the research project plan for Volcanic Systems of the Basin and Range (Stirewalt et al., 1994). Volcanic regions currently included in the database are cones and flows of the YMR (Nevada), Cima (California), Big Pine (California), Lunar Crater-Reveille Range (Nevada), and Coso (California) volcanic fields. Data from the Springerville and San Francisco volcanic fields in Arizona will be added at a later date. The database currently contains the following types of data: vent locations, lava flow outlines, age determination information, fault trace locations, geochemical analysis information, geologic contacts, and topography.

The purpose of this review is to consider the data in light of their relevance, accuracy, and sufficiency for developing and assessing the following four classes of models that should be contemplated for addressing the ability to determine frequency and nature of past volcanic events in the YMR and to assess probability and consequences of future volcanism in that region:

- Model 1 — Nonparametric probability models
- Model 2 — Parametric probability models
- Model 3 — Geochemical evolution models
- Model 4 — Tectonic models.

These model classes, discussed in detail in Chapter 4, vary in approach from those models addressing volcanism from a purely probabilistic perspective to those that are more deterministic and can be used to test specific volcanological hypotheses about the tectonic setting of volcanism in the region. The purpose addresses the objective of the review as described in the research project plan by

Stirewalt et al. (1994). Simply stated, that objective is to assess the volcanism GIS database for accuracy and sufficiency of data, including consideration of uncertainties related to data collection, analytical methods, and assumptions made in existing volcanism models.

2 RELEVANCE OF DATA IN THE VOLCANISM GIS DATABASE

Characterization of past volcanic events and assessment of the potential for future volcanism are important aspects of the scientific investigations conducted during the prelicensing phase for the candidate repository at Yucca Mountain. In connection with these investigations, acceptable models must be developed to analyze possible interactions between volcanism and tectonism, in addition to magma-repository interactions.

The present database was assembled by structuring it around specific types of volcanological and structural data necessary for analyzing the four model classes listed in Chapter 1. Therefore, the data are deemed most germane and essential for developing and assessing models for the purpose of better understanding past volcanic events and considering both the likelihood of future volcanism in the YMR and the consequences of magma-repository interactions.

Concerning relevance of data in the volcanism GIS database to regulatory considerations, insight gained through use of the data in the Volcanic Systems of the Basin and Range research project (Stirewalt et al., 1994) will support the following sections of the License Application Review Plan (LARP) (Nuclear Regulatory Commission, 1994): (i) Section 3.2.1.9, Evidence of igneous activity as a potentially adverse condition; (ii) Section 3.2.2.7, Impact of volcanism on groundwater movement; and (iii) Section 6.1, Assessment of compliance with the requirement for cumulative releases of radioactive materials. Compliance Determination Strategies (CDSs) and Compliance Determination Methods (CDMs) for these sections of the LARP (Nuclear Regulatory Commission, 1994) are currently under development, and four Key Technical Uncertainties (KTUs) related to igneous activity have been identified as part of the CDS concerned with evidence of Quaternary igneous activity. The four KTUs are:

- Low resolution of exploration techniques to detect and evaluate igneous features
- Inability to sample igneous features
- Development and use of conceptual tectonic models as related to igneous activity
- Prediction of future system states (disruptive scenarios).

The KTUs arise largely because volcanic systems of the western Great Basin are disparate. Type 5 KTUs are included, indicating that evaluation of the KTUs related to volcanism may require independent NRC research efforts. In addition to KTU evaluation, independent research in volcanism is needed to provide the basis for assessing the research plans of the Department of Energy (DOE) for addressing probability and potential consequences of igneous activity on repository performance. Development of the volcanism GIS database directly addresses some of these KTUs, particularly those related to the inability to sample igneous features, development and use of conceptual tectonic models as related to igneous activity, and disruptive scenarios.

The volcanism GIS database will be utilized in reactive work, including NRC-DOE technical exchanges and review of topical reports, study plans, and related reports for which hypotheses must be evaluated in a timely manner. Specifically with regard to reactive work, the GIS database will be used for the following purposes:

- Facilitating NRC and CNWRA staff review of the completeness and adequacy of DOE volcanism research for demonstrating compliance with 10 CFR Part 60 requirements related to igneous activity

- Providing confirmatory data for addressing issues related to waste isolation

- Providing data that may be necessary to explore safety and isolation concerns by alternate means not used by DOE.

The volcanism GIS database also will be used to assist with addressing KTUs that must be considered by other ongoing research projects at the CNWRA. In particular, the GIS database will aid investigations in the Field Volcanism research project, an NRC research project that concentrates on eruption energetics, degassing, and controls on magma movement at shallow levels; the Tectonic Setting of the Central Basin and Range research project; and Geologic Setting Element technical assistance in conjunction with the Division of Waste Management on faulting and dike interaction. The link between volcanism studies and Iterative Performance Assessment (IPA) has been established, and the database is being used to develop and test probability models that will be implemented during IPA Phase III analyses. Hence, the relevancy of the volcanism GIS database is firmly founded in requirements for use of data in assessing regulatory and technical issues during both prelicensing and licensing phases for the candidate repository at Yucca Mountain.

3 ACCURACY AND ADEQUACY OF DATA IN THE VOLCANISM GIS DATABASE

This chapter focuses on evaluating accuracy of data from the sources used for the volcanism GIS database and adequacy of these data for development and assessment of models for YMR volcanism. Geology of the volcanic fields currently included in the GIS database (i.e., YMR, Cima, Big Pine, Lunar Crater, and Coso) was presented in Connor and Hill (1994) and will not be reviewed again in this report. All data contained in the Volcanism GIS database were compiled from published literature. The compilation involved incorporation of data from a wide variety of sources and commonly necessitated interpretation of volcano and sample locations from sketch maps. Although some of the locations are not precise, they are accurate within limitations of the original data sources. Notwithstanding the sometime lack of precision in location of volcanoes and samples, this type of spatial data is perhaps the best known and best qualified feature of many volcanic fields in the western Great Basin. Both location (spatial) and numerical data were reviewed for accuracy when they were entered into the database by checking entries against original information. When possible, maps in the GIS database were also compared against originals to assess the accuracy of digitizing and to detect any problems in joining and matching discrete coverages.

The GIS database was also reviewed to eliminate the same data reported in more than one reference when poor sample control made it appear as two different pieces of information. For example, about 25 percent of the age determinations for the Coso volcanic field originally included in the database were actually duplicate publications of the same data with poor sample location information. These duplicated data have been removed from the database coverage.

Although detailed literature searches have been performed for the volcanic fields in the volcanism database, it is likely that additional information about these fields is contained in publications that do not emphasize the volcanic geology of the area. For example, age determinations for lava flows may be contained in publications about the structural evolution of nearby mountain ranges. One goal of this report, therefore, is to prompt the reader to identify additional publications that are not currently cited as data sources but which may contain useful information for inclusion in the GIS database.

3.1 SUMMARY OF DATA NEEDS

Models for YMR volcanism require the following types of data: (i) volcano locations, (ii) volcano ages, (iii) fault locations, (iv) local and regional topography, (v) eruption volumes, (vi) geochemistry of eruption products, and (vii) evidence of dike-fault interactions. These data needs are summarized in this chapter for each volcanic field in the database. For each field, topography is available at 200-m contour intervals from regional Digital Elevation Model (DEM) data. Smaller contour intervals were produced for some areas by digitizing topographic maps (e.g., Big Pine Volcanic Field) or from higher resolution DEM data (e.g., YMR).

Several data-related uncertainties are common to every volcanic field, and the most important is that volcano locations are relatively well known for Quaternary centers but poorly known for Neogene centers. This uncertainty reflects the relatively low resolution of geologic mapping available for all areas and the difficulty in readily identifying moderately to highly eroded older volcanic centers. Although some vent location information exists for most volcanic fields, significant interpretation was needed to determine vent locations of some Quaternary and many Neogene centers. Only the YMR field has mapping of sufficient detail to permit tracing of many lavas (i.e., flows from which most of the dated or analyzed samples were taken) back to the appropriate vents. Basic map information is also at a scale too coarse to accurately determine volumes of eruption products. This lack of data critically limits the utility of these fields for developing and testing magmato-tectonic models.

Significant amounts of unpublished data exist for all seven volcanic fields discussed in this report, and some of these data have remained unpublished for over a decade. Also, there has been a general reluctance on the part of some researchers to make unpublished data available, so accuracy of the data could not be assessed. Therefore, most of these unpublished data have not been incorporated into the volcanism GIS database due to concerns about quality of the data and how unpublished information should be used in the license review process.

3.2 YUCCA MOUNTAIN REGION

Although the YMR is the most widely studied volcanic field in the western Basin and Range, there are still significant knowledge gaps for Pliocene and older volcanoes in this field relative to the model development requirements established for the Volcanism Research Project. Because of the obvious importance of YMR volcanism data in the GIS database, data for this field need to be assessed in relatively greater detail than data from the other volcanic fields.

The YMR has been the site of recurring basaltic volcanism since the cessation of Miocene caldera-forming activity in the Southwestern Nevada Volcanic Field. Basalts younger than about 9 Ma are petrogenetically distinct from older basalts and better represent the mafic system that produced Quaternary eruptions in the YMR (Crowe et al., 1983; 1986). Figure 3-1 illustrates the location of mapped and inferred basaltic vents younger than about 9 Ma. The location of YMR basaltic vents and their estimated ages are given in Table 3-1.

Recognition of vent locations is particularly difficult for many Pliocene and older volcanic centers. Vent locations in Table 3-1 were generally reported as such on geologic maps and in reports (from references shown in Figure 3-1) or interpreted in the field from the presence of feeder dikes, vent agglutinate, or cinder cone remnants. Some of the Miocene volcanic centers have been eroded to hundreds of meters below the paleosurface, removing most of the evidence for vent locations. Therefore, the number of vents reported for Pliocene and older volcanic centers should be regarded as a minimum estimate.

Over 200 isotopic age determinations have been published for YMR basaltic rocks younger than about 9 Ma. Many of the older analyses have relatively low degrees of precision and are occasionally inaccurate. For example, dates as old as 10.4 ± 0.4 Ma are reported for the basalt of Pahute Mesa (Crowe et al., 1983), which overlies the 9.40 ± 0.03 Ma Rocket Wash Tuff (Sawyer et al., 1994). Whenever possible, age estimates reported in Table 3-1 are selected from more recent analyses, which are generally considered to be more precise and accurate than older analyses (e.g., Crowe, 1994). For units with multiple analyses, the age estimates represent the mean and one standard deviation of the data set, with reported analytical uncertainties propagated through the calculations. Several of these age estimates require further explanation.

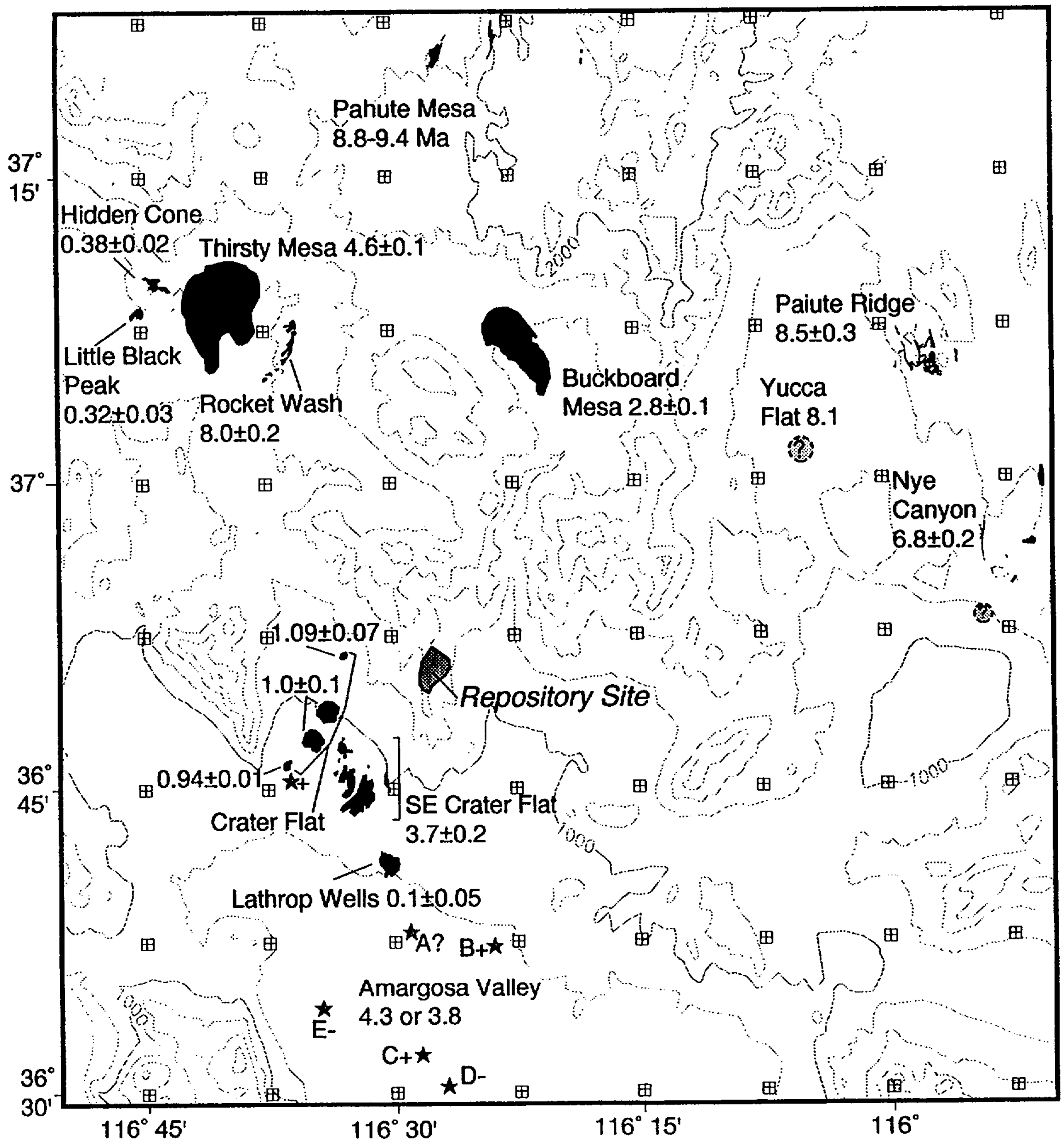

Figure 3-1. Basaltic vents, lavas, and intrusions of the YMR younger than about 9 Ma. Geology compiled from Byers et al. (1966); Ekren et al. (1966); Carr and Quinlivan (1966); Byers and Barnes (1967); Byers and Cummings (1967); Hinrichs et al. (1967); Noble et al. (1967); Tschanz and Pampeyan (1970); Cornwall (1972); Crowe et al. (1983, 1986); Carr (1984); Swadley and Carr (1987); and Faulds et al. (1994). Locations of aeromagnetic anomalies (stars) from Kane and Bracken (1983) and Langenheim et al. (1993). Sources for age estimates listed in Table 3-1. Contours generated from regional 3-arc-second Digital Elevation Model by B. Henderson, Southwest Research Institute, 200 m contour interval. Map projection is Universal Transverse Mercator (UTM) zone 11, NAD27 datum, Clarke 1866 spheroid.

Table 3-1. Summary of vent locations and best current estimated ages for volcanoes of the YMR

Volcano	UTM Coordinates	Age Estimate (Ma)	Source	Explanation
Lathrop Wells	543780E 4060380N	0.1±0.05	Turrin et al. (1991) Zreda et al. (1993) Crowe et al. (1992a) Poths et al. (1994)	U/Th and Ar/Ar dates generally >100 ka, ^{36}Cl and ^{3}He exposure dates generally <90 ka.
Hidden Cone	523230E 4112530N	0.38±0.02	Turrin (1992)	Ar/Ar step-heating, 1 date.
Little Black Peak	522130E 4110340N	0.32±0.03	Fleck et al. (in review)	K/Ar, best estimate from 4 dates.
Northern Cone	540330E 4079130N	1.09±0.07	Faulds et al. (1994)	K/Ar on plagioclase separate, 1 date.
Black Cone	538840E 4073990N	1.0±0.1 0.71±0.06	Perry (1994) Faulds et al. (1994)	Ar/Ar, average of 4 dates. K/Ar on plagioclase separate, 1 date.
Red Cone	537450E 4071470N	1.0±0.1	Faulds et al. (1994)	K/Ar on plagioclase separate, average of 3 dates.
Little Cone NE	535500E 4069490N	0.77±0.04	Faulds et al. (1994)	Age based on correlation with Little Cone SW
Little Cone SW	535131E 4069220N	0.77±0.04 0.94±0.01	Faulds et al. (1994) Heizler et al. (1994)	K/Ar on plagioclase separate, 1 date. Ar/Ar step-heating on sanidine xenocrysts, 1 sample.
Buckboard Mesa	554680E 4108970N	2.87±0.06	Fleck et al. (in review)	K/Ar, best estimate from 4 dates.
Buckboard Mesa SE	556060E 4107580N	2.87±0.06	Fleck et al. (in review)	Age based on correlation with main Buckboard Mesa vent.

Table 3-1. Summary of vent locations and best current estimated ages for volcanoes of the YMR (cont'd)

Volcano	UTM Coordinates	Age Estimate (Ma)	Source	Explanation
Crater Flat	540232E 4071610N	3.7±0.2	Perry (1994)	Average of 3 Ar/Ar step-h eating dates for undifferentiated Crater Flat basalts. All events are assumed synchronous based on similar magnetic orientations (Champion, 1991).
Crater Flat	540330E 4070050N	3.7±0.2	Perry (1994)	
Crater Flat	540365E 4068790N	3.7±0.2	Perry (1994)	
Crater Flat	540696E 4067830N	3.7±0.2	Perry (1994)	
Crater Flat	540300E 4068390N	3.7±0.2	Perry (1994)	
Amargosa Valley B	553720E 4052990N	4.3±0.1 3.8±0.1	Turrin (1992) Perry (1994)	Aeromagnetic anomaly drilled and dated by Ar/Ar. *Reversed* magnetic polarity.
Amargosa Valley A	546130E 4054260N	4.3±0.1 3.8±0.1	Turrin (1992) Perry (1994)	Aeromagnetic anomaly, assumed to correlate roughly with anomaly B.
Amargosa Valley E	538300E 4047200N	4.3±0.1 3.8±0.1	Turrin (1992) Perry (1994)	Aeromagnetic anomaly, assumed to correlate roughly with anomaly B, *normal* magnetic polarity.
Amargosa Valley C	547050E 4042950N	4.3±0.1 3.8±0.1	Turrin (1992) Perry (1994)	Aeromagnetic anomaly, assumed to correlate roughly with anomaly B, *reversed* magnetic polarity.
Amargosa Valley D	549430E 4040080N	4.3±0.1 3.8±0.1	Turrin (1992) Perry (1994)	Aeromagnetic anomaly, assumed to correlate roughly with anomaly B, *reversed* magnetic polarity.
Thirsty Mesa	529390E 4112330N	4.6±0.1	Fleck et al. (in review)	K/Ar, best estimate from 3 dates.

Table 3-1. Summary of vent locations and best current estimated ages for volcanoes of the YMR (cont'd)

Volcano	UTM Coordinates	Age Estimate (Ma)	Source	Explanation
Nye Canyon	603230E 4095790N	6.8±0.2	Crowe et al. (1983)	Average of 3 K/Ar dates, for nondifferentiated Nye Canyon.
Nye Canyon	602170E 4088960N	6.8±0.2	Crowe et al. (1983)	
Nye Canyon	600950E 4085920N	6.8±0.2	Crowe et al. (1983)	
Nye Canyon	600550E 4085450N	6.8±0.2	Crowe et al. (1983)	
Nye Canyon	599160E 4085820N	6.8±0.2	Crowe et al. (1983)	
Nye Canyon	598030E 4090090N	6.8±0.2	Crowe et al. (1983)	
Nye Canyon	≈597900E ≈4082500N	6.8±0.2	Crowe et al. (1983)	Drillhole in Frenchman Flat, assumed correlation.
Rocket Wash	536110E 4109120N	8.0±0.2	Crowe et al. (1983)	K/Ar date, 1 sample.
Yucca Flat	≈577800E ≈4082400N	8.1	Carr (1984)	Basalt in drillholes UE1h and UE6d, 1 K/Ar date, no reported error.
Paiute Ridge	594860E 4107970N	8.5±0.3	Crowe et al. (1983)	Average of 3 K/Ar dates, nondifferentiated Paiute Ridge. Vent locations marked by exposed vent breccia, feeder dikes, or cinder cone remnants.
Paiute Ridge	595780E 4106340N	8.5±0.3	Crowe et al. (1983)	
Paiute Ridge	592810E 4105890N	8.5±0.3	Crowe et al. (1983)	
Paiute Ridge	593410E 4105540N	8.5±0.3	Crowe et al. (1983)	
Paiute Ridge	591480E 4105170N	8.5±0.3	Crowe et al. (1983)	

Table 3-1. Summary of vent locations and best current estimated ages for volcanoes of the YMR (cont'd)

Volcano	UTM Coordinates	Age Estimate (Ma)	Source	Explanation
Pahute Mesa	548920E 4133270N	<9.40±0.03	Sawyer et al. (1994)	Overlies Pahute Mesa Member of the Thirsty Canyon Tuff (Ekren et al. 1966).
Pahute Mesa	554090E 4134530N	8.8±0.1	Crowe et al. (1983)	
Pahute Mesa	562370E 4132680N	8.8±0.1	Crowe et al. (1983)	

The dipolar aeromagnetic anomalies in Amargosa Valley (Kane and Bracken, 1983; Langenheim et al., 1993) have both normal (Figure 3-1, sites B and C) and reversed (Figure 3-1, sites D and E) magnetic orientations. Anomaly B, which has been drilled directly, is dated at 4.3±0.1 (Turrin, 1992) or 3.8±0.1 Ma (Perry, 1994). Magnetic orientations are used to constrain the ages of the other anomalies, which are interpreted to represent buried basaltic centers (Langenheim et al., 1993). The aeromagnetic anomaly in southern Crater Flat likely represents a buried basaltic unit with normal magnetic orientation (Kane and Bracken, 1983; Crowe et al., 1986). The age of this unit is problematic, as all of the other basalts in Crater Flat have reversed magnetic orientations (Crowe et al., 1986). This possible volcanic center is not included in the data set. Over 100 age determinations are published for the Lathrop Wells volcano, ranging from about 0.4 Ma to younger than 0.01 Ma and representing numerous analytical methods such as $^{40}Ar/^{39}Ar$ (Turrin et al., 1991), U-series disequilibrium (Crowe et al., 1992a), and cosmogenic isotopes (Poths and Crowe, 1992; Zreda et al., 1993; Poths et al., 1994). Some of the variation in the Lathrop Wells dates may represent polycyclic activity (e.g., Crowe et al., 1992a). In an attempt to encompass many of the higher precision age determinations for Lathrop Wells, an estimated age of 0.1±0.05 Ma is incorporated into the database for this volcano.

Summary of Available Data:

- Vent locations—Excellent map coverage, with 8 Quaternary, 13 Pliocene and 17 Miocene surface vents located. Lavas can generally be correlated with vent location. Uncertainties on aeromagnetic anomalies in Amargosa Valley and locations of Miocene vents due to erosion.
- Vent ages—Known for surficial Pliocene and younger vents, but most sample locations are unknown. Miocene vents are dated directly or by stratigraphic relationships.
- Volumes—Data are available for Quaternary deposits, although the amount of dispersed material needs further evaluation. Poorly known for most older units, involves assumptions on eroded volumes that are not documented.

- Geochemistry—Good on Quaternary units, relatively good on older centers. Most data have unknown sample locations. Some ambiguities between trace element data in Vaniman and Crowe (1981) and Crowe et al. (1986).

- Fault locations—The Nevada Test Site has been mapped at 1:24,000 and most areas adjacent to it are mapped at 1:62,500. Relative to other locations in the region, excellent coverage exists on fault locations and displacement data.

- Dike-fault—Little published data, although DOE studies at Paute Ridge are ongoing (e.g., Valentine et al., 1992). Miocene centers exhibit numerous parallel alignments between dikes and faults.

3.3 CIMA VOLCANIC FIELD, CALIFORNIA

Relatively large amounts of geochemical and geochronological data are available for the Cima Volcanic Field (Cima). However, it is difficult to put these data into a proper volcanological context because there have been few physical volcanological studies at Cima. The only geological maps available are regional 1:250,000 scales, or sketch maps in M.S. theses or publications. Volcanoes at Cima are distributed over a relatively small area, which is equivalent to the Crater Flat region (Figure 3-2). Pliocene volcanism at Cima is very poorly studied, but limited geochronology shows that the locus of volcanism migrated 0 to 30 km south from the Pliocene to Quaternary.

There have been two M.S. theses on Cima that focused on the southern part of the field (Bibliography). The remainder of the information on Cima is contained in journal articles focused primarily on the age and geochemistry of lava flows, geomorphology of volcanic features, and mantle xenoliths. Unpublished and ongoing studies at Cima by the U.S. Geological Survey include $^{40}Ar/^{39}Ar$ geochronology and detailed mapping of lava flows and correlations to source vents.[1]

Summary of Available Data:

- Vent locations—31 Quaternary volcanoes, most are easily identified from topographic maps. At least 15 Pliocene vents at the surface, 1 Miocene volcano at the southeast (Figure 3-2).

- Vent ages—At least 9 Quaternary and 10 Pliocene vents are not dated (Figures 3-2, 3-3). There are many sample locations with unknown vents or vents with contradictory data due to lack of resolution of flow boundaries. Numerous centers have multiple cinder cones in close proximity but at different ages.

- Volumes—Mapping accomplished at a resolution too low to accurately calculate volumes.

- Geochemistry—133 major element analyses, 9 on Pliocene flows (Figure 3-4). Forty analyses are only for cone "A" (located in Figure 3.2) and the remainder focus on the southern part of the Quaternary field. Trace element analyses are primarily in the southern part of the Quaternary field.

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[1] Turrin, B. Personal Communication to B. Hill RE: USGS unpublished geochronological research at Cima Volcanic Field. December, 1994.

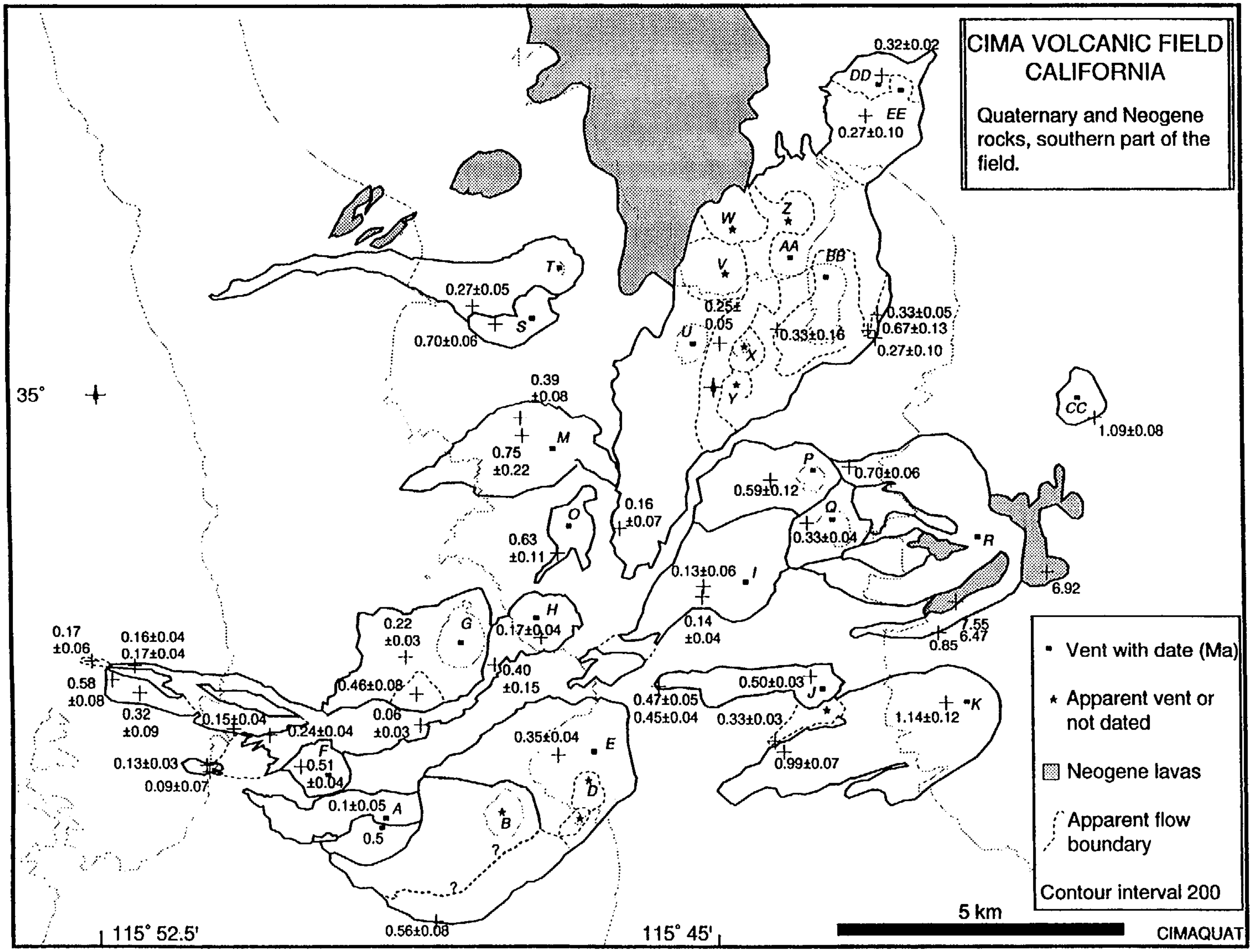

Figure 3-2. Quaternary and Neogene volcanoes of the southern part of the Cima Volcanic Field, California. Geology and age estimates from Katz (1981); Dohrenwend et al. (1984, 1986); and Turrin et al. (1985). Apparent flow boundaries interpreted from 1:40,000 aerial photography. Map projection is UTM zone 11, NAD27 datum, Clarke 1866 spheroid.

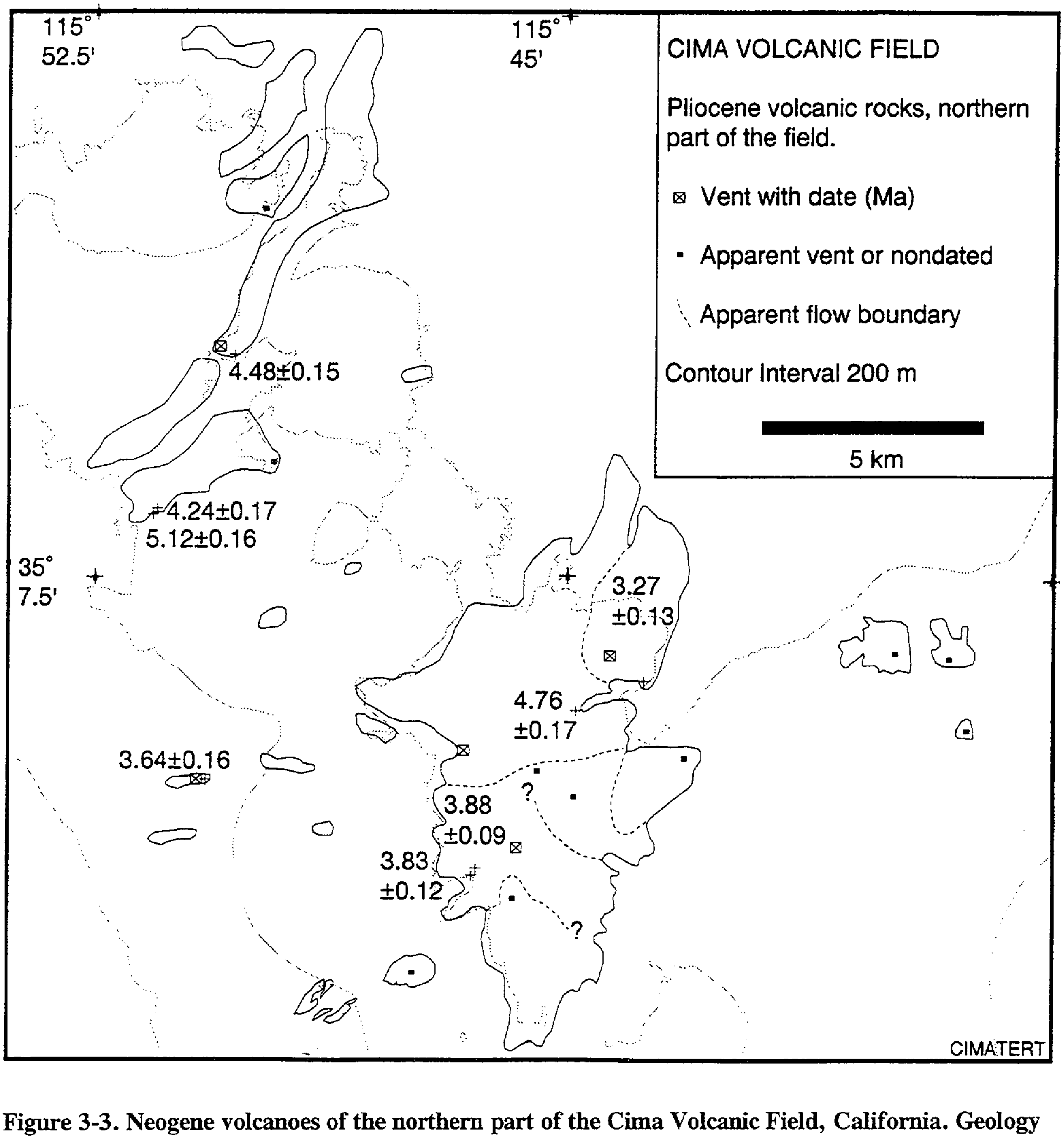

Figure 3-3. Neogene volcanoes of the northern part of the Cima Volcanic Field, California. Geology and age estimates from Jenkins (1961) and Turrin et al. (1985). Apparent flow boundaries interpreted from 1:40,000 aerial photography. Map projection is UTM zone 11, NAD27 datum, Clarke 1866 spheroid.

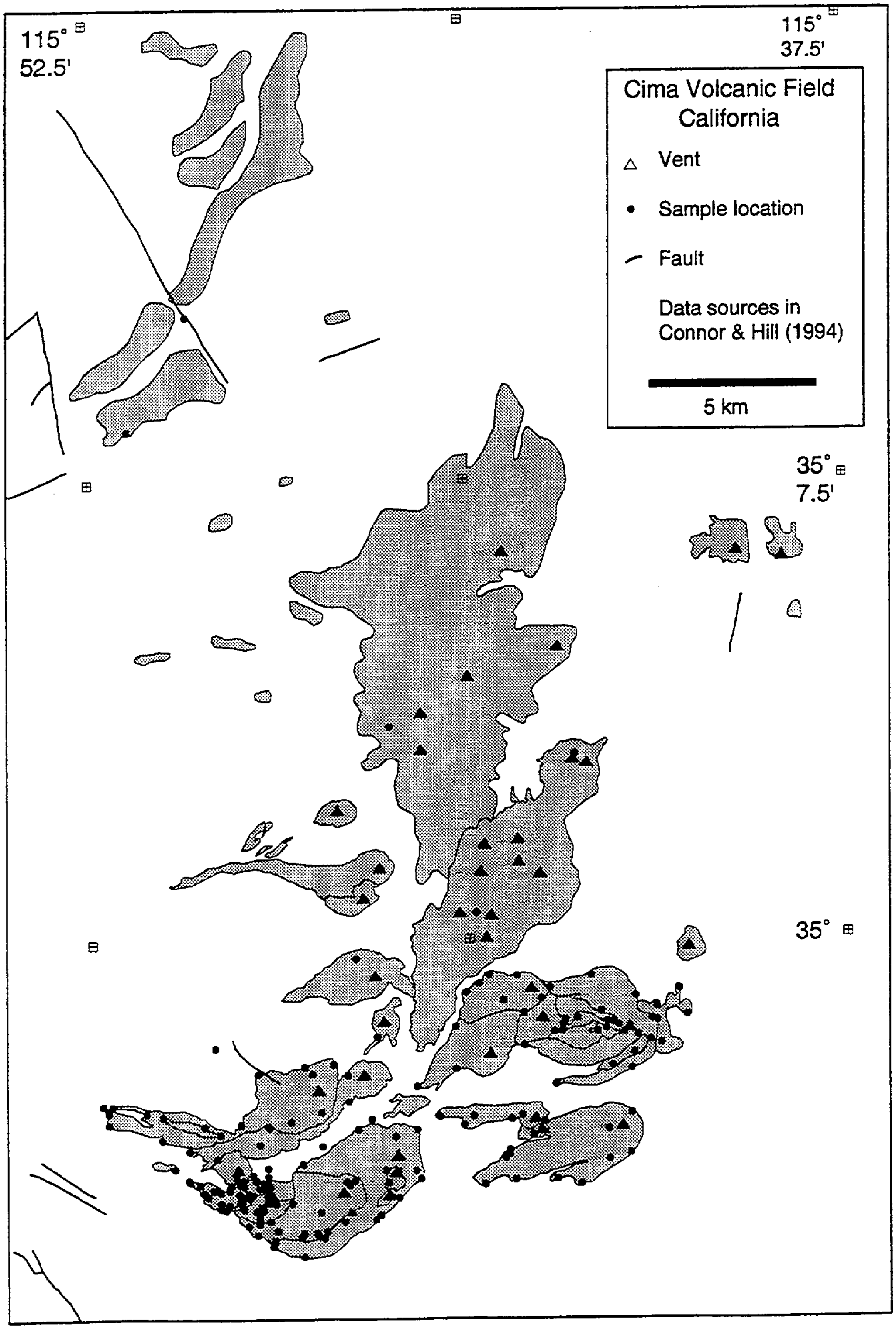

Figure 3-4. Volcanoes and lavas of the Cima Volcanic Field, California, with locations of geochemical analysis samples. Map projection is UTM zone 11, NAD27 datum, Clarke 1866 spheroid.

- Fault locations—Mapping only at 1:250,000 scales. Few mapped faults, Mojave block tectonics.

- Dike-fault—Little data published, although there are deep exposures due to vertical incision in the northeast part of the Pliocene volcanics.

3.4 BIG PINE VOLCANIC FIELD, CALIFORNIA

The Big Pine Volcanic Field (Big Pine) has been studied only at a reconnaissance level, although relatively large amounts of geochemical data are available. However, these data cannot be put into a proper volcanological context because no physical volcanological studies have been performed at Big Pine. Although parts of the Big Pine field have been mapped at 1:62,500 scales, most map information is available only at 1:250,000 scales or as sketch maps in theses or publications. Volcanic activity at Big Pine ranges only from about 1.4 to 0.13 Ma and shows no regular shift in the locus of activity with time (Figure 3-5). There are, however, significant variations in several key petrogenetic processes within that time. Basalts range from alkaline olivine basalt to tholeiitic basalt, with the undersaturated compositions restricted to the northern part of the field but produced between at least 1.1 and 0.3 Ma (Ormerod, 1988). Both basalt types erupted over significant differences in elevation, at times exceeding 800 m in vertical relief. In addition, a small rhyolitic dome formed at about 1 Ma. Understanding these processes will lead to a greater comprehension of the types of basaltic magmatic processes that may have occurred, or could potentially occur, in the YMR.

There has been one Ph.D. and one M.S. thesis at Big Pine, both of which focused on the geochemistry of the field. The remainder of the information on Big Pine is contained in journal articles that focus primarily on the age and geochemistry of lava flows and Quaternary faulting in the Owens Valley (Bibliography). The area is readily accessible, and many data needs could be met by research directed toward delineating flow boundaries and vent correlations, field checking of aerial photograph interpretations, and a limited number of geochemical and geochronological analyses.

Summary of Available Data:

- Vent locations—24 Quaternary vents, about half of which are reliably identified. No basic volcanology studies for this field. No Neogene volcanism present.

- Vent ages—Only 9 vents actually dated (Figure 3-5). Many dates for southern part of field, but most of these sample locations have unknown vents.

- Volumes—Mapping accomplished at a resolution too low to accurately calculate volumes.

- Geochemistry—Adequate coverage of major flow units (Figure 3-6). However, sparse sampling of central and southern parts of the field.

- Fault locations—Regional mapping only. However, Owens Valley Quaternary faults are well located and studied in relative detail.

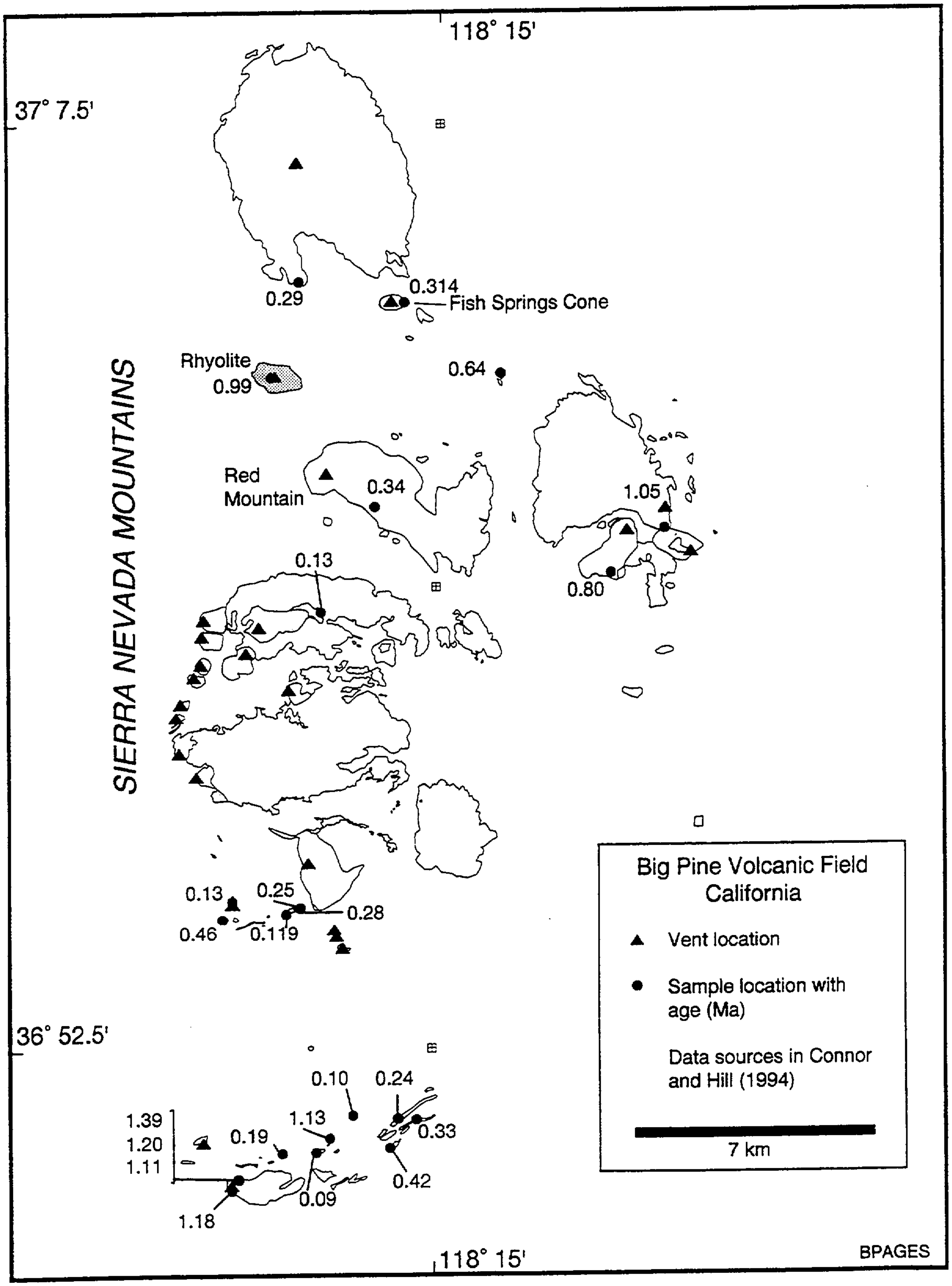

Figure 3-5. Vents and lava flows of the Big Pine Volcanic Field, California, with locations of dated samples. Map projection is UTM zone 11, NAD27 datum, Clarke 1866 spheroid.

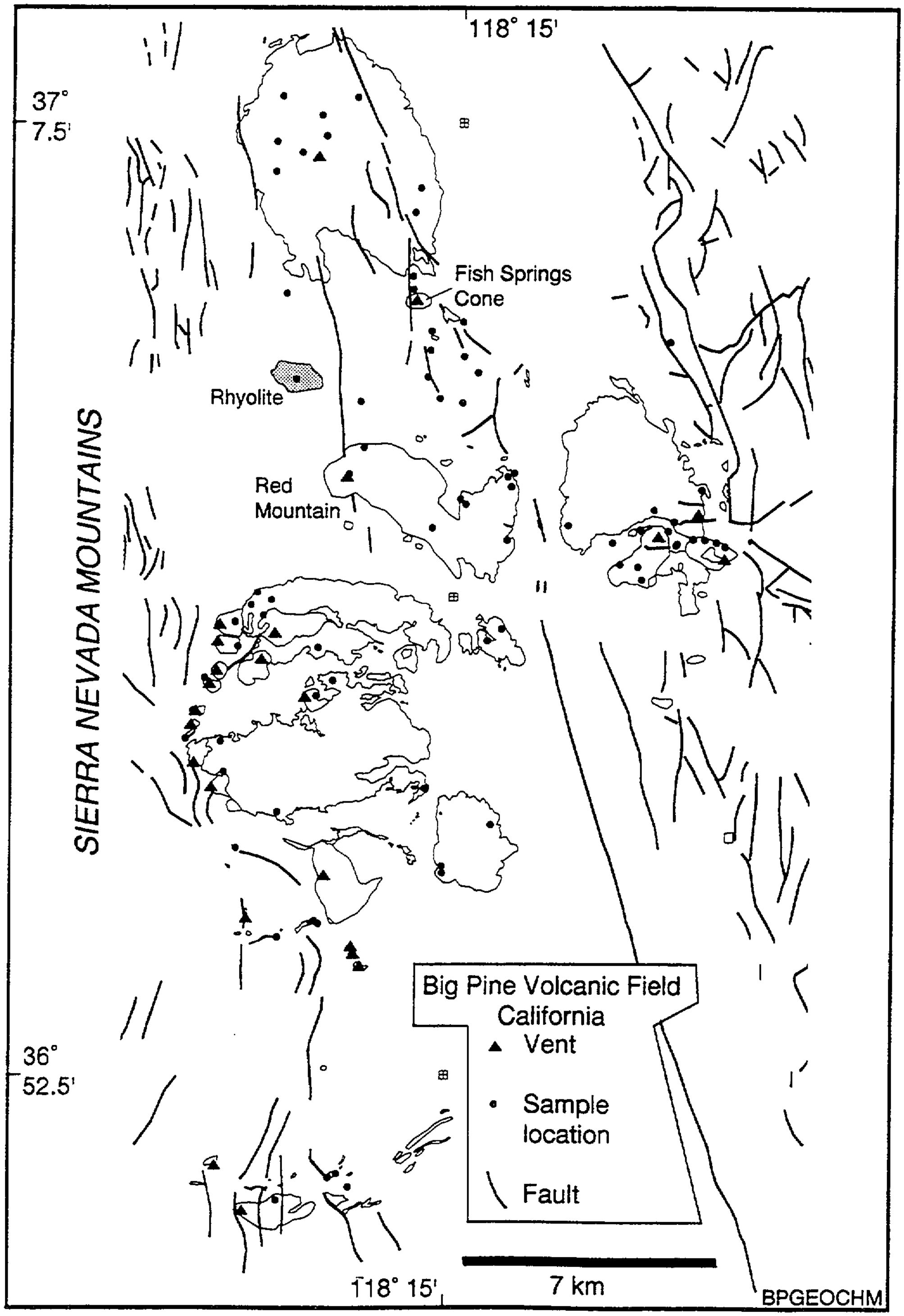

Figure 3-6. Volcanoes and lavas of the Big Pine Volcanic Field, California, with locations of geochemical analysis samples. Map projection is UTM zone 11, NAD27 datum, Clarke 1866 spheroid.

- Dike-fault—Very interesting alignments on the eastern flank of the Sierra Nevada Mountains (Figure 3-6). Red Mountain located on a fault, Fish Springs Cone offset by a fault (Figure 3-6). Possible dikes about 90° difference in strike from N-trending faults at southern part of field.

3.5 LUNAR CRATER-REVEILLE RANGE, NEVADA

Volcanoes in the Lunar Crater-Reveille Range Volcanic Field have been relatively well studied, although the level of investigation is often insufficient for completion of model-building tasks using the volcanism GIS database. Much of the Lunar Crater and parts of the Reveille Range fields have been mapped at 1:48,000 scales. However, many lava flows and associated samples cannot be related to specific vents. Volcanism shows an overall migration in age from early Pliocene in the southern Reveille Range to late Quaternary in the northeastern Lunar Crater field (Bergman, 1982). Basalts also show a shift from hypersthene-normative in the Reveille Range to nepheline-normative in the Lunar Crater field (Foland and Bergman, 1992).

Much of the data for this field is contained in two Ph.D. and two M.S. theses (Bibliography). These theses emphasized the geochemistry of the volcanic fields, but little physical volcanology was done. Additional studies have focused on the petrology of mantle xenoliths and regional stratigraphic or structural investigations. Ongoing work in the Reveille Range by E.I. Smith and coworkers at the University of Nevada, Las Vegas, involves detailed mapping (1:24,000) of Neogene volcanic rocks including the relationship between faults and dikes, and geochronology and petrology studies.[2]

Summary of Available Data:

- Vent locations—At least 84 Quaternary vents, most of which are reasonably well identified from topographic maps or sketch maps (Figure 3-7). At least 52 Pliocene vents in the Reveille Range.

- Vent ages—Only 15 Quaternary and 11 Pliocene vents have correlatable dates. At least 25 dated lavas cannot be correlated with source vents.

- Volumes—Mapping accomplished at a resolution too low to accurately calculate volumes.

- Geochemistry—Only 59 major element and 101 trace element analyses reported, most of which cannot be correlated with a vent location (Figure 3-8).

- Fault locations—Regional mapping in the adjoining ranges is relatively good, but little faulting is present in the Lunar Crater basalts (Figure 3-8). The work ongoing in the Reveille Range should provide for high resolution of fault locations.[3]

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[2] Yogodzinski, G. Personal Communication to B. Hill RE: status of ongoing UNLV research in Reveille Range, NV. November, 1994.

[3] Ibid.

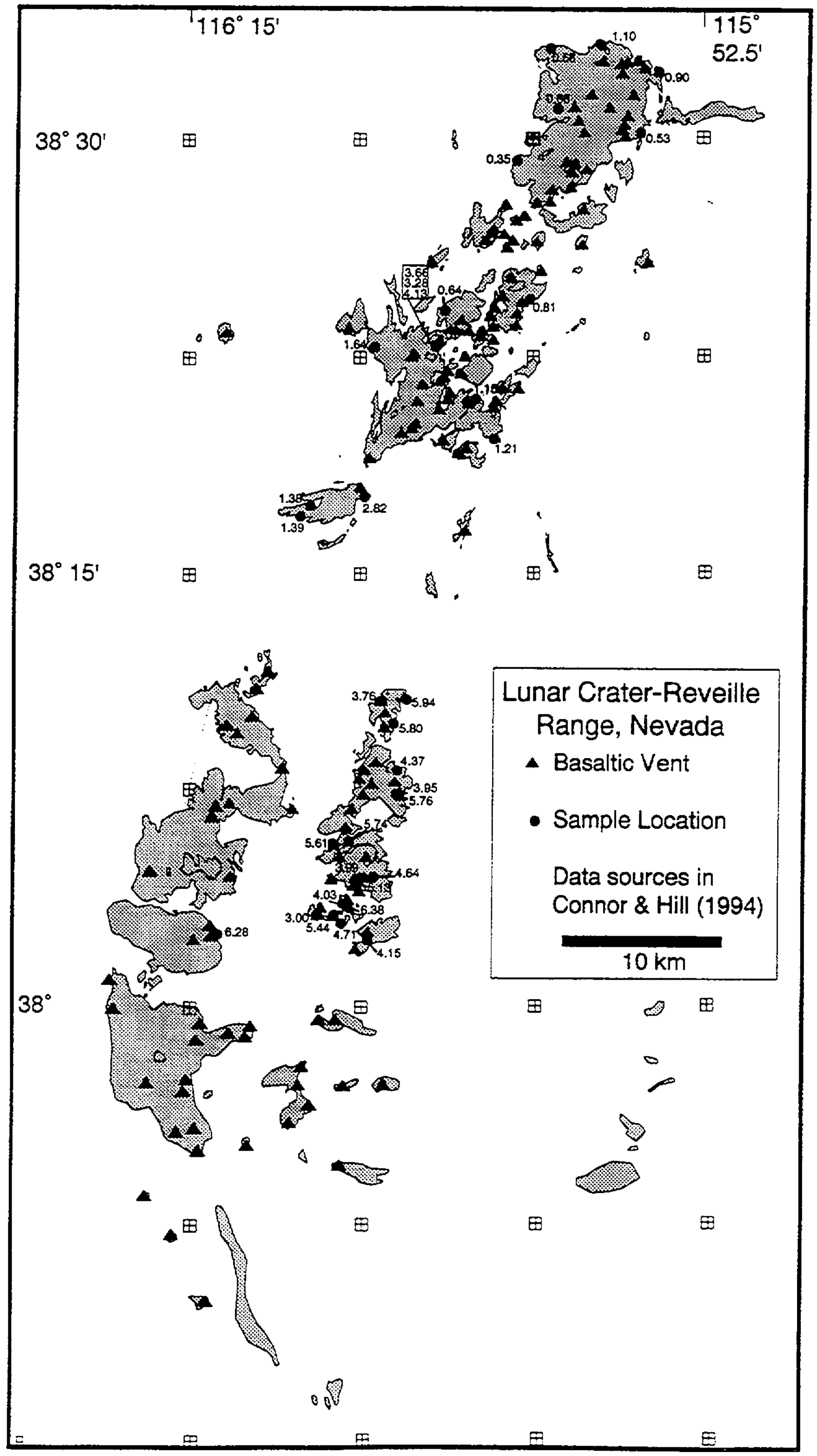

Figure 3-7. Vents and lava flows of the Lunar Crater and Reveille Range Volcanic Fields, Nevada, with locations of dated samples. Map projection is UTM zone 11, NAD27 datum, Clarke 1866 spheroid.

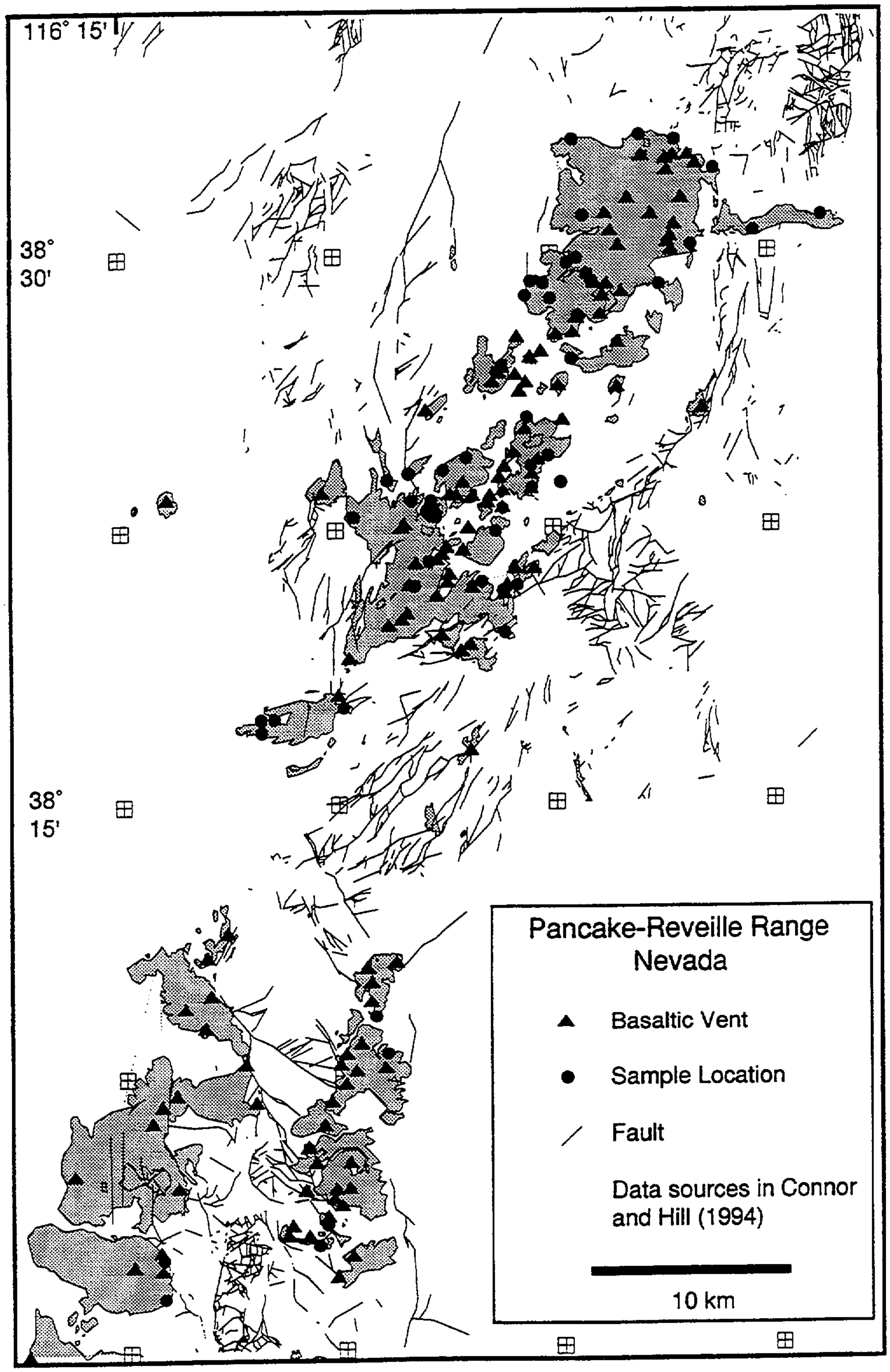

Figure 3-8. Volcanoes and lavas of the Lunar Crater and Reveille Range Volcanic Fields, Nevada, with locations of geochemical analysis samples. Map projection is UTM zone 11, NAD27 datum, Clarke 1866 spheroid.

- Dike-fault—Little data published, but the Reveille Range appears to be an excellent place to investigate dike-fault relationships.[4]

3.6 COSO VOLCANIC FIELD, CALIFORNIA

The Coso Volcanic Field (Coso) has been relatively well studied due to the occurrence of geothermal resources associated with Quaternary rhyolitic volcanism at the field. However, the presence of 27 Quaternary rhyolite domes and flows and their apparent interaction with the basaltic magma system limits the analogy between Coso and the YMR. Pliocene and younger volcanic features at Coso have been mapped at scales of 1:50,000, whereas older features are mapped at scales of 1:62,500 to 1:250,000. Studies on Coso basaltic rocks have generally focused on the geochemistry of the magma system; there have been few physical volcanological studies at Coso. Like the Lunar Crater-Reveille Range and Cima Volcanic Fields, Coso also shows a migration in magmatism in the field from north during the Miocene to southward through the Pliocene and Quaternary (Figure 3-9).

Data for Coso generally are located in published U.S. Geological Survey maps and reports, and in reviewed journal articles (Bibliography). Most of the research at Coso has focused on rhyolitic magmatism and the local tectonic setting of the area, which are directly related to the significant geothermal resources at Coso. A large part of the field is located on the China Lake Military Reservation, which has restricted general access to the Coso field.

Summary of Available Data:

- Vent locations—23 Quaternary, 32 Pliocene, and 3 Miocene basaltic vents mapped. Most lavas cannot be correlated with specific vents.

- Vent ages—Most sample locations with unknown vents. There are 51 dates, of which only 13 can be correlated with a vent (Figure 3-9).

- Volumes—Mapping accomplished at a resolution too low to accurately calculate volumes.

- Geochemistry—29 Quaternary, 29 Pliocene, and 5 Miocene basalt analyses, most of which cannot be correlated with a vent (Figure 3-10).

- Fault locations—Excellent map coverage showing complicated fault patterns and older structures in the surrounding areas (Figure 3-10).

- Dike-fault—Little data published. The Pliocene rocks appear syndepositional with basin sediments and probably are not deeply eroded.

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[4] Yogodzinski, G. Personal Communication to B. Hill RE: status of ongoing UNLV research in Reveille Range, NV. November, 1994.

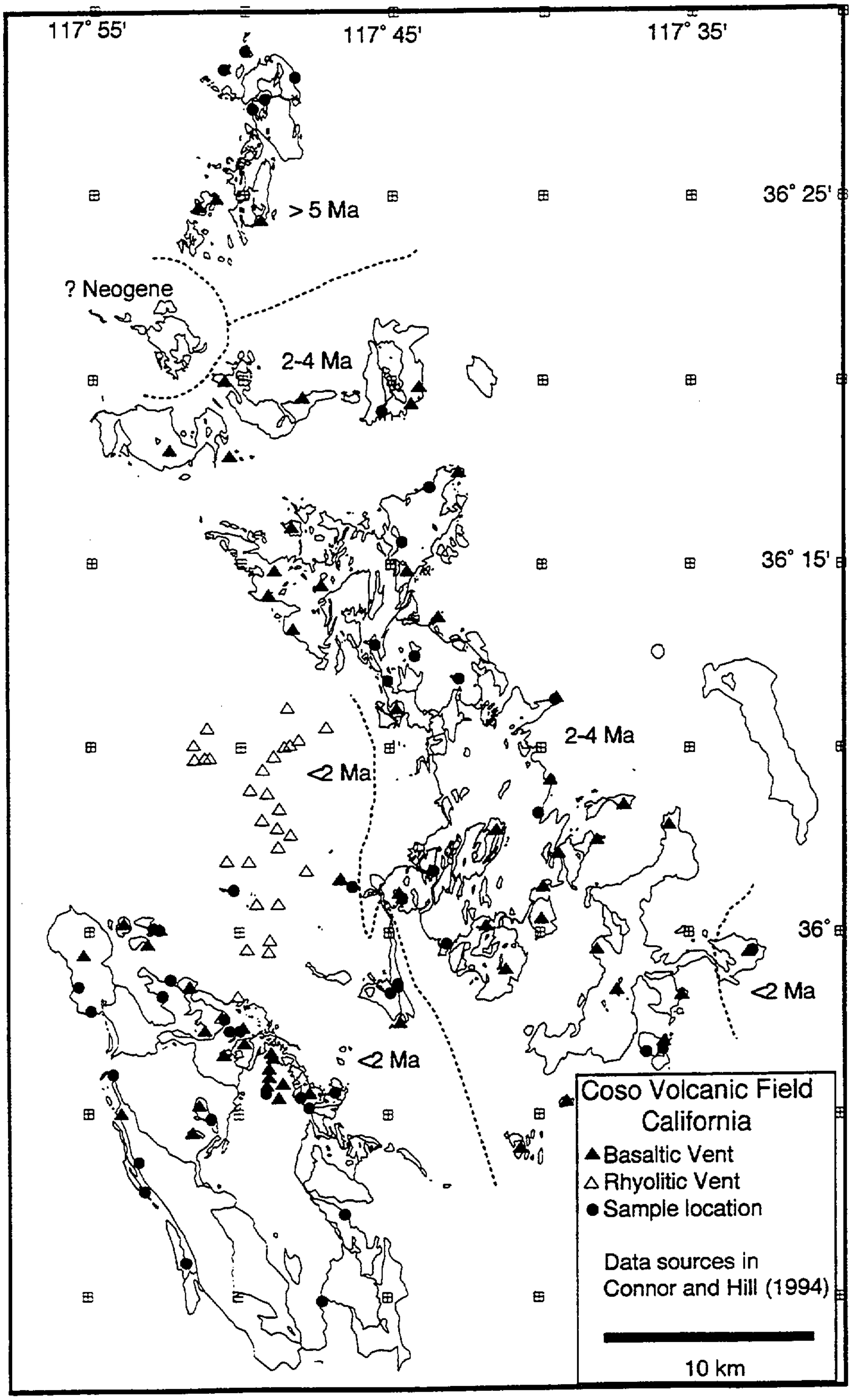

Figure 3-9. Vents and lava flows of the Coso Volcanic Field, California, with locations of dated samples. Individual dates not shown for clarity. Map projection is UTM zone 11, NAD27 datum, Clarke 1866 spheroid.

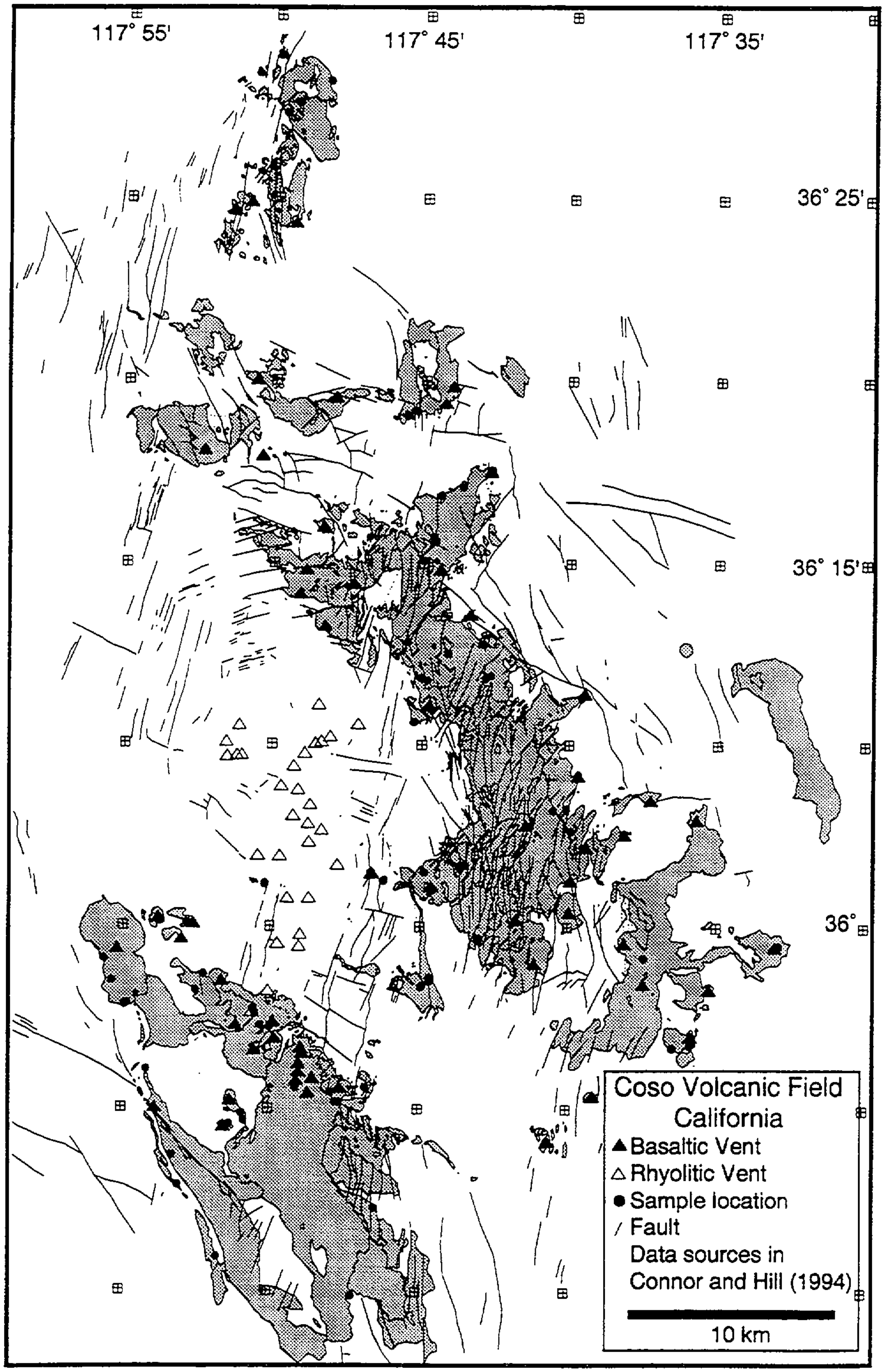

Figure 3-10. Volcanoes and lavas of the Coso Volcanic Field, California, with locations of geochemical analysis samples. Map projection is UTM zone 11, NAD27 datum, Clarke 1866 spheroid.

3.7 SPRINGERVILLE VOLCANIC FIELD, ARIZONA

Detailed volcanological data for the Springerville Volcanic Field only recently became available and have not been entered into the database. These data will be entered into the GIS database because the Springerville field appears to be an excellent site for testing probability models. Although there are over 400 Pliocene and Quaternary volcanoes and only about 40 are dated, the ages of most other volcanoes can be reasonably constrained by the detailed volcanic stratigraphy of the area. The Springerville field also has been mapped in detail sufficient to correlate all surficial lavas and associated samples to the source vent (Condit et al., 1994).

Summary of Available Data:

- Vent locations—Excellent coverage. 407 mapped vents, lavas correlated with source vents.
- Vent ages—About 10 percent of the Quaternary vents dated directly, but most others constrained by stratigraphy and paleomagnetics.
- Volumes—Data are available to calculate volumes based on assumed unit thicknesses from maps.
- Geochemistry—Excellent coverage. Over 200 analyses available, most of which can be correlated with source vents (Condit et al., 1989; 1994).
- Fault locations—Excellent coverage of faults adjacent to volcanic field, vent alignments prominent.
- Dike-fault—Only by inference of vent alignments.

3.8 SAN FRANCISCO VOLCANIC FIELD, ARIZONA

Although detailed investigations are ongoing,[5] few data are available for this field, and none are in the database. The San Francisco field has been mapped at 1:62,500, but many geochemical samples cannot be correlated directly with source vents.

Summary of Available Data:

- Vent locations—Over 600 basaltic vents. Good Quaternary locations, fair for Pliocene vents.
- Vent ages—Poor. Too many vents and stratigraphy is not yet well constrained.

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[5] Condit, C. Personal Communication to B. Hill and C. Connor RE: ongoing research at San Francisco Volcanic Field. April, 1994.

- Volumes—Data are available to calculate volumes based on assumed unit thicknesses from maps.

- Geochemistry—Fair coverage but lots of vents and many samples not correlated with vents.

- Fault locations—Excellent coverage of faults adjacent to volcanic field, vent alignments prominent.

- Dike-fault—Only by inference of vent alignments.

4 APPLICATION OF THE VOLCANISM GIS DATABASE FOR DEVELOPING SPECIFIC MODELS

The sufficiency of the volcanism GIS database is best evaluated in light of models proposed to describe volcanism in the western Great Basin, and in particular the YMR. These models range from standard probability models to tectonic and geochemical models that attempt to provide a more deterministic basis for volcanic hazard analyses. The models require different types of data of varying precision and accuracy. For example, homogeneous Poisson probability models require little geological data (i.e., accurate vent locations and ages need not be known). However, application of parametric probability models requires more accurate geochronological and spatial information. Thus, the available data discussed in Chapter 3 will be evaluated in the context of such models in Chapter 4. This evaluation is critical because these models will likely be used directly in Phase 3 efforts for IPA. Basic patterns in cinder cone volcanism that must be incorporated into any model are also discussed in this chapter. Recognition of these patterns in basaltic volcanism emerged, in part, through review of the GIS database.

The following four classes of models are reviewed in this chapter:

- Nonparametric probability models
- Parametric probability models
- Geochemical evolution models
- Tectonic models

Data requirements for each model are emphasized, followed by an assessment of how well the current GIS database meets these requirements.

The first two sets of models, nonparametric and parametric probability models, rely on timing and distribution of past volcanism to calculate the probability of volcanic disruption of the proposed repository. In both cases, spatial, temporal, and certain additional information may be incorporated into the models to varying degrees. Geochemical models are classically applied in volcanic fields with the goal of understanding the depth of origin of the magmas, degree of heterogeneity in the magmatic system, and state of magma production in the system—whether it is waxing, waning, or steady-state. This information is critical to the successful implementation and evaluation of probability models. Similarly, tectonic models may provide insight into the timing and spatial pattern in cinder cone volcanism, which will modify probability estimates.

4.1 PATTERNS IN BASALTIC VOLCANISM

Patterns in the distribution and timing of cinder cone volcanism in the YMR are similar to patterns identified in other, often more voluminous, volcanic fields. For example, abrupt shifts or migration in the loci of volcanism over periods of millions of years have been documented in many basaltic volcanic fields. In the Coso Volcanic Field, California, Duffield et al. (1980) found that basaltic volcanism occurred in essentially two stages. From approximately 4 to 2.5 Ma, eruption of basalts took place over a broad area in what are now the northern and western portions of the Coso Volcanic Field.

In the Quaternary, the locus of volcanism shifted southeast, and the youngest basalts erupted in the southern portion of the Coso field (Figure 3-9). Condit et al. (1989) noted the tendency for basaltic volcanism to gradually migrate from west to east in the Springerville Volcanic Field between 2.5 and 0.3 Ma. Other examples of volcanic fields in which the loci of cinder cone volcanism migrated include the San Francisco Volcanic Field, Arizona (Tanaka et al., 1986), the Lunar Crater Volcanic Field, Nevada (Foland and Bergman, 1992) (Figure 3-7), the Michoacán-Guanajuato Volcanic Field, Mexico (Hasenaka and Carmichael, 1985), and the Cima Volcanic Field, California (Dohrenwend et al., 1984; Turrin et al., 1985) (Figures 3-2 and 3-3). In some instances, migration is readily explained by plate movement, as is the case for the San Francisco and Springerville Volcanic Fields (Tanaka et al., 1986; Condit et al., 1989; Connor et al., 1992). In other areas, the direction of migration or shifts in the locus of volcanism do not correlate with the direction of plate movement. In either case, models developed to describe the recurrence rate of volcanism or to predict locations of future eruptions in volcanic fields need to account for these shifts in the location of volcanic activity.

On a smaller scale, cinder cones are known to cluster within many volcanic fields (Heming, 1980; Hasenaka and Carmichael, 1985; Tanaka et al., 1986). Spatial clustering can be recognized through field observation or through the use of exploratory data analysis or cluster analysis techniques (Connor, 1990). Clusters identified using the latter approach in the Michoacán-Guanajuato and the Springerville Volcanic Fields were found (Hasenaka and Carmichael, 1985; Conner et al., 1992) to consist of 10 to 100 individual cinder cones. Clusters in these fields are roughly circular to elongate in shape with diameters of 10 to 50 km. The simplest explanation for the occurrence, size, and geochemical differences between many clusters is that these areas have higher magma supply resulting from persistent partial melting or higher rates of partial melting. Factors affecting magma pathways through the upper crust, such as fault distribution, appear to have little influence on cluster formation (Connor, 1990; Connor and Condit, 1994). In some volcanic fields, the presence of silicate melts in the crust may influence cinder cone distribution by impeding the rise of basaltic magma (Eichelberger and Gooley, 1977; Bacon, 1982) and result in the formation of clusters. This clustering is evident in the YMR (Figure 3-1) and the Big Pine Volcanic Field (Figure 3-5).

Tectonic setting, strain-rate, and fault distribution all may influence distribution of basaltic vents within clusters and sometimes across whole volcanic fields (Nakamura, 1977; Smith et al., 1990a; Parsons and Thompson, 1991; Takada, 1994). Kear (1964) discussed local vent alignments in which vents of the same age are easily explained by a single episode of dike injection and regional alignments in which vents of varying age and composition are aligned over distances of 20 to 50 km or more. Abundant examples of alignment are found in the GIS database (e.g., Figure 3-8). Numerous mathematical techniques have been developed to identify and map vent alignments at different scales, including the Hough transform (Wadge and Cross, 1988), two-point azimuth analysis (Lutz, 1986), and frequency-domain map filtering techniques (Connor, 1990). Regional alignments identified using these techniques are commonly collinear or parallel to mapped regional structures. For example, Draper et al. (1994) mapped vent alignments in the San Francisco Volcanic Field, which are parallel to, or collinear with, segments of major fault systems in the area. About 30 percent of the cinder cones and maars in the San Francisco Volcanic Field are located along these regional alignments (Draper et al., 1994). In the Big Pine Volcanic Field, alignments parallel the Owens Valley fault system (Figure 3-5). Lutz and Gutmann (1994) identified similar patterns in the Pinacate Volcanic Field, Mexico. Although alignments can clearly form due to episodes of dike injection (Nakamura, 1977) and therefore are sensitive to stress orientation (Zoback, 1989), there are also examples of injection along pre-existing faults (e.g., Kear, 1964; Draper et al., 1994) oblique to maximum horizontal compressional stress.

Cumulatively, these studies indicate that models describing the recurrence rate, or probability, of basaltic volcanism should reflect the clustered nature of basaltic volcanism and shifts in the locus of basaltic volcanism through time. Models should also be amenable to comparisons with basic geological data, such as fault patterns and neotectonic stress information, which may impact vent distributions on a comparatively more detailed scale. Data in the GIS database capture these essential aspects of cinder cone distribution. Probability models should also incorporate uncertainties in the distribution and timing of volcanism. Uncertainty in the distribution of volcanoes is particularly important for pre-Quaternary volcanoes. These volcanoes may be buried as a result of subsequent volcanic activity (e.g., Condit et al., 1989) or sedimentation (e.g., Langenheim et al., 1993) or may have been so deeply eroded that vent locations cannot be recognized. Uncertainty in the ages of volcanoes is the result of variations in the precision and accuracy of different techniques used to date the volcanoes and open-system behavior of volcanoes (e.g., Hill et al., 1993). As discussed in Chapter 3, this temporal uncertainty is a major limitation of the volcanic GIS database.

Finally, it is possible to define a volcanic event in various ways. A simple definition that can be applied to young cinder cones, spatter mounds, and maars is based on morphology: an individual edifice represents an individual volcanic event. In the literature, volcanic events used in distribution analyses are defined as mapped vents (Condit et al., 1989; Connor et al., 1992; Lutz and Gutmann, 1994; Wadge et al., 1994) or volcanic edifices of a minimum size (Hasenaka and Carmichael, 1985; Connor, 1990; Bemis and Smith, 1993). Events defined in this manner are readily handled by the GIS database. In older, eroded systems, evidence of the occurrence of vents, such as near-vent breccias or radial dikes, is required. These data are not readily available in the GIS database. Furthermore, several edifices can form in single, essentially continuous, eruptive episodes. An example of the formation of multiple edifices during a single, continuous eruptive episode is shown by the three closely spaced cinder cones formed during the 1975 Tolbachik fissure eruption (Tokarev, 1983; Magus'kin et al., 1983). In this case, the three cinder cones represent a single eruptive event that is distributed over a larger area than is represented by a single cinder cone. The three 1975 Tolbachik cinder cones have very different morphologies and erupted adjacent to three older (late? Holocene) cinder cones (Braytseva et al., 1983). Together this group forms a 5-km long north-trending alignment. Without observing the formation of this alignment, it would likely be difficult to resolve the number of volcanic events represented by these six cones. This type of eruptive activity results in uncertainty in the number of volcanic events represented by individual cones even where the cones are well preserved.

The uncertainties discussed above in this section represent a serious problem in most, if not all, volcanic fields because often there is no clear way to resolve them. An alternative approach is to ascertain the impact of this uncertainty on the probability model. This approach is likely the only one possible using the GIS database.

4.2 NONPARAMETRIC MODELS

The expected volcano recurrence rate per unit area (Diggle, 1977, 1978; Ripley, 1977, 1981; Cressie, 1991) must be estimated in most volcanic fields because clustering causes a marked departure of recurrence rate per unit area from the average recurrence rate. Three nonparametric estimates of recurrence rate are described in this section. All three methods are nonparametric, and the recurrence rate estimates are controlled by the distribution and timing of past volcanism.

4.2.1 Method 1: Spatio-Temporal Nearest-Neighbor Estimate

The first method provides a spatial and temporal estimate of recurrence rate:

$$\lambda_r(x,y) = \frac{m}{\sum_{i=1}^{m} u_i t_i} \tag{4-1}$$

where near-neighbor volcanoes are determined as the minimum, $u_i t_i$, t_i is the time elapsed since the formation of the i^{th} nearest neighbor volcano, and u_i is defined as the area of a circle whose radius is the distance between volcano i and point x,y, with $u_i \geq 1$ km^2.

The relationship between this estimate of recurrence rate and homogeneous Poisson models, in which the recurrence rate is a constant over time and within a specified area, can be illustrated by describing the behavior of $\lambda_r(x,y)$ when a completely spatially and temporally random process is sampled. Modifying Eq. (4-1) slightly:

$$z_i = u_i t_i \tag{4-2}$$

$$\lambda_r(x,y) = \frac{m}{\sum_{i=1}^{m} z_i} \approx \frac{1}{E(Z)} \tag{4-3}$$

where $E(Z)$ is the expected value of z. If volcanoes form as the result of a completely spatially and temporally random process, $E(Z)$ can be thought of as the expected time and area within which n volcanoes will form, and z must have a gamma density distribution (Ripley, 1981). Therefore, the probability density function for z is:

$$f_z(z) = \frac{\lambda^n}{(n-1)!} z^{n-1} e^{-\lambda z} \tag{4-4}$$

where λ is the average recurrence rate within some specified area and over some specified time interval. The expected value of z, given this probability density function, becomes:

$$E(Z) = \frac{\lambda^n}{(n-1)!} \int_0^\infty z^n e^{-\lambda z} dz \tag{4-5}$$

$$E(Z) = \frac{\lambda^n}{(n-1)!} \frac{n!}{\lambda^{n+1}} = \frac{n}{\lambda} \tag{4-6}$$

In order to compare $E(Z)$ with the recurrence rate per unit area, as defined in Eq. (4-3), $E(Z)$ is evaluated for $n=1$, that is, the expected time and area within which one new volcano will form. Combining Eqs. (4-3) and (4-6),

$$\lambda_r(x,y) = \lambda \tag{4-7}$$

for completely spatially and temporally random distributions. The near-neighbor estimate of recurrence rate, $\lambda_r(x,y)$, becomes a constant equal to the average recurrence rate over some specified area if the underlying distribution is completely spatially and temporally random. This near-neighbor nonhomogeneous Poisson model is simply a general form of homogeneous Poisson models. One distinct advantage of using the more general near-neighbor nonhomogeneous Poisson models rather than homogeneous Poisson models is that regions within which λ is taken to be constant need not be defined.

Therefore, it is reasonable to compare the expected regional recurrence rate calculated using various near-neighbors Eq. (4-1):

$$\lambda_t = \int_X \int_Y \lambda_r(x,y) dy dx \tag{4-8}$$

with the observed regional recurrence rate. In practice, recurrence rates, $\lambda_r(x,y)$, are calculated on a grid, and these values are summed over the region of interest:

$$\lambda_t = \sum_{i=0}^{q} \sum_{j=0}^{n} \lambda_r(i,j) \Delta x \Delta y \tag{4-9}$$

where, in this case, Δx and Δy are the grid spacing used in the calculations, and q and n are the number of grid points used in the x and y directions, respectively.

In summary for Method 1, several assumptions are made in the application of Eq. (4-1) to estimate the intensity of volcanism and the probability of volcanic eruptions in a particular volcanic field. The most important assumption is that the appropriate number of near-neighbor volcanoes can be estimated from the regional recurrence rate. In areas of concentrated volcanism, such as the Springerville Volcanic Field, the frequency of vent-forming eruptions is high enough to make recurrence-rate estimates fairly straightforward (Connor and Condit, 1994). In other areas, such as the YMR, greater uncertainty exists in estimates of the recurrence rate because of the comparatively fewer number of events (Crowe et al., 1982; Ho et al., 1991). In addition, the use of Eq. (4-1) assumes that u_i and t_i have been adequately determined for each volcano. Here, t_i is taken to represent the time of formation of the volcano. Finally, it is assumed that each volcano is adequately represented as a point. However, as described below, various area terms may be used to alleviate this assumption. In practice, it is relatively simple to test the sensitivity of results to both uncertainty in the ages of volcanoes and estimates of the regional recurrence rate of volcanism by computing the recurrence rate using a range of parameters.

4.2.2 Method 2: Kernel Estimate

Lutz and Gutmann (1994) applied a kernel method (Silverman, 1986) for estimation of the spatial recurrence rate of volcanism in their study of vent alignment distribution in the Pinacate Volcanic Field. In the kernel estimation technique, spatial variation in estimated recurrence rate is a function of distance to nearby volcanoes and a smoothing constant, h. The kernel function is a probability density function that is symmetric about the locations of individual volcanoes. Following the example of Lutz and Gutmann (1994), an Epanechnikov kernel is used (Cressie, 1991). For a purely spatial, bivariate distribution:

$$\kappa(u) = \frac{2}{\pi}\left(1 - \frac{\overline{pv_i}}{h}\right), \quad \text{if } \frac{\overline{pv_i}}{h} < 1 \tag{4-10}$$

$$\kappa(u) = 0, \text{ otherwise}$$

where h is the smoothing constant, used to normalize the distance between point p, the location for which recurrence rate is estimated, and volcano v_i. The spatial recurrence rate at point p is then:

$$\lambda_h(p) = \frac{1}{e_h(p)} \sum_{i=1}^{n} h^{-2}\kappa(u) \tag{4-11}$$

where n volcanoes are used in the analysis and $e_h(p)$ is an edge correction (Diggle, 1985; Cressie, 1991). In the case of a volcanic field, integrating $\lambda_h(p)$ over some large area, A, relative to the size of the field and the smoothing constant, h, should yield n. For the Epanechnikov kernel, letting $x = \overline{pv_i}/h$:

$$y = \frac{2}{\pi}(1-x),$$

$$\int_0^{2/\pi} \pi\left(1 - \frac{\pi}{2}y\right)^2 dy = \frac{2}{2} \tag{4-12}$$

Therefore, if $e_h(p) = \frac{2n}{3}$ then $\int_A \lambda_h(p)\,dp = 1$, where the units of $\lambda_h(p)$ are volcanoes/km^2. Using this value for $e_h(p)$, $\lambda_h(p)$ can be multiplied by an estimate of the temporal recurrence rate, λ_t, to calculate the expected number of volcanoes per unit area per time. The value of $\lambda_h(p)$ at a given point p depends on the number of volcanoes found within a distance h of p. If no volcanoes are located within h of a point p, then $\lambda_h(p) = 0$.

Eruptions will have a high probability close to existing volcanoes if h is chosen to be small. Conversely, a large value of h will result in a more uniform probability distribution. Clearly, utility of the kernel model depends on the assumption that the smoothing constant can be estimated in a geologically meaningful way. Silverman (1986) recommends using a wide range of smoothing constants in density calculations, an approach adopted by Lutz and Gutmann (1994). A spatial cluster analysis can further constrain the range of reasonable smoothing constants. The shape of the kernel function is an additional assumption in the model. Alternative kernel functions include uniform random and normal density distributions. Although Cressie (1991) and Lutz and Gutmann (1994) indicate the choice of the kernel function is not as important as the choice of an appropriate smoothing constant, several different kernels can be simply applied in volcano distribution models. In practice, the kernel function has a trivial impact on probability calculations compared with the choice of a smoothing constant.

4.2.3 Method 3: Nearest-Neighbor Kernel Estimate

In Method 3 a value $r_m(p)$ is substituted for the smoothing constant, h, in Eq. (4-11), where $r_m(p)$ is the distance between point p and the m^{th} nearest-neighbor volcano (Silverman, 1986). In this case, the nearest-neighbor is determined on the basis of distance only rather than using the measure $u_i t_i$ used in Method 1. For $m > 1, \lambda_r(p) > 0$ everywhere. Thus, this nearest-neighbor kernel method produces smoother variation in the probability surface than is calculated for all but the largest values of a smoothing constant in Method 2. Nonetheless, the estimated recurrence rate will be higher near the center of clusters than is estimated using the large values for the smoothing constant in Method 2. As in Method 1, the number of near neighbors used to estimate $\lambda_r(p)$ will strongly impact the results, and experimentation using a range of near-neighbors is necessary to identify the resulting variation in $\lambda_r(p)$.

4.2.4 Use of Nonparametric Models with GIS Data

Commonality between the three methods lies in the fact that each method depends fundamentally on the distribution of past volcanic events in order to estimate the probable locations of future volcanism. In the case of Methods 1 and 3, the m nearest-neighbor volcanoes are defined by the distance to, or distance to and time since, past eruptions in the area. In Method 2, only nearby volcanoes are used in the estimate of recurrence rate where nearby is defined by the smoothing constant. As noted in Chapter 3, the spatial distribution of volcanism is the best known feature of many volcanic fields in the western Great Basin.

In all three methods, the calculation of probability of future volcanism at a given location within a volcanic field depends on an estimate of the regional recurrence rate, λ_t, which is generally not known (McBirney, 1992; Ho, 1991). Lack of sufficient geochronological information makes it impossible to estimate sufficiently in most volcanic fields. For example, limited geochronological data in the Cima Volcanic Field make application of spatio-temporal near-neighbor models difficult. However, sufficient geochronological data exist for the Cima Volcanic Field to enable the comparison of nonparametric spatial models, such as the kernel and nearest-neighbor kernel models.

Thus, with clear limits on resolution in some cases, these spatial techniques may be applied. With brief and concentrated field investigations, several volcanic fields may be analyzed using these nonparametric methods. It is concluded that the GIS database has sufficient data to test many aspects of nonparametric models, with limits on the geochronology being the greatest constraint. Within important and often restrictive bounding conditions it is possible to test nonparametric probability models using data in the GIS database.

4.3 PARAMETRIC PROBABILITY MODELS

4.3.1 Bivariate Gaussian

Sheridan (1992) suggests that one parametric method of accounting for spatial heterogeneity in vent distribution is to assume that post 4-Ma volcanoes located close to the candidate repository are formed as a result of steady-state activity and that the dispersion of these vents represents two standard deviations on an elliptical Gaussian probability surface. Using this assumption, Sheridan (1992) modeled the probability of repository disruption by Monte Carlo simulation for both volcanic events and dike intrusions noting that variations in the shape of the probability surface significantly alter the probability of igneous disruption of the proposed repository.

Clearly the main assumptions in this type of model are that the pattern of cinder cone volcanism in a region can be captured by a relatively simple distribution and that two parameters, the mean and variance of this distribution, can be determined or estimated. Using the vent location data available in the volcanism GIS database, this type of parametric model can be tested.

4.3.2 Spatio-Temporal Markov

A slightly more elaborate parametric model involves calculation of the probability of a volcanic event by treating each volcanic event as part of a spatio-temporal Markov sequence. The model stems from early ideas of Wickman (1969) for treating sequences of eruptions at individual composite volcanoes as Markov sequences. This approach can be extended to incorporate spatial shifts in the locus of volcanism. Markov models are unique in comparison with previously proposed volcanism probability models because, given that model parameters can be estimated, migration in the locus of volcanism on several scales may be accounted for directly in the probability estimate. For example, the most probable location of a future volcanic event changes as a function of time, dependent on the estimate of a mean process velocity vector. Therefore, probability estimates made using spatio-temporal Markov models can directly account for migration in volcanic activity. On a different scale, vent alignment development and polycyclic volcanism are readily modeled using a spatio-temporal Markov model. As a result, the power of the Markovian approach to volcanism in the YMR lies in the utility of the model to test various hypotheses of likely patterns of future volcanic activity in the YMR rather than direct calculation of the probability of volcanic disruption of the repository.

If it is assumed that a volcanic event such as the formation of a new cinder cone located at $x(t)$ and occurring at time t is a continuous Markov variable, then the conditional probability density of $x(t)$ is

$$P(x, t; x_o, t_o) = P\{x \mid x(t_o) = x_o\} \qquad t > t_o \tag{4-13}$$

for $x(t_o) = x_o$, and x_o is the most recent volcanic event prior to $x(t)$, having occurred at time t_o. The most probable location of eruptive event $x(t)$ immediately following the eruption $x_o(t_o)$ is at $x_o(t)$. Now consider that the volcanic event located at x_n has a discrete sequence of values (volcano positions in this case)

$$a_1, a_2, ..., a_n \qquad for\ n = 1\ to\ N \tag{4-14}$$

This sequence of x_n is a Markov chain when

$$P\{x_N = a_N | x_{N-1} = a_{N-1}, ...x_1 = a_1\} = P\{x_N = a_N | x_{N-1} = a_{N-1}\} \tag{4-15}$$

Using this definition of the Markov chain, the probable location of the next event x_N depends only on the location and timing of the previous event, x_{N-1}. This definition of a Markov chain is termed homogeneous. A nonhomogeneous Markov model is one in which the probable location of future events depends on the previous series of events; in the nonhomogeneous case, location and timing of the next cinder cone eruption would depend on timing and location of all previous events, usually weighted by age or location (Cressie, 1991).

By definition, for $t \to t_o$,

$$P(x,\ t;\ x_o,\ t_o) \to \delta(x - x_o) \tag{4-16}$$

and

$$\int_{-\infty}^{\infty} P(x,\ t;\ x_o,\ t_o)\, dx = 1 \tag{4-17}$$

So in this homogeneous spatio-temporal Markov model, the probability of a volcano forming at a given instant over some large region, such as in the YMR, is near unity. In other words, the model can describe the most probable location of future eruptive events should they occur at a given instant or over a given time interval.

If $x(t)$ can be described by a Markov process, then P satisfies the Fokker-Plank equation:

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial x}(\eta P) - \frac{1}{2}\frac{\partial^2}{\partial x^2}(\sigma^2 P) = 0 \tag{4-18}$$

The parameters η and σ^2 are the mean velocity and variance of mean velocity, respectively, and must be estimated in some geologically meaningful way. The parameters η and σ^2 are defined mathematically in terms of the conditional mean, $a(t)$, and the conditional variance, $b(t)$, of $x(t)$. In other words, $a(t)$ is the expected mean position of $x(t)$:

$$a(x_o,t,t_o) = E\{x(t)|x(t_o) = x_o\} \quad (4\text{-}19)$$

$$a(x_o,\ t,\ t_o) = \int_{-\infty}^{\infty} x(t) P(x,\ t;\ x_o,\ t_o)\, dx \quad (4\text{-}20)$$

Similarly, *b(t)* is the expected conditional variance of *x(t)* and is defined by:

$$b(x_o,t,t_o) = E\ \{[x(t) - a(x_o,t,t_o)]^2 \mid x(t_o) = x_o\} \quad (4\text{-}21)$$

$$b(x_o,\ t,\ t_o) = \int_{-\infty}^{\infty} [x(t) - a]^2 P(x,\ t;\ x_o,\ t_o)\, dx \quad (4\text{-}22)$$

Note that immediately after the first event in the sequence:

$$a(x_o, t_o, t_o) = x_o \quad (4\text{-}23)$$

$$b(x_o, t_o, t_o) = 0 \quad (4\text{-}24)$$

The parameters η and σ^2 are defined as the derivatives of $a(x_o,t,t_o)$ and $b(x_o,t,t_o)$ at time $t = t_o$ as

$$\eta(x_o,t_o) = \frac{\partial a(x_o,t,t_o)}{\partial t}\bigg|_{t=t_o} \quad (4\text{-}25)$$

$$\sigma^2(x_o,t_o) = \frac{\partial b(x_o,t,t_o)}{\partial t}\bigg|_{t=t_o} \quad (4\text{-}26)$$

Parameters η and σ^2 estimated in this way can be used in Eq. (4-18) if it is assumed the volcanic event at location *x(t)* satisfies the stochastic differential equation

$$\frac{dx(t)}{dt} = \eta(t) + \frac{dw(t)}{dt} \quad (4\text{-}27)$$

where *w(t)* represents the continuous random error in the estimate of *x(t)* using $\eta_{(t)}$, such that

$$E\{dw\} = 0 \quad (4\text{-}28)$$

$$E\{[dw]^2\} = \sigma^2\, dt \tag{4-29}$$

Integration of Eq. (4-27) gives

$$w(t) = w_o + x(t) - x_o - \eta\,(t-t_o) \tag{4-30}$$

Thus, the probability density function can be defined in terms of the two variables t and $w(t)$

$$\frac{\partial P}{\partial w} = \frac{\partial P}{\partial x} \tag{4-31}$$

$$\frac{\partial P}{\partial t} = -\eta\,\frac{\partial P}{\partial w} + \frac{dP}{dt} \tag{4-32}$$

Using Eqs. (4-31) and (4-32), Eq. (4-27) reduces to

$$\frac{dP}{dt} - \frac{\sigma^2}{2}\frac{d^2 P}{dw^2} = 0 \tag{4-33}$$

Solving this differential equation gives

$$P = \frac{1}{\sqrt{2\pi\,\sigma^2 (t-t_o)}}\exp\left[-\frac{(w-w_o)^2}{2\sigma^2 (t-t_o)}\right] \tag{4-34}$$

and substituting in Eq. (4-30),

$$P = \frac{1}{\sqrt{2\pi\,\sigma^2 (t-t_o)}}\exp\left\{-\frac{[x(t)-x_o-\eta\,(t-t_o)]^2}{2\sigma^2 (t-t_o)}\right\} \tag{4-35}$$

Expanding Eq. (4-35) into two dimensions gives,

$$P = \frac{1}{2\pi (t-t_o)\sqrt{\sigma_x^2\sigma_y^2}}\ \exp\left\{-\frac{[x(t)-x_o-\eta_x(t-t_o)]^2}{2\sigma_x^2 (t-t_o)} - \frac{[y(t)-y_o-\eta_y(t-t_o)]^2}{2\sigma_y^2 (t-t_o)}\right\} \tag{4-36}$$

where η_x and η_y are the x and y components of η, respectively, and σ_x and σ_y are the x and y components of σ, respectively.

Clearly, the results of any probability model formulated using Eq. (4-36) will be governed by the estimates of components of the mean velocity and variance of the mean velocity of the Markov process. The utility of the probability estimate is a function of the confidence with which this estimate may be made. A simple way to estimate these parameters is to use existing vent location data and ages to estimate the parameters. For example, a linear square error method based on volcano locations may be used to estimate mean process velocity,

$$x = \eta_x t + c_1 \tag{4-37}$$

$$y = \eta_y t + c_2 \tag{4-38}$$

where the coordinate system is chosen to maximize η_x. The time derivatives of the variance can then be estimated by

$$\sigma_x^2 = \frac{1}{N \Delta t} \sum_{i=1}^{N} \left(x_i - \eta_x t_i + c_1\right)^2 \tag{4-39}$$

$$\sigma_y^2 = \frac{1}{N \Delta t} \sum_{i=1}^{N} \left(y_i - \eta_y t_i + c_2\right)^2 \tag{4-40}$$

where N is the average repose period between the formation of new volcanoes or episodes of volcanism.

Several variations on the homogeneous spatio-temporal Markov model formulated in the above paragraphs are possible. For example, nonhomogeneous models may be used in which the position of event *x(t)* is determined using a larger number of prior events. Second, the mean and variance of the process velocity may be estimated in a variety of ways. For example, the mean velocity η_x might be related to plate velocities lending the model a more deterministic foundation.

As currently envisaged, application of the Markov model or a set of Markov models would focus on the evaluation of several working hypotheses of controls on patterns in cinder cone distribution in a formal probabilistic sense rather than serving as a means of directly estimating the probability of volcanic disruption of the proposed repository. Two hypotheses which may be evaluated using these models are (i) the time scale of migration in the locus of volcanism in areal volcanic fields is long compared with the proposed isolation period of 10,000 years, and (ii) sequential development of vent alignments is long compared to the time since the formation of Lathrop Wells. A simple approach for using Markov models to test these hypotheses is:

- Estimate the mean process velocity and variance using vent location and age data.
- Develop a Markov probability distribution based on these estimates.
- Determine the predictive ability of this distribution by application to other data sets.
- Compare the outcome of this stochastic approach with rates of known geological processes, such as plate movement or fault-slip rates.

Used in this focused way, spatio-temporal Markov models provide a valuable link between deterministic modeling of volcanism and current probability models of volcanic disruption of the proposed repository.

4.3.3 Use of Parametric Models with GIS Data

Parametric models such as the bivariate Gaussian model of Sheridan (1992) require accurate vent location data. Such data are readily available for many volcanic fields. It is possible, for example, to estimate the mean location and variance of volcano locations within clusters in several western Great Basin volcanic fields in order to better constrain estimates of these parameters. The homogeneous spatio-temporal Markov model and similar Markov models require information on the timing of volcanism in addition to spatial information. Geochronological information is less well known for many volcanic fields (cf. Chapter 3) and application of Markov models is limited by the availability of these data in the GIS database. Some of this limitation can be alleviated by bounding assumptions on the geochronological data, an approach similar to that implemented for nonparametric models. This approach may be adopted in the Springerville Volcanic Field for example, or to subsets of vent distribution data available in some western Great Basin volcanic fields.

4.4 GEOCHEMICAL AND PETROGENETIC MODELS

Geochemical and petrogenetic models can provide some deterministic basis for recurrence rate estimates. For example, Condit et al. (1989) documented waning magmatism in the Springerville Volcanic Field, Arizona, using geochemical variation as a criterion. Condit et al. (1989), Connor et al. (1992), and Connor and Condit (1994) found that waning could be related to change in the magma-volume output of the system, which is assumed to reflect magma supply, recurrence rate of cinder cone and vent formation, and volcano clustering. Thus, in the Springerville field many aspects of spatial and temporal patterns in cinder cone volcanism can be correlated with the basalt petrogenesis.

Geochemical analysis and petrogenetic modeling provide evidence of changes in several magmatic processes, including:

- Percent of partial melting in the source
- Magma supply into the system
- Source region composition
- Source region depth
- Assimilation of crust

From a hazard analysis point of view, each of these processes may influence estimates of the regional recurrence rate of volcanism and eruptive styles. However, no single set of geochemical analyses can readily distinguish between this set of processes. Rather, a complete set of major element, trace element, and mineralogical analyses, possibly supplemented by isotopic analyses, must be collected and modeled for a given field before these various processes can be distinguished successfully. Furthermore, in order to investigate these processes in a rate-dependent fashion, analyses must be related to a flow or vent for which age determinations exist. Thus, it is clear that petrogenetic models can provide tremendous insight into issues related to recurrence rate such as the occurrence of waxing and waning magmatism. However, application of these methods requires extensive modeling of data collected by numerous researchers for each volcanic field.

4.5 MAGMATO-TECTONIC MODELS

4.5.1 Regional Magmato-Tectonic Models

Based on observed regional-scale associations between extensional deformation and magmatism in the North America Cordillera, Wernicke et al. (1987) have identified four stages in the evolution of strongly extended domains for all parts of the orogen including the Basin and Range: (i) formation of early intermontane basins (i.e., incipient extension and subsequent basin subsidence), (ii) eruption of predominantly intermediate to silicic volcanic rocks, (iii) areally-restricted, large-magnitude crustal extension, occurring during or immediately after magmatism, and (iv) basaltic or bimodal volcanism, accompanied regionally by varied amounts of extension. Also, temporal and geographic distribution patterns of late Cenozoic volcanism within the Basin and Range region appear broadly correlative with boundaries between major tectonic-physiographic provinces (Luedke and Smith, 1991). Such broad correlations between extension and volcanism suggest that tectonic deformation and magmatism in the Basin and Range are somehow integral parts of the system and processes within the earth that control development of extensional tectonic structures and volcanic fields. However, specific cause and effect relationships between tectonic extension and spatially and temporally associated magmatism and volcanism are difficult to ascertain.

Reflecting the difficulty in ascertaining relationships between extension and magmatism, examples of differences of opinion on a regional model which spatially and temporally link magmatism and extension are numerous in the literature. Stirewalt et al. (1992) have previously reviewed the pertinent literature and summarized some of the different interpretations related to assessment of cause and effect relationships between regional extensional deformation and late Cenozoic magmatism. Based on conclusions drawn from this thorough review of literature addressing the volcanic-magmatic and tectonic history of the Basin and Range (Stirewalt et al., 1992), it is clear that multiple magmato-tectonic models have been applied for the Basin and Range which spatially and temporally link volcanism and extension at a regional scale. For example, Anderson (1989) concluded that syn-extensional magma intrusion extended indiscriminately across stable blocks and extended regions. Wernicke (1991) further considered the volume of late Cenozoic magmatic belts and the occurrence of magmatic centers outside regions of extension to suggest that mantle magmatic flux does not preferentially occur beneath strongly extended domains and would, therefore, not likely be the driving force for formation of the extended domains as advocated by some modelers (e.g., Dickenson and Snyder, 1979; Gans et al., 1989). Rather than being the driving force, Wernicke (1991) thought that early syn-extensional magmatism (intermediate to silicic) within extended domains may be a passive response to extension, triggered by perturbation of a mid-crustal (i.e., 15 to 30 km deep), magma-rich, fluid layer as stable blocks initially separated. Sonder et al. (1987) also suggested a partially molten deep crust existed when major extension began based on the observation that magmatism in the extended domains occurred either synchronously with or slightly prior to severe extension in a region as Wernicke et al. (1987) suggested in their four-stage history. With respect to the observation that later stages of extension were characterized by Basin and Range block faulting and mafic or bimodal magmatism (Wernicke, 1991), Sonder et al. (1987) considered that generation of basaltic melt during extension resulted from adiabatic decompression of asthenosphere, and intrusion of such melts into the lower crust already close to the solidus produced bimodal volcanism.

Other models, however, (e.g., Wernicke, 1991) considered that decompression melting alone would likely not have produced magma sources beneath the extended domains. Wernicke (1991) proposed that his hypothesized fluid layer may pond later stage basaltic/bimodal magma in the lower crust until cooling of the crust during extension permitted brittle deformation and increased the likelihood that the ponded mafic magma would erupt at the surface.

Further, there are areas that have been strongly extended but do not show magmatic or volcanic activity. As an example in the YMR, Wernicke et al. (1988) pointed out that the area of greatest extension in the Basin and Range, along the latitude of Las Vegas, is virtually free of volcanism—a fact that caused Scott (1990) to express strong doubts that crustal extension and volcanism have close temporal and spatial relationships at Yucca Mountain. Notwithstanding this fact, Smith et al. (1990b) reported on the extensive magmatic and volcanic materials that occur in the Lake Mead area south of this "amagmatic zone." They interpret the change from calc-alkaline to dominantly basaltic volcanism in that area to have accompanied a change in structural style during regional extension.

Based on multiple interpretations found in the literature (Stirewalt et al., 1992), it is clear that cause and effect for generation of basaltic magma synchronous with regional extension is not qualified through a single magmato-tectonic model at the present time. Many questions remain that are difficult to answer. Further, the data contained in the volcanism GIS database are not sufficient to permit the construction of a regional-scale magmato-tectonic model at this time. Also, data for construction of this regional model will come, in part, from the tectonics GIS database, which is currently being assembled at CNWRA and is not complete. A key limitation constraining use of data in the volcanism and tectonics GIS databases is the lack of definition of temporal history for both faulting and volcanism. In the case of faulting, lack of geochronological control for fault history makes it difficult to ascertain slip history and strain rates—aspects that are very important for assessing the temporal and spatial associations of faulting and volcanism.

4.5.2 Magmato-Tectonic Models for Yucca Mountain and Vicinity

At the scale of individual volcanic fields, some basaltic eruptive centers clearly show vents aligned along faults to indicate spatial association of faulting and volcanism. This apparent surficial (local) spatial control of volcanic vents sheds little light on plausible deeper (regional) structural controls on volcanism or on temporal associations of faulting and volcanism. In the YMR volcanic field, for example, faulting apparently controls the locations of some volcanic centers (Crowe, 1990; Smith et al., 1990a; Naumann et al., 1991; Crowe et al., 1992b), although there is controversy about orientation of some of the controlling structures both at the surface and at depth (e.g., Smith et al., 1990a). Scott (1990) has proposed an episodic model of faulting for Yucca Mountain, which generally relates extension, faulting, and volcanism. He suggested five fault-movement age periods for the YMR based on ignimbrite depositional relationships: about 14 to 13.5 Ma, 13.5 to 13 Ma, 13 to 11.5 Ma, 11.5 to 1.7 Ma and 1.7 Ma to present. Crowe (1990) indicated the following episodes of basaltic volcanism: 11.5 to 8.5 Ma in connection with termination of silicic volcanism, older postcaldera basalts (OPB) at 9 to 6.3 Ma, and younger postcaldera basalts (YPB) at about 4.5 Ma to late Pleistocene. Scott (1990) speculated that the hiatus in volcanism between roughly 10 to 4 Ma may have been causally related to a hiatus in faulting, with fault displacements resuming with renewed volcanism at about 3.7 Ma. However, the causal relationships were not defined and Scott (1990) expressed preference for a stepwise decreasing rate deformation model that did not consider how volcanism may be linked with extensional faulting. The model of Scott (1990) admittedly suffers from a lack of temporal data constraint between 11.5 and

1.7 Ma. The general lack of temporal data makes it difficult to develop a reasonable magmato-tectonic model for the Yucca Mountain vicinity.

Based on conclusions drawn from the literature review that was directed to consider the volcanic-magmatic and tectonic history of the Basin and Range (Stirewalt et al., 1992), the relationships between extension and volcanism remain unresolved for the YMR at scales applicable for consideration of high-level radioactive waste disposal facilities and no magmato-tectonic models exist linking volcanism and extension for that area. Faults adjacent to Yucca Mountain (e.g., the northeast-trending and west-dipping Paintbrush, Stagecoach Road, and Bow Ridge faults to the east and the Solitario Canyon fault to the west) contain basaltic ash in fault-related fissures, further indicating contemporaneous volcanism and tectonic deformation (Menges et al., 1994). However, this observed association does not resolve either the detailed temporal or spatial considerations necessary for development of a magmato-tectonic model for Yucca Mountain and vicinity. Just as is the case for a regional model, additional age determinations are needed on both faults and volcanic deposits (ash in this case) to narrow temporal models for volcanism and faulting. Without temporal data on faulting to unravel slip/strain history and some information on strain partitioning in the YMR, the data necessary for construction of magmato-tectonic models is incomplete. Consequently, data in the existing volcanism and tectonics GIS databases are insufficient at this time to permit construction of a magmato-tectonic model that temporally and spatially associates volcanism and faulting at Yucca Mountain. The lack of strain history data also makes it difficult to determine concise relationships between dike emplacement and faulting.

4.5.3 Dike-Fault Interaction

Geologic factors may play a role in altering current probability estimates of volcanic disruption of the candidate repository through dike interaction with pre-existing structural features such as joints or fault zones. This disruption could result in lateral transport of magma during the emplacement of cinder cones and a focusing of magma along or near fault traces at the surface. This type of scenario has resulted in a comparatively high estimated probability of volcanic disruption of the repository (Smith et al., 1990a). This process, if significant, would increase the probability of volcanic eruptions in faults zones, such as along the Solitario Canyon fault, compared with other regions. Little is known, however, about the mechanisms by which structures redirect magmas as they ascend, the circumstances under which this type of dike capture might occur, or the magnitude of lateral transport of magma that can occur once the dike has been captured by a fault zone.

Numerous examples of dike-fault interaction have been discussed in the volcanic fields represented in the volcanism GIS database, but some vents in these fields show little relation to mapped structures. Several factors likely complicate models of dike-fault interaction. First, current models of dike propagation (McDuffie et al., 1994) indicate that the properties of rock surrounding the dike have relatively little or no control on ascent rate or related dike properties. Second, Parsons and Thompson (1991) have noted that the intrusion of dikes into extending lithosphere creates strain in a manner quite similar to faulting. As a result, faulting and related topography are suppressed in regions of active dike intrusion. One result is that it is difficult to determine if a relationship exists between faults and dikes in many active fields. Third, regional stress state likely impacts slip tendency along a given fault, depending on fault strike and dip (Ferrill et al., 1994; Morris et al., 1994). Fourth, the depth of intersection of a propagating dike may influence the tendency for dikes to be captured by faults (McDuffie et al., 1994; Young et al., 1994).

To fully evaluate dike-fault interaction in light of these complicating factors, data must be available on:

- Fault and dike distribution (mapped pattern)
- Fault and dike dips as a function of depth
- Mechanical rock properties
- Principal stress orientations

To adequately address the relationship between faulting and dike emplacement in a specific volcanic field, a model that realistically represents subsurface associations of dikes and faults for that field is needed. Data for construction of models that realistically portray the subsurface geometry of faults and associated dikes are not currently contained in the volcanism or tectonics GIS databases because there has been a lack of detailed study related to subsurface associations of dikes and faults.

5 SUMMARY

The current goal of the Volcanic Systems of the Basin and Range Research Project is to evaluate spatial and temporal patterns of other volcanic fields in the western Great Basin volcanism and apply the models of these patterns to the YMR to assess the likelihood of future volcanism at or near Yucca Mountain and the potential for disruption of the candidate repository site (Stirewalt et al., 1992). Other volcanic fields in the western Great Basin analogous to the YMR must be included in the model development and assessment because past volcanic activity in the YMR does not represent the full range of magmatic processes which have occurred elsewhere in the past in the Basin and Range and may possibly occur in the future in the YMR. The YMR also contains an insufficient number of volcanoes to test many models with high levels of confidence. Previous work (Stirewalt et al., 1992; Connor and Hill, 1994) has shown that the Cima, Big Pine, Coso, and Lunar Crater-Reveille Range Volcanic Fields in the western Great Basin are analogous to varying degrees with the YMR. In addition, the Springerville and San Francisco Volcanic Fields in Arizona also have experienced magmatic processes that are analogous to those which occurred in the YMR. In order to effectively and accurately develop volcanic process models in this research project, available data from the western Great Basin volcanic fields have been entered into the database which accommodates both spatial and tabular data. Data from the Arizona fields will be added at a later date.

Data in the CNWRA volcanism GIS database have been reviewed for accuracy and sufficiency for use in developing and assessing models of volcanic activity for the YMR. Although Quaternary volcano locations and areal extent of associated lava flows are well known for many volcanic fields in the western Great Basin, little information is available to relate individual flows to source vents. In addition, ages of many volcanoes and individual flows are often poorly constrained. A significant amount of the published geochemical and geochronological data cannot be related to specific volcanoes in a field because samples collected on lava flows often cannot be correlated with the source of the flows. The many poorly constrained relationships between lava flows and source volcanoes and geochemical and geochronological sample locations and source volcanoes in many volcanic fields of the western Great Basin currently limit the utility of the volcanism GIS database for rigorously developing and assessing a variety of volcanism models.

Two of the four classes of models specifically discussed in this report covered nonparametric and parametric probability analyses of volcanic fields. Both types of probability models rely on temporal and spatial relationships (i.e., timing and distribution) of past volcanism for calculating the probability of disruption of the proposed repository at Yucca Mountain. Nonparametric models are also critically dependent on estimates of volcanism recurrence rates. At least three different methods (spatio-temporal nearest-neighbor, kernel, and nearest-neighbor kernel) can be used to determine recurrence rates from the distribution and timing of past volcanism. Even though a lack of direct geochronological information makes it difficult to rigorously estimate regional recurrence rates for most volcanic fields, other geological data often can provide reasonable constraints on the timing of past volcanic events. In spite of the limitations in the geochronology, the volcanism GIS database contains sufficient information to test nonparametric probability models if reasonable bounding assumptions are established for the geochronological data.

Parametric volcanism models do not estimate recurrence rates but still require spatial and temporal data. The bivariate Gaussian model requires vent location data which are readily available for all volcanic fields in the GIS database. The spatio-temporal Markov model has the advantage of being able to test hypotheses about the likely patterns of future volcanic activity in the YMR rather than the direct calculation of the probability of future eruptions. However, this model requires both temporal and spatial information for past volcanic events. Although geochronological information is necessary for application of the Markov model, problems with these data can be overcome if reasonable bounding assumptions are established. Consequently, both parametric and nonparametric models can be treated with the data in the volcanism GIS database, if reasonable bounding assumptions are established for geochronological data.

Geochemical evolution (i.e., petrogenetic) models are the third class of models which can be considered for volcanic fields. Existing published data on geochemistry of the volcanic fields contained in the GIS database are limited by the inability to relate much of the data to source vents and by incomplete sampling. However, there are sufficient data to evaluate overall petrogenetic trends and relate these processes to resolvable spatial or temporal trends. Although numerous petrogenetic models are published for western Great Basin Volcanic Fields, these models are subject to alternative interpretations based on available data. In particular, current models are biased toward variations in the amount and type of partial melting in the mantle source region and away from open-system recharge and fractionation effects. Whereas the application of parametric and nonparametric models is relatively straightforward, petrogenetic modeling is relatively complex and subjective. Detailed petrogenetic models cannot be developed for other western Great Basin Volcanic Fields as part of this research project and such models will be difficult to complete within the next year for the YMR. However, these models are extremely valuable for constraining volcanism probability models and should be developed to the extent possible.

Tectonic models are the fourth class of models which should be considered using data from the volcanism GIS database. Inadequate data currently exist in both the volcanism and tectonics GIS databases to distinguish between existing regional-scale magmato-tectonic models or to develop reasonable alternative models. At the scale of the YMR, data in the volcanism and tectonics GIS databases are also not sufficient to construct reasonable alternative magmato-tectonic models. Without a magmato-tectonic model for a volcanic field, it is difficult to address the relationships between faulting, strain accumulation, and dike emplacement. Consequently, the lack of data in the volcanism and tectonics GIS databases likewise influences the progress on assessment of fault-dike interactions in specific fields.

Therefore, development of the volcanism GIS database has been most useful as a mechanism for determining the extent of available data and review of these data. Based on the knowledge of the authors, if data are not currently in the GIS database then they either do not exist or, in some cases, are not obtainable because they are not yet published. This completeness makes the volcanism GIS database a valuable regulatory tool. As a research tool, the database is most useful for examining spatial relationships between vents and faults. Thus, in a limited way, several parametric and nonparametric probability models can be tested using the database. As an example, it is possible to test the bivariate Gaussian model using vent locations in several volcanic fields.

As discussed in Chapter 3, the major weakness in the GIS database is lack of temporal information. As a result, many of the models discussed in Chapter 4 cannot be fully tested. For example, although the basic distinction between Quaternary and Pliocene cinder cones has been made in most fields, finer temporal resolution is not currently possible for most volcanic fields. This is a problem because it is not possible to distinguish episodes of volcanism, which have undoubtedly occurred in the some fields (e.g., Cima) with the precision necessary to compare them to the time scales of interest for isolation of high-level radioactive waste.

Although the volcanism GIS database is of limited utility for direct application as a research tool, it does provide a platform for focused research into specific volcanic processes. Based on this critical review, several conclusions can be drawn concerning the utility of the database:

- It is possible to test and contrast probability models in the broadest sense (i.e., with low temporal resolution) using data in the volcanism GIS database. This is currently underway and will be the topic of a future CNWRA report.

- It is not possible to estimate recurrence rates of volcanism accurately on time scales of less than the Quaternary using existing data in the GIS database. However, compilation of the available data indicates that focused field work in select areas may resolve much of the uncertainty about the timing of volcanism in several fields.

- Cinder cone alignment development and relationship to tectonic processes cannot be assessed with available data in the GIS database, primarily because of the dependence of these models on temporal information.

- Geochemical models of waxing and waning volcanism can only be tested by using the broadest temporal distinctions. Although this testing is useful, geochemical trends on the time scales of interest to high-level radioactive waste disposal cannot be identified using the GIS database.

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