CNWRA 92-025

# A REVIEW OF PERTINENT LITERATURE ON VOLCANIC-MAGMATIC AND TECTONIC HISTORY OF THE BASIN AND RANGE

*Prepared for*

**Nuclear Regulatory Commission**
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# ABSTRACT

The long-range goal of the Volcanism Research Project is to assess likelihood of volcanic and magmatic activity in the Yucca Mountain area and the potential for disruption of a repository at Yucca Mountain by that activity. To this end, this report discusses extent of available volcanic and tectonic data for the Basin and Range Physiographic Province, assesses usefulness of these data for constraining conceptual models of tectonism and associated volcanism in the Basin and Range, and addresses use of nonlinear dynamics for analyzing patterns of volcanism. Based on data from review of existing literature, the following conclusions and recommendations are drawn to provide guidance for future work in the remaining tasks of this project: (i) middle to late Cenozoic (i.e., less than 55 million years ago) volcanism in the Basin and Range Province can be broadly correlated with extensional strain in space and time, although no single tectonomagmatic model currently exists for quantifying this correlation, (ii) relationships between Quaternary volcanism and extensional strain and faulting useful for assessing volcanic and magmatic hazard at the scale of Yucca Mountain are not immediately apparent from existing data, (iii) to generate a larger-volume database, Task 2 should concentrate on compilation of data from the NNW-trending Mojave-Death Valley-Sierra Nevada-Central Nevada tectonomagmatic corridor, (iv) data compilation in this corridor should focus on description and characterization of silicic and basaltic volcanism and correlative tectonics for late Neogene (i.e., starting about 6 million years ago) through Holocene time, (v) data will be compiled into an appropriate database, plotted on common base maps, and analyzed in order to make judgments about sufficiency of data for assessing likelihood of volcanism at Yucca Mountain, and (vi) the compiled expanded database should be analyzed for attractor and fractal characteristics during Task 3 analyses and used to constrain tectonomagmatic models of magma intrusion and eruption during Task 4 modeling.

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# ACKNOWLEDGMENTS

Very able support for final preparation of this report was provided by Barbara Long, Pamela Smith, Tim Fischer, Joyce Fogelle, Corky Gray, Rita Hogue, Richard Klar, and Thilda Outhuok. Their efforts are deeply appreciated. Important technical contributions to the report were provided by William P. Leeman, James F. Luhr, Bruce D. Marsh, Ronald H. Martin, and Brian P. Wernicke and are gratefully acknowledged. Particularly useful input for Chapter 3 was provided by Brian P. Wernicke and William P. Leeman. Coauthor Kenneth D. Mahrer was instrumental in preparation of Chapter 4, and solely prepared Appendix A, the tutorial on dynamics, chaos, fractals, and stochastics.

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-88-005. The activities reported here were performed on behalf of the NRC Office of Nuclear Regulatory Research, Division of Regulatory Applications. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

# 1 INTRODUCTION

Staff of the U. S. Nuclear Regulatory Commission (NRC) will be required to evaluate the license application of the Department of Energy (DOE) for a proposed high-level radioactive waste (HLW) repository at Yucca Mountain, Nevada. A key issue in the evaluation will be whether a mined geologic repository at that location will provide effective post-closure isolation of the waste from the accessible environment in accordance with the requirements set forth by the Environmental Protection Agency (EPA) in 40 CFR Part 191 and by the NRC in 10 CFR Part 60. As an indication of the recognition by the NRC of potential implications related to volcanic hazard for a repository site, two potentially adverse conditions which specifically relate to igneous activity and volcanism are included in 10 CFR Part 60: (i) 60.122(c)(15), evidence of igneous activity since the start of the Quaternary (i.e., within about the last 2 million years), and (ii) 60.122(c)(3), potential for changes in the regional groundwater flow system and resultant adverse effects on repository performance induced by large-scale surface water impoundments due to volcanic activity.

Processes and events which controlled silicic and basaltic magmatism and volcanism in the Basin and Range Physiographic Province during the last 15 million years of the Cenozoic Era (i.e., from about middle to late Tertiary through the Quaternary into the Holocene), a time of major extensional deformation for the region including Yucca Mountain (Kruse et al., 1991; Wernicke et al., 1988), are not completely understood. Quaternary basaltic volcanism is known to have occurred in the vicinity of Yucca Mountain (Crowe, 1990; Smith et al., 1990; Champion, 1991; Turrin and Champion, 1990) and may have been as recent as Holocene (i.e., less than 100,000 years old) in the case of Lathrop Wells Cone (Crowe, 1990). Consequently, concerns exist about the potential for renewed magmatic or volcanic activity in the Yucca Mountain area, assessment of future likelihood of such activity and potential for disruption of a repository at Yucca Mountain, and possible effects on long-term waste isolation for a repository at Yucca Mountain. Key elements for addressing these concerns are related to complexities of magma production and supply systems, and to factors that cause or control volcanic eruptions in Basin and Range extensional terrains. These elements are being analyzed in this research project on Volcanic Systems of the Basin and Range.

Many critical questions exist concerning processes and events associated with occurrence of silicic and basaltic volcanism in the Basin and Range which are particularly difficult to answer because to do so requires information on subsurface conditions which is not readily obtainable. Moreover, the answers to the questions encompass explanations for why, how, when, and where volcanism and magmatism may occur — information which bears on the ability to assess patterns of volcanism, possible repetition of those patterns in space and time, and consequent likelihood of volcanic or magmatic activity at a given location. Examples of critical questions that must be addressed to properly assess likelihood of future volcanic or magmatic activity in the Yucca Mountain area include: What is the relationship between magmatic history and tectonic position in major detachment fault systems? What are the relationships between magmatic history and the contemporary stress and strain fields within and around the volcanic complexes? How do factors such as magma source region and magma storage reservoir location and size relate to tectonic factors and shallow crustal magmatism? This report presents information from review of literature pertinent to answering these and related questions.

Little detailed information exists about factors which may strongly influence likelihood of occurrence of volcanic and magmatic activity, although tectonism is likely to exercise a controlling influence.

Consequently, Task 1 of the Volcanism Research Project is organized to assess data pertinent for understanding relationships between structural deformation and patterns of volcanic and magmatic activity. Discussion of data proceeds from crustal to regional (i.e., the Basin and Range Province) to local (i.e., the Yucca Mountain area) scale. Discussed initially is the contemporary deformation field, with regional faulting and magmatism in the Basin and Range treated as separate topics. The focus is then shifted to correlation of temporal and spatial patterns of extensional tectonism and volcanism. The Yucca Mountain area is placed into the overall tectonomagmatic framework of the Basin and Range Province, and then relationships between local volcanism and structural deformation are reviewed. Finally, application of chaos theory and methods of analyzing nonlinear systems are reviewed with respect to potential applicability of nonlinear dynamics methods in estimation of the potential for magmatic disruption of a repository at Yucca Mountain.

The approach used for Task 1 of this research project on Volcanic Systems of the Basin and Range is warranted because data on volcanic events in the Yucca Mountain area are sparse, and, as pointed out by Ho (1992), present understanding of eruptive mechanisms is not sufficiently advanced to permit reliable deterministic predictions of future volcanic or magmatic activity. It is anticipated that patterns of volcanism and magmatism in the Yucca Mountain area will be better understood by investigating volcanic history in relation to possible associations between volcanism and magmatism and structural deformation in the Basin and Range. This approach should assist in providing additional data for use in assessing likelihood of future volcanic or magmatic activity in the Yucca Mountain area and potential for associated disruption of a repository at Yucca Mountain.

# 2 PURPOSE AND SCOPE

The primary goal of the Volcanism Research Project is to assess the likelihood of future silicic or basaltic volcanic and magmatic activity in the Yucca Mountain area and the potential for disruption of a repository at Yucca Mountain by volcanic or magmatic activity. To satisfy this goal, Task 1 is organized to proceed from crustal to regional to local scale in assessing data related to patterns of volcanic and magmatic activity and structural deformation. Consequently, there is a need to review existing literature and other pertinent sources of data related to Cenozoic volcanic and tectonic history of the Basin and Range.

Effective review and evaluation of data and models related to assessment of hazards due to potential volcanic activity at the proposed Yucca Mountain site will depend particularly upon an understanding of small-volume mafic igneous complexes that are common in the Basin and Range Tectonic Province. The Timber Mountain caldera complex and adjacent Crater Flat Valley are notable loci of geologically recent mafic igneous activity expressed as small-volume basaltic lava flows and associated cinder cones. The extent to which regional tectonic trends or specific geologic structures exert direct influence on intrusion and eruption processes is not well known. However, mafic igneous activity is known to be especially associated with extensional tectonics. By far the most common occurrence of mafic magmatism on Earth is at mid-ocean ridge spreading centers which are sites of rapid tectonic extension. Oceanic spreading systems are developed along divergent boundaries between tectonic plates. While significant mafic magmatism is found in both oceanic and continental intraplate settings (Duncan and Richards, 1991) the occurrence of mafic magmas within the actively spreading Basin and Range suggests a relationship between basaltic volcanism and extensional tectonism. In a broad sense, these basaltic volcanic complexes appear linked to the tectonic evolution of the Basin and Range, tending to occur in belts of active deformation near the margins of the province and generally following episodes of intense intermediate to silicic magmatism and extensional tectonism. The broad tectonic control on these centers suggests that more specific relations between magmatism and tectonism may exist. Understanding the details of the tectonic environment of these volcanic complexes in relation to their magmatic histories (i.e., time, place, style and volume of shallow intrusive and extrusive activity) may provide an improved basis for assessing and predicting future activity.

This report discusses extent and availability of existing volcanic and tectonic data, including assessment of usefulness of data for constraining conceptual models of tectonism and associated volcanism in the Basin and Range. Also, potential application of nonlinear dynamics (including chaos) for assessing patterns of volcanism and potential for magmatic disruption of a repository at Yucca Mountain is considered. A key purpose of the Task 1 literature review is to provide guidance for future work in the remaining tasks of the research project.

# 3 EXTENT AND AVAILABILITY OF PERTINENT DATA

## 3.1 CONTEMPORARY GEODYNAMICS OF THE BASIN AND RANGE REGION

Crustal-scale neotectonic deformation of the Basin and Range province is strongly tied to the dynamics of relative motion between the Pacific and North America tectonic plates (Eaton, 1979). Space geodetic measurements of present day Pacific-North America relative plate motion (Ward, 1990) are in exceptional agreement with geologically instantaneous plate velocities determined from sea floor spreading rates averaged over the last 3 million years (DeMets et al., 1990). This remarkable correlation suggests crustal-scale deformation rate and geometry within the Great Basin may be consistent over a time span of a few million years. Furthermore, improvement in confidence level of plate motion determinations and plate tectonic reconstruction permits good estimates of broad, crustal-scale, constraints on deformation patterns and rates for the recent geologic past (i.e., the last 3-6 million years). Direction and rate of contemporary tectonic extension of the Great Basin region appear to be directly correlated with the extensional component of the total Pacific-North America relative convergence vector. Thus, the combined plate tectonic and geodetic relative motion estimates serve as limiting conditions for regionally distributed deformation in the Great Basin. Geodetic measurements of deformation throughout western North America further constrain displacement direction and rate, and improve resolution of regional patterns of extensional strain.

### 3.1.1 Plate Tectonics

The continental margin of western North America is exceptional in its tectonic activity, juxtaposition of plate boundary types, and complexity and extent of distributed continental deformation (Figure 3-1). The margin is comprised by a progressive serial coupling of the three known types of plate tectonic boundaries (Crowell, 1987) and by integral evolution and northward migration of the Mendocino triple junction system (Severinghaus and Atwater, 1990). Divergent plate motion in the actively extending Gulf of California is linked northward to transform motion along the San Andreas Fault, which in turn gives way to plate convergence and resultant subduction north of Cape Mendocino (Crowell, 1987). Spatial and temporal patterns of Quaternary and contemporary tectonic deformation and magmatism are broadly influenced by relative plate motion along this complex boundary. Highly specific correlation of plate boundary dynamics and continental tectonism and volcanism cannot be supported by data currently available in the literature. However, broad spatial and temporal domains of tectonic and volcanic style have been defined (Gans et al., 1989; Severinghaus and Atwater, 1990; Armstrong and Ward, 1991; Wernicke, 1991).

The overall plate tectonic setting of Yucca Mountain, that is, of the southern Great Basin, is a broad zone of continental margin deformation resulting from motion between the Pacific and North America tectonic plates. Reconstruction of plate configurations using marine magnetic anomalies suggests overall motion of the Pacific Plate during the past 3 million years of 47 mm/yr, oriented N36W with respect to North America (DeMets et al., 1990). Accommodation of the relative motion of the two plates now occurs mainly along the San Andreas Fault, which exhibits right-lateral slip at a rate of 35 mm/yr along most of its trace (Lisowsky et al., 1991; Brown, 1990; Thatcher, 1990). This leaves approximately 12 mm/yr that must be accommodated within the broad regions of active deformation east and west of the San Andreas Fault.

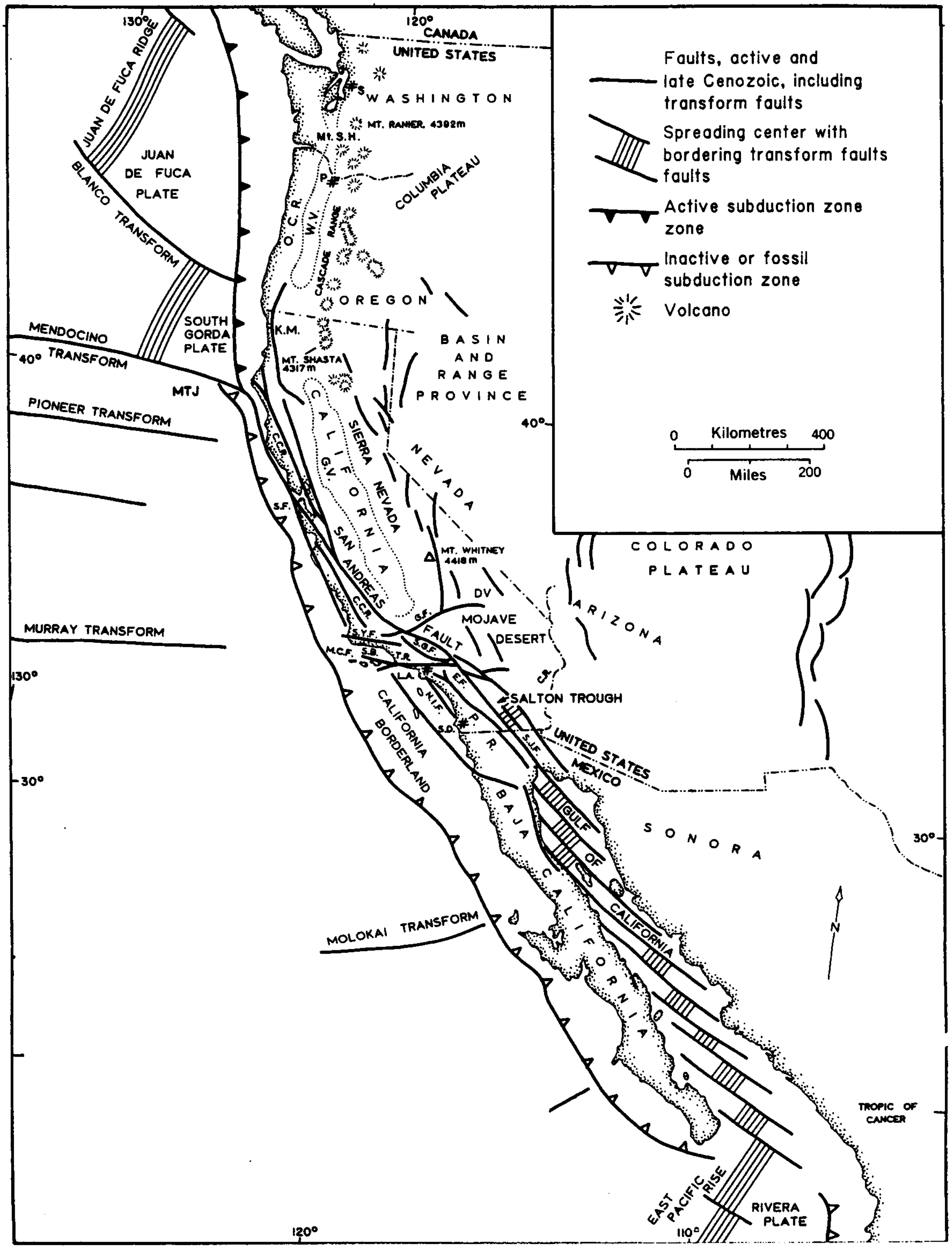


**Figure 3-1. Tectonic map of western United States (from Crowell, 1987)**

## 3.1.2 Space-Geodetic Measurements of Contemporary Deformation

Determination of the contemporary strain field is an active area of research and is currently focused on use of space-geodetic measurements of relative and absolute plate motion and definition of continental-scale displacement fields (Gordon and Stein, 1992). Geodetic methods have been widely applied over the last several decades, especially adjacent to the San Andreas Fault and locally within the Basin and Range (Savage et al., 1987; Savage et al., 1990). Until recently, most of this work involved relatively cumbersome land-based leveling and trilateration geodesy, generally requiring line-of-site coordination between sites, and often giving information on absolute distances, angles or relative vertical displacement only.

A major breakthrough in geodesy has resulted from the development and application of space-geodetic methods for crustal-scale geodynamic analyses. Space-geodetic methods are used to make precise measurements of position on the surface of the Earth. These methods have recently been shown to be applicable to determination of displacements of tectonic plates and to definition of large-scale intraplate deformations. Changes in position of measurement stations, which may be up to about 12,000 kms apart, over periods of several years are used to determine deformation geometry and rate (Gordon and Stein, 1992).

Gordon and Stein (1992) review the basic operation and geodynamics applications of the three primary space-geodetic systems: (i) very long baseline radio interferometry (VLBI), (ii) satellite laser ranging (SLR), and (iii) the global positioning system (GPS). VLBI methods utilize radio telescopes to determine the time delay of signals from deep space radio-frequency sources. The distance measurement between VLBI base stations can currently be repeated to within $5\text{mm}+2\text{x}10^{-9}(\text{L})$, where L is the length of the baseline (Gordon and Stein, 1992). GPS and SLR require successive measurements of base station positions and baseline lengths over a period in excess of about a decade to attain about 1 mm/yr accuracy in relative motion.

VLBI shows that, over the last decade, relative motion of the Pacific and North America plates is virtually the same as that deduced from reconstruction of the tectonic plates (Gordon and Stein, 1992; Argus and Gordon, 1991; Lisowsky et al., 1991; Ward, 1990; Clark et al., 1987; DeMets et al., 1987; Kroger et al., 1987; Heki et al., 1987). Thus, motion between the two plates appears to be remarkably consistent over the 3 million year averaging interval of sea floor spreading models (DeMets et al., 1990). Consequently, it appears likely that relative motion of the Pacific and North American plates may not vary appreciably from present-day values over the next 10,000, to perhaps 100,000 years.

Results of geologic estimates, local geodesy, large-scale geodesy and plate motion studies suggest that the approximately 12 mm/yr of plate motion not accommodated by slip on the San Andreas Fault is taken up mainly east of the fault. Ward (1990) has determined that instantaneous, path-integrated extensional deformation measured from VLBI is in the range of 8.2 ($\pm$1.3) mm/yr directed N34W ($\pm$7 degrees) to 8.8 ($\pm$1.1) mm/yr directed N25W ($\pm$8 degrees) for the Basin and Range region. Minster and Jordan (1987) and DeMets et al. (1990) document approximately 9 mm/yr net extensional displacement accumulating across the Great Basin region.

### 3.1.3 Regional Spatial Patterns of Neotectonic Deformation

Regional partitioning of strain is best constrained in southern California, where trilateration networks have demonstrated that 6-8 mm/yr is currently being accommodated by a series of strike-slip faults in the central Mojave Desert (Sauber et al., 1986; Dokka and Travis, 1990b), recently dramatically displayed by the June 28, 1992 Landers earthquake that broke precisely across the geodetically active area (Hauksson et al., 1992). The southern California trilateration results are corroborated by VLBI measurements across the whole Basin and Range (Minster and Jordan, 1987), but do not resolve where or how the strain is accommodated. The remaining 3-4 mm/yr is apparently being taken up west of the fault and has a component of contraction normal to the San Andreas Fault, as the Basin and Range has an extensional component (Minster and Jordan, 1987; DeMets et al., 1987). Argus and Gordon (1991) have determined from VLBI measurements that the eastern edge of the Sierra Nevada range is moving at 11 mm/yr($\pm$1 mm/yr) directed N36W ($\pm$3 degrees) relative to the North American craton. Similarly, Savage et al. (1990) indicate approximately 8 mm/yr of Pacific-North America relative plate motion are being accommodated by right lateral slip distributed within a shear zone oriented about N35W and traversing the Mojave Desert between the Transverse Range bend of the San Andreas Fault and Owens Valley, on the east flank of the Sierra Nevada block.

#### 3.1.3.1 Patterns of Contemporary Strain Accumulation

The central Great Basin region is tectonically complex, and it is not generally clear how contemporary strain is partitioned across this wide belt of active deformation. The key question is, how does this strain relate to late Cenozoic mafic igneous complexes in general, and to estimates of the probability of magmatic disruption of a potential high level waste (HLW) repository at Yucca Mountain in particular?

While most of the Basin and Range's contribution to relative plate motion is currently accommodated by deformation in the central Mojave at about latitude 36N (Argus and Gordon, 1991), it is not yet known how it is partitioned across the province to the north at the latitude of Yucca Mountain. The Yucca Mountain area lies just east of a triangular-shaped region of high local relief and major Quaternary faulting (Wernicke et al., 1988; Brogan et al., 1991), bounded on the west by the Sierra Nevada, on the south by the Garlock Fault, and on the northeast by the Death Valley Fault zone. By comparison to this region, Yucca Mountain appears less active in the Quaternary. However, significant Holocene faulting is known from the west side of Crater Flat along the Bare Mountain Fault (Reheis, 1988) and numerous small Quaternary faults are present at and around Yucca Mountain and along the east flank of Crater Flat Valley (Scott, 1990). Further, levelling surveys between Las Vegas and Tonopah since 1911 reveal pronounced subsidence localized south of, and along, the structural trend of Crater Flat Valley (Gilmore, 1990).

Even if it were understood how strain is accumulating across the entire province on the basis of geodetic studies, it is uncertain exactly how reliable such measurements might be at sub-regional spatial scales on a timescale of 10,000 years. Whereas the plate motion rates seem to be consistent over the timescale of 3 million years, it is not absolutely certain that patterns of strain accumulation across the Basin and Range, as measured today, will remain constant over any particular timescale. For example, the entire width of the northern Basin and Range appears to have been actively extending during much or most of Quaternary time. However, the last 100 years of seismicity is focused in two relatively narrow belts, one on the eastern margin of the province (Wasatch Front area) and another to the west in the Carson Sink/Dixie Valley region (a northward continuation of the Owens Valley Fault zone). The recurrence intervals for major earthquakes along range-bounding faults appear to be rather long, perhaps on a timescale of 1,000-10,000 years (Wallace, 1984). As discussed later, seismicity is not necessarily a good indication of strain accumulation. However, it is possible that both seismicity and strain accumulation have migrated back and forth across the Basin and Range (Wallace, 1984) on the 1000 to perhaps the 100,000-year timescale, although the details of such migrations are unknown.

#### 3.1.3.2 Active Fault Systems (Quaternary)

Another important way to determine the strain field is geological analysis of Quaternary faulting (Allen et al., 1965). By trenching across active faults and dating various offset units, displacement rates on the timescale of hundreds to thousands of years or more can be deduced for individual fault zones (Sieh, 1984; Sieh and Jahns, 1984). When combined with space-geodetic, local and regional leveling and trilateration techniques, these methods provide a powerful means for understanding the contemporary displacement field and how strain is accommodated, whether by earthquakes, aseismic creep, folding or — most importantly for this work — by magma injection.

In the geomorphically spectacular region west of Yucca Mountain, three major fault zones (i.e., Death Valley, Panamint Valley, and Owens Valley fault zones) are clearly active during the Holocene, but their relative contributions to total spreading in the Basin and Range and strain across Yucca Mountain are not known. Modern seismicity is concentrated in the Owens Valley (Bolt, 1979; Hill et al., 1991; Hutton et al., 1991; Rogers et al., 1991) in apparent continuity with the Landers earthquake swarm (Hauksson et al., 1992), in the central Mojave deformation belt mentioned above, and in an east-west trending belt immediately north of Yucca Mountain. The Owens Valley Fault was also responsible for what is probably the largest earthquake in California history, the 1872 Magnitude (M)8 Owens Valley event centered near Lone Pine (Smith et al., 1989). Geodetic data from trilateration networks suggest that nearly all of the 8 mm - 12 mm/yr displacement east of the San Andreas Fault may be accommodated in the Owens Valley at about the latitude of Yucca Mountain, perhaps becoming more diffuse to the north (Savage et al., 1990). However, VLBI data (Ward, 1990), including stations within the zone of deformation identified from the trilateration networks, show at least 8 mm/yr of motion relative to North America, indicating even more strain may be accommodated east of Owens Valley.

Eddington et al. (1987) produced maps of deformation rates determined from fault slip measurements and reported rates ranging from 0.001 mm/yr to 0.08 mm/yr for the southern and western Great Basin region, and from 0.03 mm/yr to 7.4 mm/yr along the eastern margin of the Great Basin. Discrepancies between deformation rates determined from fault slip measurements compared to those determined seismically are attributed to insufficient geologic mapping of Quaternary faults and incomplete data on slip and fault geometry.

#### 3.1.3.3 Earthquake Seismicity

Seismicity, if present, gives an indication that a given area is tectonically active. By considering the crust in regions of finite volume and adding moments of individual earthquakes, it is possible to determine the contemporary strain for that volume of crust (Patton and Zandt, 1991). Two main pitfalls to this approach are errors in the volume considered and the time over which seismicity is averaged. The historical record of seismicity may not fully record strain release, particularly over the relatively short interval (approximately 50 years) that reliable information on seismic moments has been available. For example, the two locked segments of the San Andreas Fault are essentially aseismic, yet obviously were important contributors to seismic strain release in the 1857 Fort Tejon (Hutton et al., 1991) and 1906 San Francisco (Hill et al., 1991) earthquakes. Thus, averaging seismic strain release over various volumes of crust may seriously underestimate the contemporary crustal strain field (Allen et al., 1965).

**Spatial Patterns**

The Panamint Valley and Death Valley Fault zones, like the locked segments of the San Andreas, are essentially aseismic at present (Rogers et al., 1991), but both are associated with Holocene fault scarps and have major Quaternary displacements (Brogan et al., 1991). Studies of the Panamint Valley Fault zone suggest 9 km of offset over the last 3.5 million years (Ma) along its northern trace, suggesting 2-3 mm/yr slip rate, also inferred for the southernmost part of the fault zone by analysis of offset Quaternary deposits there (Zhang et al., 1990). Leveling surveys across the central Death Valley fault zone near Furnace Creek indicate vertical displacement rates in the range of 1-3 mm/yr across a Holocene fault scarp (Sylvester and Bie, 1986). The southern Death Valley fault appears to offset Quaternary fan gravels as much as 20 km, suggesting displacement rates in the 10 mm/yr range (Troxel, 1986). These studies underscore the need for detailed geodetic studies to determine how strain is partitioned across the province (Wernicke, 1991).

The M7.3 1983 Borah Peak (Smith et al., 1989) and the M7.5 1992 Landers (Hauksson et al., 1992) earthquakes were good examples of the unpredictable nature of seismic strain accumulation in the Basin and Range, since both broke along major fault zones that had not been recently active. Although the Landers event occurred in an area of known major strain accumulation and moderate seismicity, the Borah Peak region was aseismic prior to the 1983 event. In both areas, it is reasonable to assume that strain accumulation, either seismic or aseismic, has varied considerably during the last 10,000 years.

**Moment Tensors**

Smith et al. (1989), using earthquake seismic data for the period 1850 to 1983 primarily from Eddington et al. (1987), determined horizontal components of regional extensional strain. Summation of seismic moment tensors (Eddington et al., 1987) yields an integrated deformation rate of 8 mm/yr to 10 mm/yr for the Basin and Range Province. Smith et al. (1989) also produced a map of seismically determined strain and deformation rates for the western United States. Regional extensional displacement rates for the southern and western Great Basin region range from 0.22 mm/yr to 7.5 mm/yr. However, for the region comprised by the central Basin and Range (Wernicke, 1991), including most of the Mojave Desert (south of the Garlock Fault) and the Death Valley normal fault system (Wernicke et al., 1988), earthquake induced extensional deformation rates as high as 28 mm/yr - 30 mm/yr are determined by including the 1872 M8.3 Owens Valley, California event (Smith et al., 1989). Clearly, a single large earthquake can dominate seismically determined deformation rates. As pointed out previously, there is significant uncertainty in defining appropriate time periods and crustal volumes over which to average earthquake induced deformation. In general, however, Smith et al. (1989) conclude that seismically determined extensional deformation rates are remarkably compatible with geologically instantaneous plate tectonic and geodetic rates, and further speculate that most of the extensional deformation distributed throughout the Great Basin region is accounted for by seismic faulting (brittle fracture) in the upper 10 km to 15 km of the crust.

### 3.1.4 Regional Geophysical Framework

#### 3.1.4.1 Crustal-scale Stress State

Zoback (1989) documents most of the measured and computed crustal stress state data for the central and northern Basin and Range province. In general, the least horizontal principal stress component is oriented east-west to northwest-southeast (Zoback, 1989; Zoback and Zoback, 1991) and is consistent with crustal geodetic and plate-scale extensional deformation. However, Zoback (1989) reports substantial variability of *in-situ* stress states throughout the region and points out that both east and west margins of the Great Basin are characterized by nearly east-west least horizontal stress directions, while northwest-southeast extension is more prominent in the interior regions of the Great Basin. Similarly, Patton and Zandt (1991) document a generally uniform northwest-southeast orientation pattern of the minimum horizontal compressive stress components determined from moment tensor analyses of about 50 earthquakes that occurred between 1962 and 1984.

#### 3.1.4.2 Deformation Rates Derived from Heat Flow Measurements

Extensional deformation rates between 5 mm/yr and 10 mm/yr have been determined by Lachenbruch and Sass (1984) and Lachenbruch (1979) for the northern Basin and Range region using constraints of heat flow measurements and deformation models that include thermal effects (Smith et al., 1989). Blackwell et al. (1991) attribute the relatively high regional heat flow of the Great Basin region to the overall back-arc plate tectonic setting, and generally attribute regional variability to tectonic complexity, regional hydrologic advection and variations in heat source and radiogenic heat production. Using data from Shearer and Reiter (1981) on radiogenic heat production in the upper crust of the Basin and Range region, Reiter et al. (1991) conclude that increased heat flow is due mainly to increased heat production, apparently indicating little first-order influence by crustal scale tectonic or magmatic processes. Reiter et al. (1991) further suggest that tectonic-magmatic-hydrologic causes are not readily apparent for geothermal trends in the southern Great Basin.

### 3.1.5 Quaternary Volcanism

Luedke and Smith (1991) show the distribution and general composition of relatively long-lived trends of volcanic loci for variable time spans within the last 16 million years. They argue that continued, but waning, eruptive activity along "rectilinear" trends established since middle Miocene time is suggestive of large-scale tectonic control of underlying magmatic processes. The fairly distinct linear trends shown by Luedke and Smith (1991) are localized along major geologic province boundaries. Of particular significance is the trend of small-volume, isolated basaltic eruptions scattered along a line from southwest Arizona to northern California, which appears to include cinder cones and basalt flows in Crater Flat Valley and around Timber Mountain. Lunar Crater, in the Pancake Range north of Timber Mountain, may also lie on a less extensive north-northeast trend comprised by Lunar Crater-Timber Mountain/Crater Flat Valley-Cinder Hill-Lava Mountain.

### 3.1.6 Correlation of Contemporary Volcanism and Deformation

The broad linear trend of small basaltic volcanoes (Figure 3-2) spread throughout eastern California (Luedke and Smith, 1991) is roughly coincident with a zone of Quaternary faulting (Figure 3-3) and contemporary strain accumulation comprised by the Mojave shear zone (Savage et al., 1990), the Death Valley Fault system (Wernicke et al., 1988), and the bounding fault system of the Sierra Nevada. The Walker Lane tectonic zone as described by Carr (1984) essentially forms the northern boundary of this zone, or is perhaps conjugate to the zone.

## 3.2 LATE CENOZOIC TECTONIC-VOLCANIC-MAGMATIC RELATIONSHIPS IN THE BASIN AND RANGE PHYSIOGRAPHIC PROVINCE

### 3.2.1 Late Cenozoic Extensional Tectonics

Overall, the Basin and Range physiographic province is a region exhibiting major amounts of crustal extension which occurred principally during the last 15 million years of the Cenozoic Era (Kruse et al., 1991; Wernicke et al., 1988). Spatial and temporal patterns of Cenozoic extensional deformation of the Basin and Range region are not well known and considerable uncertainty exists as to how accumulated deformation and the contemporary regional displacement field are partitioned. Wernicke et al. (1988) determined that 247 km ($\pm$56 km) of extensional displacement has been accommodated in a region between the Colorado Plateau and the Sierra Nevada Range during the last 15 million years. The total relative separation is distributed along a net vector of about N73W ($\pm$12 degrees) between two distinct highly-extended terrains separated by a relatively unextended domain. The Yucca Mountain area is within the westernmost part of the highly extended regions, called the Death Valley normal fault system by Wernicke et al. (1988). Separation rates varied from an estimated maximum of 20-30 mm/yr between 10 to 15 million years ago, to a diminished rate of less than 10 mm/yr over the last 5 million years.

#### 3.2.1.1 Plate Tectonic Models

Models of Pacific-North America plate interaction comprise the fundamental regional tectonic basis for interpretation of the geological record of the Basin and Range Province (Stewart, 1984; Coney, 1987; Eaton, 1980) and provide a framework within which spatial and temporal patterns of crustal-scale tectonic and magmatic processes may be related (Dickinson and Snyder, 1979; Eaton, 1979; Severinghaus and Atwater, 1990) (Figure 3-4). At the close of late Mesozoic-early Tertiary contractional deformation (approximately 45-50 million years ago) western North America was essentially underplated by subducted oceanic lithosphere emplaced at a shallow angle and at the relatively high convergence rates extant during the Laramide orogeny (Dickinson and Snyder, 1979). Much of the spatial and temporal pattern of tectonism and magmatism within the Basin and Range can be related to the timing and pattern of delamination of the subducted oceanic plate (Best and Christiansen, 1991) from beneath the continental crust and the subsequent plate tectonic evolution of the continental margin (Coney, 1987).

The thermal and isostatic state of the continental crust at the close of Sevier-Laramide compressional deformation also strongly influenced the initiation and regional pattern of incipient extensional deformation and associated magmatism. Initiation of Cenozoic large-magnitude extension was localized along an axis of thickened continental crust left by Sevier-Laramide contraction, suggesting that gravitational spreading was an important early extensional process (Coney, 1987). Impingement of the East Pacific Rise with the western North America subduction zone and subsequent transition of the margin to transform faulting added an active extensional component to the relative velocity field that strongly influenced structural development of the Basin and Range (Eaton, 1979).

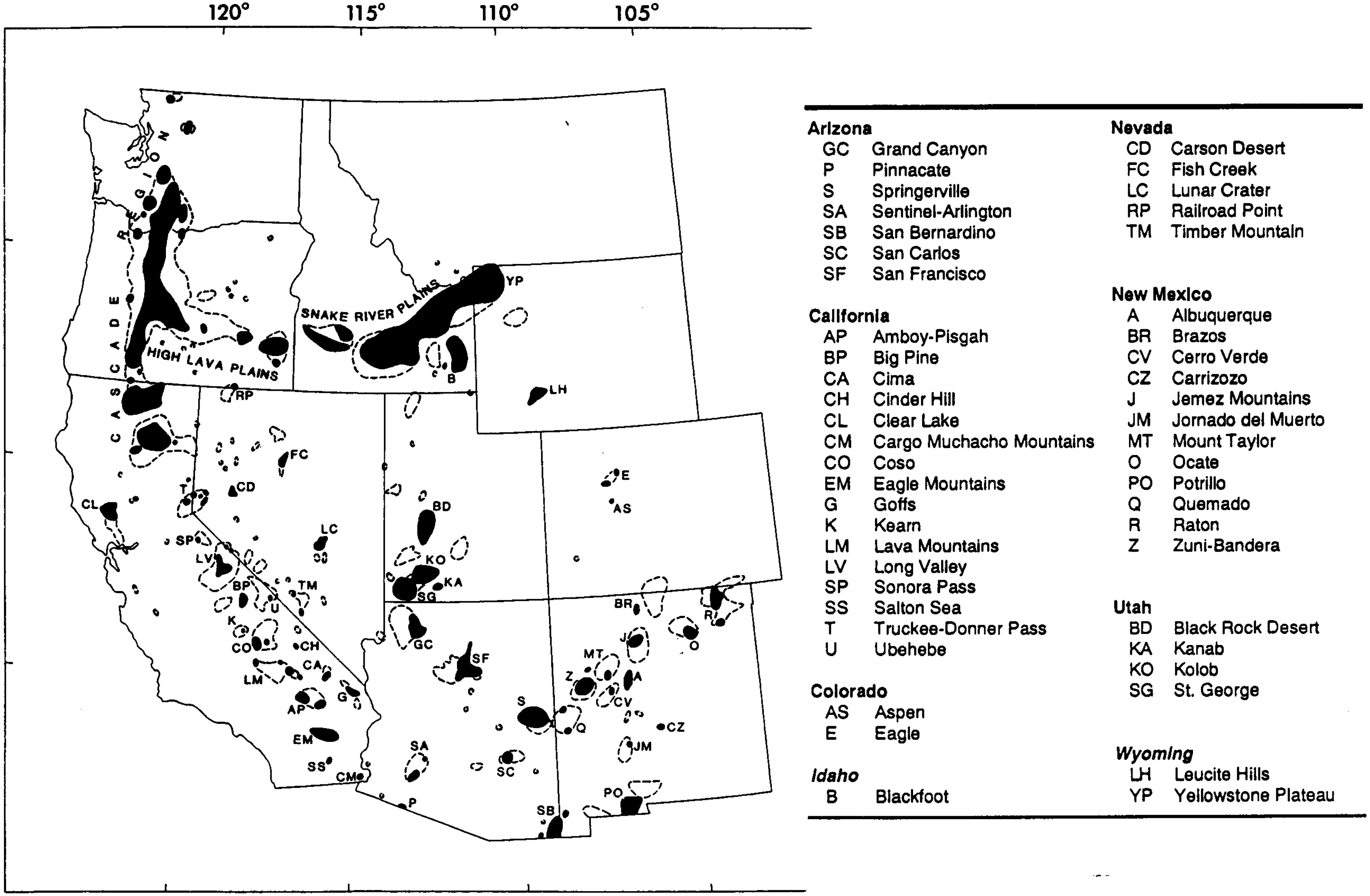


**Figure 3-2. Map of Quaternary (< 1.6 Ma) volcanic complexes (solid shaded areas). TM = Timber Mountain caldera complex. The southernmost shaded area of the TM complex marks volcanism in Crater Flat Valley, adjacent to Yucca Mountain. Dashed outlines show extent of eruptive activity during the period 0-5 Ma (from Luedke and Smith, 1991).**

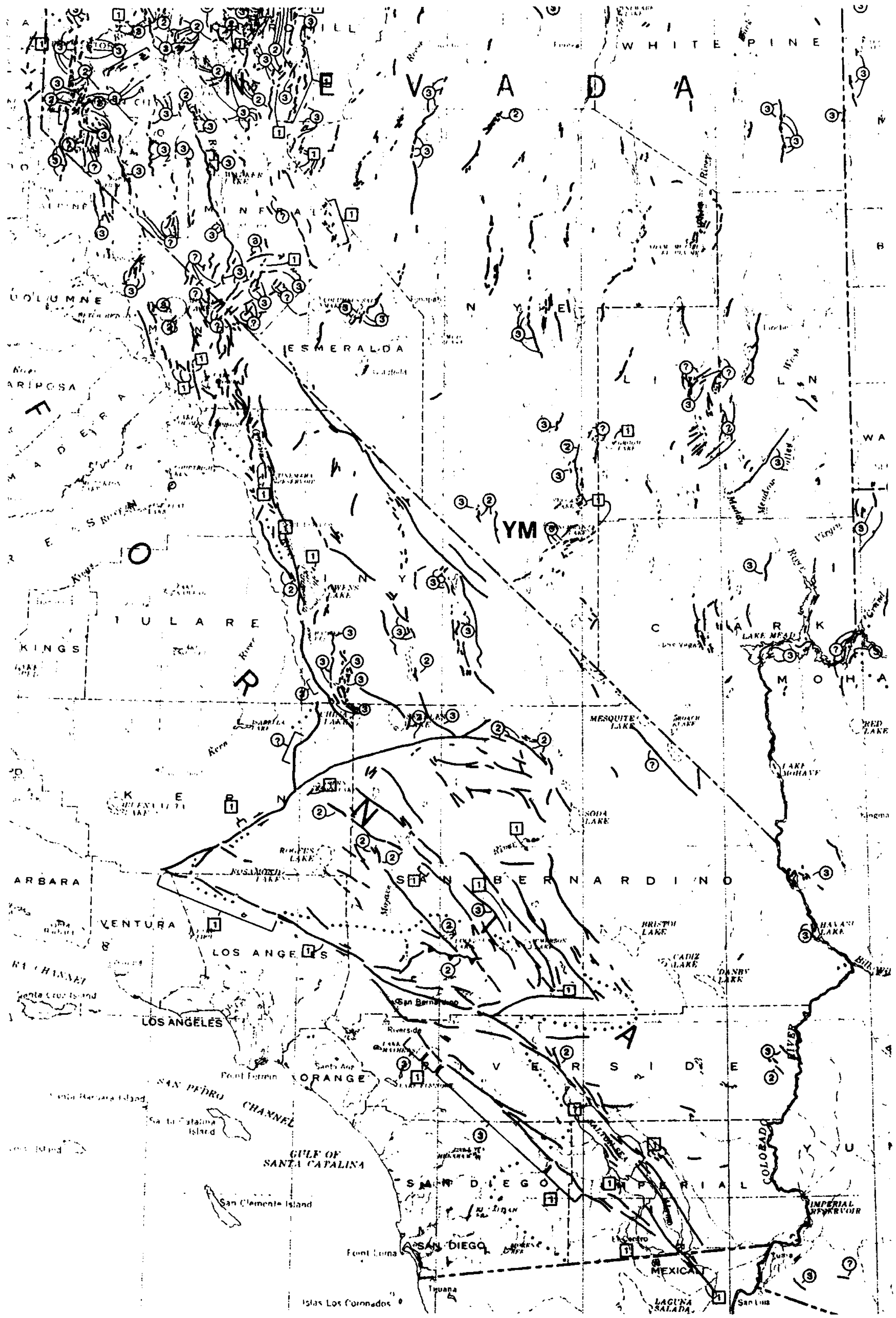


**Figure 3-3. Map of Quaternary (< 1.6 Ma) fault traces within the central Basin and Range and Mojave Desert region. YM = Yucca Mountain (modified from Nakata et al., 1982).**

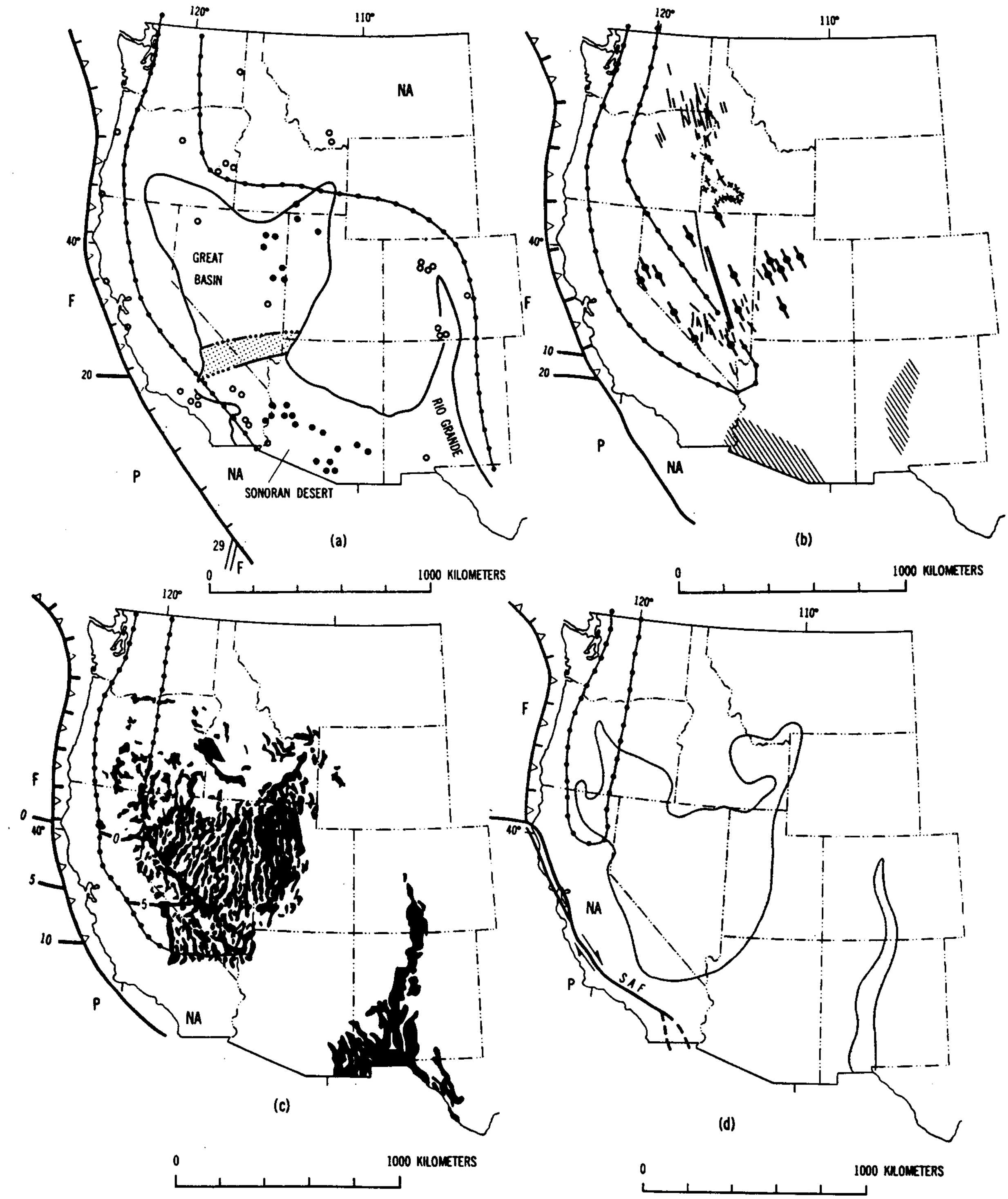


**Figure 3-4. Geographic and temporal relationships between plate tectonic elements of western United States and regional patterns of arc (subduction related) magmatism. (a) 30 Ma - 20 Ma; (b) 20 Ma - 10 Ma; (c) 10 Ma - present; and (d) Quaternary (< 1.6 Ma). Solid dotted line encloses region of arc magmatism (from Eaton, 1979).**

#### 3.2.1.2 Age and Styles of Faulting

Two general styles of extensional faults are developed in the Basin and Range region: (i) low-angle detachment fault systems, described by Coney (1973) in connection with development of extensional metamorphic core complex terranes of the North American Cordillera, accommodate large-magnitude extensional strain, and (ii) deeply penetrating, high-angle fault systems, often referred to as domino style faults, are widely interpreted to be the cause of classical Basin and Range physiography (e.g., Stewart, 1984; Okaya and Thompson, 1986; Allmendinger et al., 1987) but do not accommodate large extensional strain. These high-angle faults are most often explained as late-stage distributed overprinting of the highly extended regions. Wernicke (1991) contends that although some range-basin geomorphology is consistent with this model, much of the Basin and Range topography can be explained by detachment-style fault systems and thus does not require development of domino style faults.

Wernicke (1991) and Armstrong and Ward (1991) produced maps showing the geographic distribution and age of core complex extensional systems for most of the Basin and Range region, and Armstrong and Ward (1991) tabulated data on age of deformation for specific core complex systems. Wernicke (1991) noted that metamorphic core complexes lie within regions of large extensional strain, but that not all highly extended regions contain core complexes. The timing of strongly extended regimes (Wernicke, 1991) within the northern and southern Basin and Range is not highly resolved, and clear patterns of spatial migration are not discernable (Figure 3-5) (Figure 3-6). Development of localized regions of large-magnitude extensional strain occurred within the northern and southern Basin and Range between 40 and 16 million years ago (Wernicke, 1991), and only began to develop within the central Basin and Range after about 16 Ma. Core complex extensional systems seem to have developed first along the long (north-south) axis of the Basin and Range rift trend (during the period 40 Ma - 16 Ma). Subsequently, regional loci of strong extension moved to the eastern and western boundaries of the Basin and Range Province (Wernicke, 1991). The central Basin and Range region experienced the latest stage of core complex extension to have occurred within the overall Cenozoic extensional province. A westward migrating succession of strongly extended domains moved across the central Basin and Range region after about 16 Ma.

Armstrong and Ward (1991) produced maps of the geographic pattern of core complex extension with age resolution on the order of about 15 million years. These maps show general southward to southwest migration of core complex systems with time. The youngest of the highly extended domains, those in the age range of 10 Ma - 0 Ma, are within the Mojave-Death Valley shear zone trend. Core complexes between 25 Ma - 10 Ma in age are distributed through the central and southern Basin and Range region.

### 3.2.2 Neogene Magmatism and Volcanism

Processes and events which controlled magmatism and volcanism in the Basin and Range from about middle Miocene to the present (i.e., during the last 15 million years of the Cenozoic Era) , a time of major extension for the region including Yucca Mountain (Kruse, et al., 1991; Wernicke, et al., 1988) are not completely understood. The silicic Timber Mountain caldera complex dominates Miocene (23-5 Ma) magmatic history of the Yucca Mountain area. Quaternary basaltic volcanism occurred in the vicinity of Yucca Mountain (Crowe, 1990; Smith et al., 1990; Champion, 1991; Turrin and Champion, 1990) and may have been as recent as Holocene (i.e., less than 100,000 years old) in the case of Lathrop

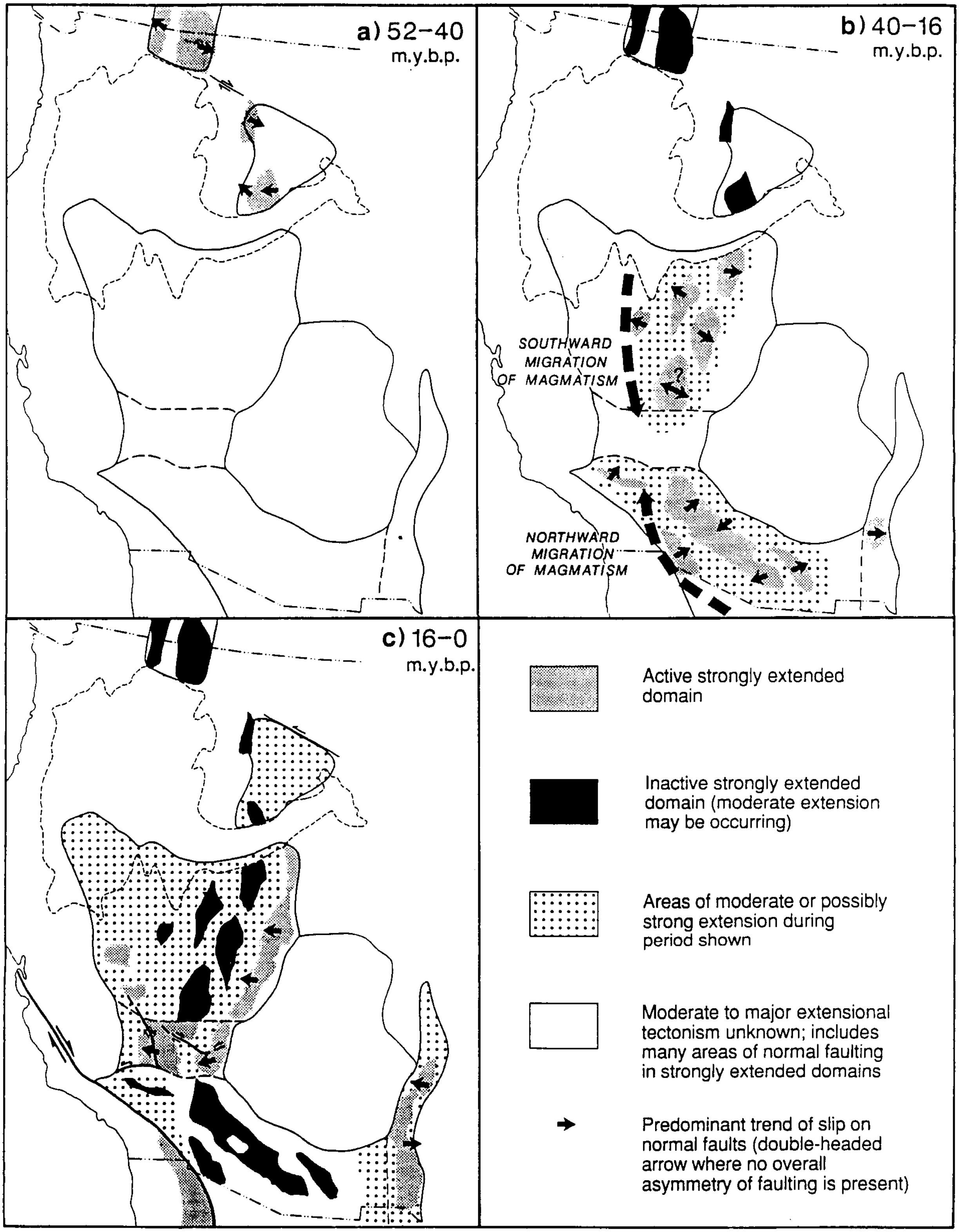


**Figure 3-5. Geographic and temporal patterns of regional tectonic extension. Large dashed arrows in (b) indicate directions of migration of magmatism with time (from Wernicke, 1991).**

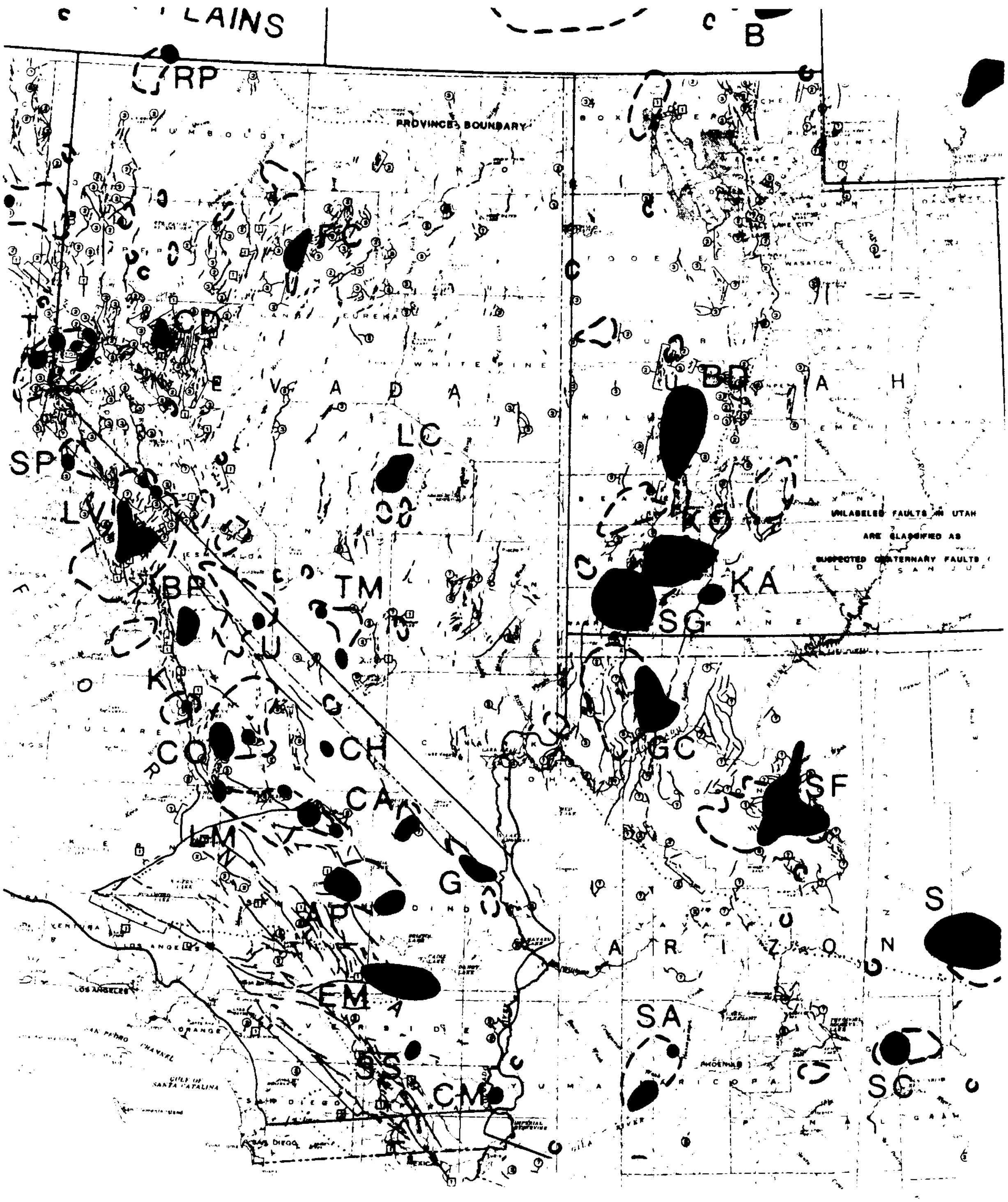


**Figure 3-6. Correlation of Quaternary (< 1.6 Ma) faulting and volcanism within the tectonically extending corridor consisting of the Mojave Desert shear zone, Greater Death Valley fault system, east Sierra Nevada flank and the central Nevada seismic zone. See Figure 3-2 for explanation of abbreviations. Compiled from Nakata et al. (1982) and Luedke and Smith (1991).**

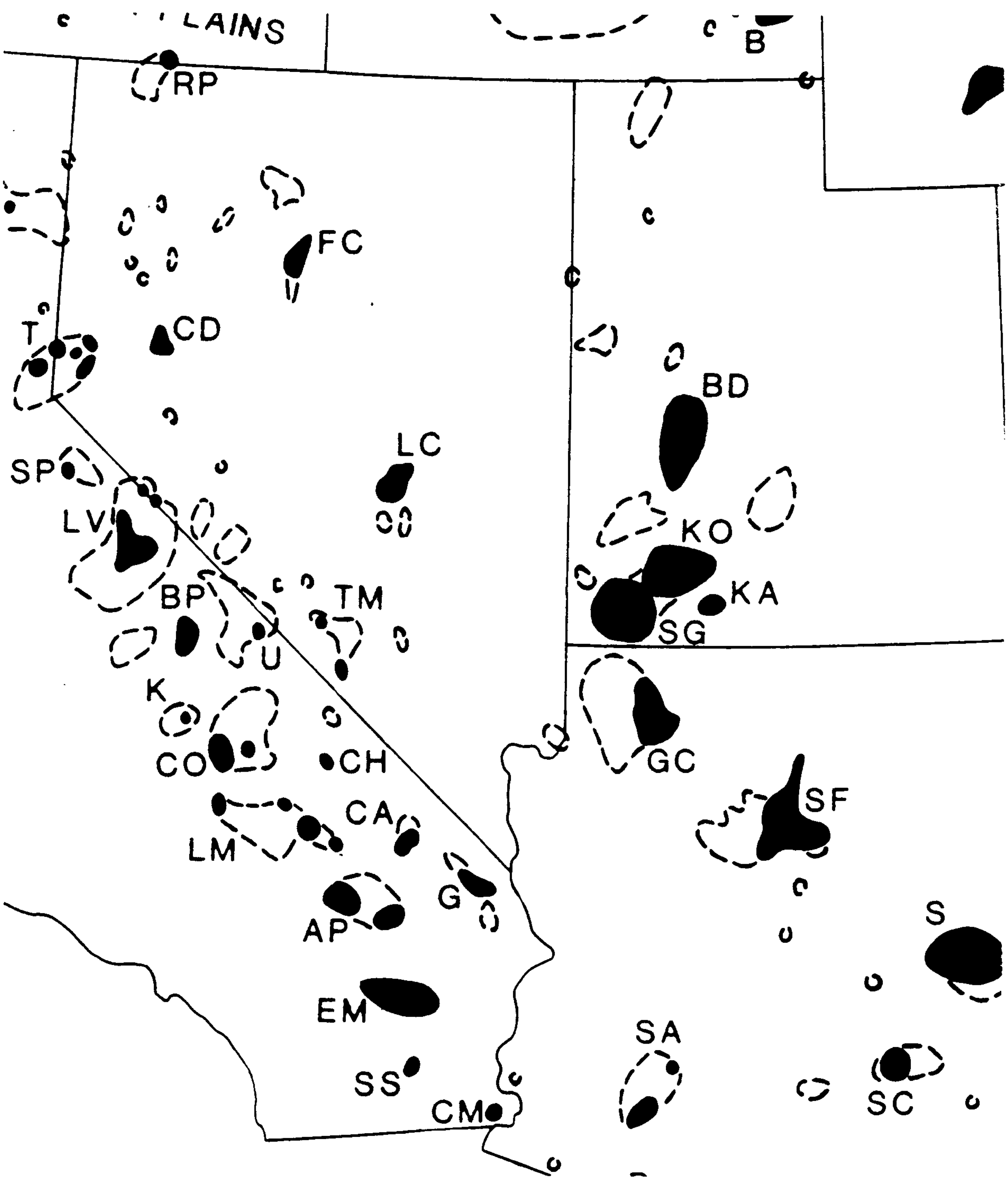


**Figure 3-6. Correlation of Quaternary (< 1.6 Ma) faulting and volcanism within the tectonically extending corridor consisting of the Mojave Desert shear zone, Greater Death Valley fault system, east Sierra Nevada flank and the central Nevada seismic zone. See Figure 3-2 for explanation of abbreviations. Compiled from Nakata et al. (1982) and Luedke and Smith (1991).**

Wells Cone (Crowe, 1990). Consequently, concerns exist about the potential for renewed volcanism and its possible effects on long-term waste isolation for a repository at Yucca Mountain.

Stewart (1980) documents the late Cenozoic onset of four fundamental types of volcanism based on eruptive style and general composition within the Great Basin. Onset of major Cenozoic igneous activity occurred from 43 Ma to 34 Ma and consisted primarily of andesite and rhyolite. Quartz latitic and rhyolitic ash flow tuffs with sparse basaltic lavas were erupted between 34 Ma and 17 Ma. Bi-modal suites of rhyolite and basalt composition developed from 17 Ma to 6 Ma. Basaltic cinder cone and small-volume lava flow eruptions are restricted primarily to less than 6 Ma. Luedke and Smith (1991) show that basaltic eruptions through the Quaternary in the Basin and Range region have followed geographic patterns established over this 6 million year period.

Eaton (1979) shows the westward migration of subduction related, calc-alkaline magmatic arc volcanism with respect to evolution of the western North American transform boundary, and migration of the Mendocino triple junction. Wernicke (1991) depicts an overall trend of Cenozoic magmatism migrating southward within the northern Basin and Range and northward within the southern Basin and Range. Volcanism is active at the northern and southern ends of the Basin and Range province by at the latest early Oligocene (about 35 Ma). The regional focus for these trends is the central Basin and Range, with onset of large-scale eruption of bi-modal suites, including the ashflow tuffs of the Timber Mountain complex (Byers et al., 1976) by middle Miocene (17 Ma - 12 Ma).

### 3.2.3 Correlation of Late Cenozoic Magmatism with Extensional Deformation — Spatial and Temporal Patterns

Broad regional patterns of the spatial distribution of volcanism throughout Cenozoic time have been summarized by Armstrong and Ward (1991) who cite most of the available literature and previous review papers on the subject. Leeman and Fitton (1989) and Lipman and Glazner (1991) also offer comprehensive overviews of the tectonic/magmatic evolution of the Basin and Range region. Ward (1991) presents a regional analysis of the relations between plate tectonics and geologic evolution of southwestern North America. Wernicke et al. (1987) address the tectonomagmatic evolution of Cenozoic extension in the North American Cordillera. An overview of the Phanerozoic geology of western North America is provided by Oldow et al. (1989).

A number of recent studies have summarized geochemical and petrological characteristics of Basin and Range basaltic magmatism (e.g., Leeman, 1982b; Vaniman et al., 1982; Menzies et al., 1983; Fitton et al., 1988, 1991; Farmer et al., 1989; Kempton et al., 1991). In general, magmatism over the last 5 million years has been dominantly basaltic throughout southern Nevada and southeastern California. The erupted volume of late Cenozoic basaltic magma is significantly less than in mid-Tertiary time and appears to have diminished systematically with time. Contemporaneous silicic volcanism has been largely restricted to the western and eastern margins of the province (e.g., Long Valley, Mono Craters, Coso, Yellowstone). If it is assumed that silicic magmas form by crustal melting due to shallow emplacement of hot mafic magmas, or that they at least incorporate significant amounts of crustal material, one of two inferences can be drawn. During the late Cenozoic, either (i) very little basaltic magma has been stored at shallow levels below southern Nevada, or if so, (ii) the crust may not be capable of generating much silicic magma following the large volume mid-Tertiary silicic volcanism in that region — that is, the crust may consist of refractory residue from extensive earlier crustal melting.

Late Cenozoic (i.e., 6 Ma to the present) continental basalts are commonly mildly alkalic and have trace elements and Sr, Nd, and Pb isotopic characteristics that indicate mantle sources similar to those inferred for many oceanic island basalts (Gill, 1981). Basalts from these two settings are virtually indistinguishable (Ormerod et al., 1988). In contrast, Mio-Pliocene (i.e., 12 Ma to 6Ma) Basin and Range basalts commonly have distinct compositions that suggest they were derived from a distinct mantle source — most likely within the lithospheric mantle. In some cases, crustal contamination may have modified the older Mio-Pliocene basalts, but detailed studies in several places indicate distinct sources for the younger and older basalts. Ormerod et al.(1988) and Lum et al. (1989) have suggested a systematic change in magma source with time, from lithospheric to asthenospheric mantle regions. Ormerod et al. (1988) showed the compositional transition migrated northward with time, closely paralleling northward migration of the Mendocino triple junction. A similar transition has been documented at about 1 Ma in north-central Nevada, but all Tertiary-Quaternary basalts further north have compositions consistent with derivation from lithospheric sources (Leeman and Manton, 1971; Doe et al., 1982; Hart, 1985; Carlson and Hart, 1987; Hildreth et al., 1991; Leeman et al., 1992). These relations have important bearing on interpretation of magmatic patterns in the southern Basin and Range Province.

Traditionally, the Basin and Range Province has been viewed as a region of continental extension, and magmatism there has been attributed to decompressional melting of crustal and asthenospheric mantle (e.g., Zoback et al., 1981; Eaton, 1982 and 1984; Hamilton, 1987). Following the work of McKenzie and Bickle (1988) on decompressional melting, it is unlikely that asthenospheric mantle could produce significant amounts of magma unless it ascended to within about 80-100 km of the surface. This is the approximate thickness of lithosphere today as inferred from shear-wave splitting studies (Savage et al., 1990). Assuming a pre-extensional lithospheric thickness around 200 km at about 40 million years ago (Coney, 1987), this would correspond to 100 percent extension across the region which is in agreement with estimates for the latitudes near Las Vegas (Wernicke et al., 1988). Given the magnitude of cumulative extension across the southern Basin and Range Province, decompressional melting of asthenospheric mantle would only recently have resulted in magma production.

However, strong constraints on the magma generation process exist if early magmatism resulted from melting of lithospheric mantle. Because lithospheric mantle must be cooler than convecting asthenosphere (cf. White, 1988), it is unlikely to have produced large melt volumes during extension if it consists largely of depleted peridotite as commonly suggested. Therefore, the large volume of early synextensional (ca. 40-30 million years ago) volcanism documented for the Basin and Range Province (Gans et al., 1989; Taylor et al., 1989; Best and Christiansen, 1991), much of which must have been produced by lithosphere or crustal melting, is enigmatic in the context of conventional views of the lithosphere and physics of melt production in extensional settings. A similar paradox exists concerning the advent of voluminous flood basalt volcanism in mid- to late Miocene time (e.g., Carlson and Hart, 1987; Lum, 1992). These paradoxes may be resolved if it is assumed that the lower lithosphere was enriched by infiltration of up to several percent of silicate melt sometime prior to onset of extension. Radiogenic isotopic data for the synextensional lavas appear consistent with melt-modification of their lithospheric sources in parallel with development of Precambrian basement, although additional melt infiltration probably occurred in conjunction with Phanerozoic subduction beneath the region (Ormerod et al., 1991). With this assumption, decompressional melting of undepleted lithosphere could produce large volumes of magma near the onset of extension in the Great Basin and continue to produce mafic magmas at decreasing rates throughout time until the mantle component was depleted. Only after the lithosphere was largely depleted of easily fusible components, and magnitude of extension was sufficient for decompressional melting of upwelling asthenosphere to occur, would asthenosphere-derived magmas develop.

Onset of middle to late Cenozoic extensional deformation in regions of eventual large-magnitude extensional strain (Wernicke, 1991) is broadly correlative with patterns of major intermediate to silicic magmatic systems (Coney, 1988; Lipman, 1980; Gans, 1989; Anderson, 1989; Armstrong and Ward, 1991). Extensional strain is strongly partitioned in these extended regions (Davis and Burchfiel 1973; Wernicke et al., 1982 and 1988; Chamberlin, 1983; Miller et al., 1983). Within the broad extended regions comprising the Basin and Range Province, extensional strain is heterogeneously distributed between strongly extended domains and stable blocks (Wernicke, 1991). Temporal patterns of extension within the extended domains are complex and regional patterns are strongly diachronous (Wernicke, 1991). Wernicke et al. (1987) recognizes four stages in the evolution of the strongly extended domains, (i) incipient extension and subsequent basin subsidence, (ii) eruption of intermediate to silicic volcanic centers, (iii) large-magnitude extension, and (iv) eruption of bi-modal and late-stage basaltic volcanic centers.

Specific cause and effect relationships between tectonic extension and temporally and spatially associated magmatism are difficult to discern. Anderson (1989) concluded heating of lithosphere due to intrusion of magma was widespread, even beyond the regions of large-magnitude extension. Wernicke (1991) further concluded that width of late Cenozoic magmatic belts and their widespread occurrence outside of regions of severe extension precludes tectonic control of large silicic eruptive centers such as Timber Mountain. Magmatism in association with strongly extended domains (Wernicke et al., 1987) suggests instead that zones of partial melt (Sonder et al., 1987) existed at middle to lower crustal levels at the onset of localized extension (Wernicke, 1991). That is, magmatism synchronous with large-magnitude extension may be due to passive eruption in response to breakup and separation of overlying blocks of upper crust (Wernicke, 1991), rather than a dominant driving mechanism (Dickinson and Snyder 1979; Gans et al., 1989).

Broad correlations of synchronous or coincident extensional deformation and volcanism suggest that tectonic deformation and magmatism in the Basin and Range are integral elements of the geodynamic system. Temporal and geographic patterns of late Cenozoic volcanism within the Basin and Range region are broadly correlative with boundaries between major tectonic-physiographic provinces (Luedke and Smith, 1991). Similarly, at the scale of individual mountain range and basin pairs, some small-volume basaltic eruptive centers occur on or directly adjacent to the trace of basin-bounding fault systems.

## 3.3 TECTONIC-VOLCANIC-MAGMATIC RELATIONSHIPS IN YUCCA MOUNTAIN AREA

In the following subsections, existing data on spatial and temporal patterns of Cenozoic deformation (faulting) and volcanic activity in the Yucca Mountain area are discussed, including geophysical data which bear on subsurface structures and the presence of possible magmatic conditions.

### 3.3.1 Location and Geometry of Structures in the Yucca Mountain Area

Field assessment of faulting at Yucca Mountain was accomplished by Scott and Bonk (1984), who mapped a series of northeast-trending, west-dipping, normal faults which both bound and occur in the potential repository block. From east to west across Yucca Mountain, these faults are: Paintbrush Canyon-Fran Ridge, assumed Midway Valley, Bow Ridge, Ghost Dance-Abandoned Wash, Solitario Canyon, Fatique Wash, and Windy Wash Faults. The northeast-trending faults are included in cross-sections AA', BB', and CC' of Scott and Bonk (1984). Scott and Bonk (1984) also mapped a series of northwest-trending strike-slip faults which occur in the northeastern part of Yucca Mountain. From north to south, these faults are: Yucca Wash, Sever Wash, Pagany Wash, and assumed Teacup Wash Faults. The northwest-trending faults are included in cross-sections DD' and EE' of Scott and Bonk (1984). Figure 3-7 shows locations of these northeast-trending normal and northwest-trending strike-slip faults and locations of the cross-sections of Scott and Bonk (1984).

Scott (1990) interprets the northeast-trending, west-dipping faults as normal faults having a listric geometry at depth based upon geometry of related deformation observed in the hanging wall blocks of the faults. He also considers a low-angle normal fault (i.e., a detachment fault) or faults to occur beneath Yucca Mountain. Two-dimensional modeling of the structures at Yucca Mountain using the data of Scott and Bonk (1984) and computer-assisted cross-section balancing methods[1] indicates interpretation of the faults as listric normal faults which flatten and merge into a detachment surface at depth is geometrically reasonable. Scott (1990) reports that offset on the northeast-trending normal faults generally increases southward along strike of the faults. As an example, the Solitario Canyon Fault branches into four major splays over a distance of 10 km and cumulative offset increases from zero in the north to about 1 km at its southern end. Amount of maximum dip displacement has been estimated by Carr (1984) on two specific faults as follows: Paintbrush Canyon Fault = 200 m; Windy Wash Fault = 450 m. However, in light of Scott's (1990) observation that offset on northeast-trending faults varies along strike, the estimated maximum displacements of Carr (1984) may differ from offsets determined elsewhere along the faults.

Quaternary movement has been documented on the northeast-trending Paintbrush Canyon, Bow Ridge, Solitario Canyon, Stagecoach Road, and Windy Wash Faults, as well as on numerous (a total of 32) other northeast-trending faults in the vicinity of Yucca Mountain (Swadley et al., 1984). However, Scott (1990) reports that no Quaternary movement has been identified on any of the northwest-trending faults, including those in the northeast part of Yucca Mountain in the vicinity of Yucca Wash. One of the faults exhibiting Quaternary displacement is the east-dipping Bare Mountain Fault which bounds Bare Mountain on the east side (Reheis, 1986). This structure is located west of Yucca Mountain and is interpreted by Scott (1990) as a deep-seated normal fault cross-cutting the low angle detachment surface which dips westward beneath Yucca Mountain. Hamilton (1988) has interpreted the Bare Mountain Fault as an eastward-tilted detachment.

Northeast-trending faults in the central and southern parts of Yucca Mountain display only minor oblique to horizontal slip. The greatest lateral displacement occurs along the Stagecoach Road Fault, with 5 to 7 meters of left-lateral offset of washes in Quaternary fan deposits (Scott and Whitney, 1987). The Stagecoach Road Fault is interpreted by Scott (1990) to project into the Paintbrush Canyon Fault to the northeast.

A 30 degree clockwise rotation of the southern end of Yucca Mountain about a vertical axis is indicated by paleomagnetic evidence (Rosenbaum et al., 1991). Scott (1990) reports that strikes of major normal faults at Yucca Mountain also swing in a clockwise direction from north to south over a 25 km distance, and interprets the surface clockwise rotation as reflecting dextral (oroflexural) bending or

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[1]Stirewalt, G.L., S.R. Young, and A.P. Morris. 1993. Balanced Cross-Sections and Development of Alternative Geometric Models for Faulting Beneath Yucca Mountain — Implications for Scenario Construction and Performance Assessment. *Special Yucca Mountain Issue of Radioactive Waste Management and the Nuclear Fuel Cycle*. In press.

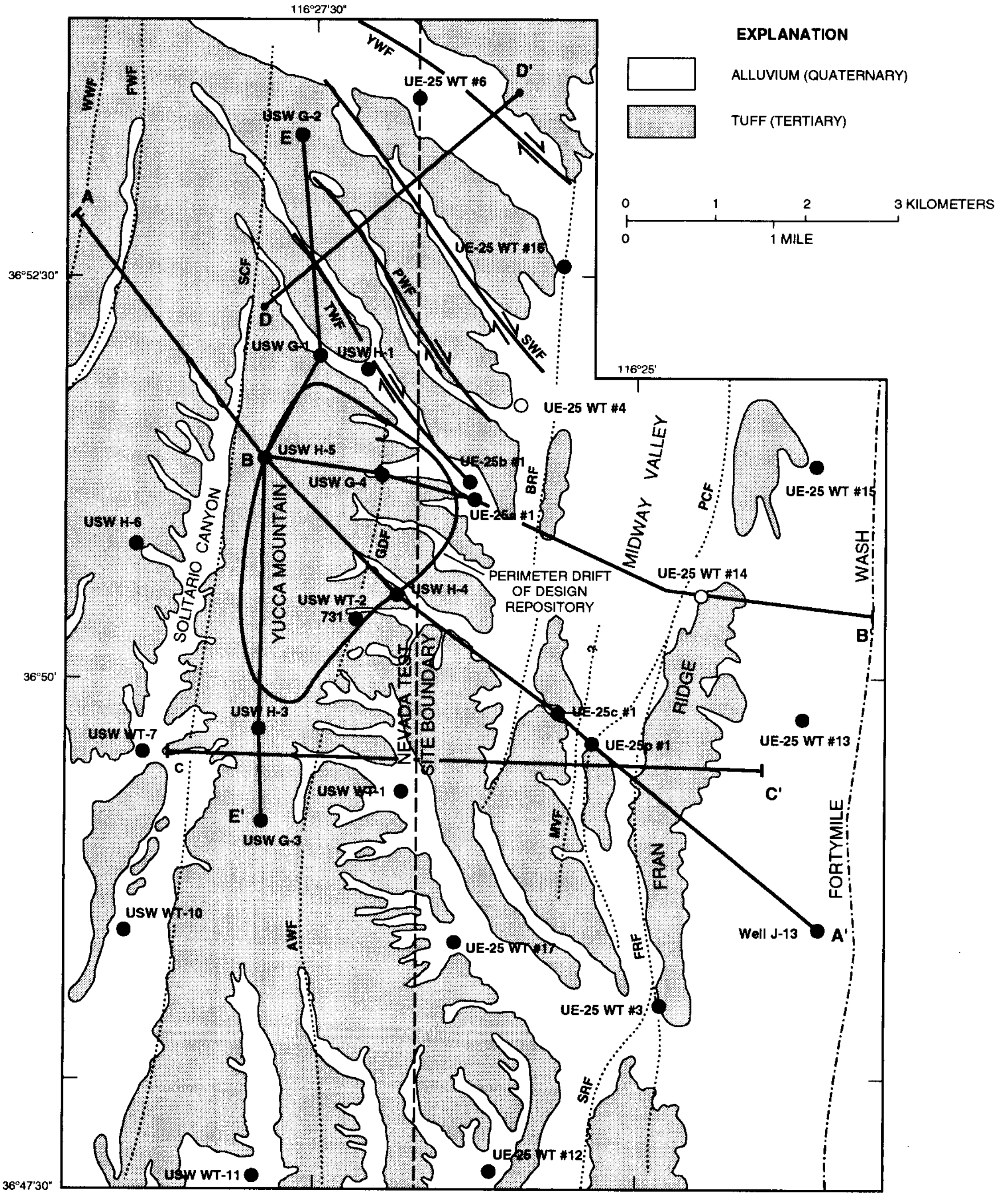


Figure 3-7. Locations of faults at Yucca Mountain and Scott and Bonk's (1984) geologic cross-sections AA', BB', CC' DD', and EE'. From east to west across Yucca Mountain, the northeast-trending normal faults are: Paintbrush Canyon-Fran Ridge-Stagecoach Road (PCF-FRF-SRF), assumed Midway Valley (MVF), Bow Ridge (BRF), Ghost Dance-Abandoned Wash (GDF-AWF), Solitario Canyon (SCF), Fatigue Wash (FWF), and Windy Wash (WWF). From north to south, the northwest-trending strike-slip faults are: Yucca Wash (YWF), Sever Wash (SWF), Pagany Wash (PWF), and assumed Teacup Wash (TWF). Geology from Scott and Bonk (1984) and Scott (1990). Map modified after Scott (1990) and Coppersmith and Youngs (1992).

shearing on deeper strike-slip zones, possibly in the Walker Lane Belt which is decoupled from the overlying system of low-angle normal faults.

In summary, although data on location and geometry of faults observed and mapped at the surface are good, subsurface data on faulting are lacking at this time. Cross-section balancing efforts by Stirewalt et al.[2] present a viable but non-unique model for geometric representation of subsurface structures at Yucca Mountain. Subsurface data on faulting, to be collected during phases of site characterization at Yucca Mountain by the Department of Energy (DOE), will be necessary for increased understanding of three-dimensional fault geometry and relationships. Subsurface structures have not been rigorously related to volcanism, although surface control of volcanic vents by faulting in the Yucca Mountain area has been addressed and will be discussed in Section 3.3.7.

## 3.3.2 Geophysical Data on Structures in the Yucca Mountain Area

The western end of seismic line AV-1 from Brocher and others (1990) contains data which may indicate down-to-the-west normal faulting in the vicinity of Fortymile Wash. In an analysis of balanced geological cross-section across Yucca Mountain, Stirewalt et al.[2] interpreted these data to suggest that listric normal faulting similar to that proposed at Yucca Mountain (Scott, 1990) occurs in the vicinity of Fortymile Wash.

Aeromagnetic data shown by Glen and Ponce (1991) indicate northeast-trending normal faults in the Yucca Mountain area tend to lie adjacent to elongate, northeast-trending magnetic lows. In the analysis of balanced geological cross-section across Yucca Mountain by Stirewalt et al.[2], listric normal faulting similar to that proposed at Yucca Mountain (Scott, 1990) is suggested to occur in the vicinity of Fortymile Wash since aeromagnetic patterns there are broadly similar to those over known faults in the Yucca Mountain block. Depth of burial of potential structures by alluvium in the vicinity of Fortymile Wash may account for the more diffuse nature of aeromagnetic patterns in the vicinity of the wash compared to those over surface and near-surface faults in the Yucca Mountain block.

In summary, more detailed geophysical information is needed to constrain interpretations of structural features at depth. This information may be collected by the DOE during investigations for site suitability and site characterization at Yucca Mountain, including gravity, magnetics, and seismic data.

## 3.3.3 Strain Partitioning on Structures in the Yucca Mountain Area

Only regional scale strain partitioning data appear in the literature. There are no data at the scale of the Yucca Mountain area, and it is not presently possible to relate the regional-scale strain partitioning data to Yucca Mountain.

## 3.3.4 Geophysical Data on Subsurface Conditions Possibly Related to Magmatism in the Yucca Mountain Area

Evans and Smith (1992) used teleseismic tomography in the Yucca Mountain region to image 3D compressional-wave velocity structure beneath 2D arrays of seismographs at crustal and upper mantle

[2]Ibid

depths. This study indicated a well-resolved, upper mantle high-velocity zone beneath the (Miocene) Silent Canyon caldera of the Southwestern Nevada Volcanic Field and the northern part of the Nevada Test Site (NTS), present from near the Moho to depths of about 200 km. If this anomaly is related to the southwestern Nevada volcanic field, Evans and Smith (1992) speculate it may represent cooled residuum at the roots of a volcanic system that is now inactive, and the existence of large silicic magma chambers (4 km across or greater) in the crust within 10 km of Yucca Mountain is not plausible. Figure 3-8 illustrates the location of the caldera complex associated with the Southwestern Nevada Volcanic Field and the distribution of basalts of the silicic episode.

The other well-resolved feature reported by Evans and Smith (1992) is a large low-velocity anomaly located south and east of the high-velocity zone and occurring at a similar depth range. This anomaly is elongate in plan view with an east-west to northeast-southwest strike, wraps around the southern part of the NTS, and abuts Crater Flat to the south and east (Evans and Smith, 1992). An apparent east-northeast extension of this feature has been described by Dueker and Humphreys (1990) beneath the St. George volcanic field which is centered about 400 km east-northeast of Yucca Mountain in south-central Utah. Evans and Smith (1992) consider that the low-velocity anomaly may be the source for the Quaternary basalt in Crater Flat as a similar anomaly beneath the eastern Snake River Plain (Evans, 1982) is the likely source of the Yellowstone hot spot. This low-velocity anomaly is overlain at both ends by areas of Quaternary volcanism - Crater Flat on the northwestern end and the St. George volcanic field on the southeastern end. It is tentatively interpreted by Evans and Smith (1992) as a zone of partial melting which may be the source for Quaternary volcanic materials at Yucca Mountain. The occurrence of Quaternary volcanic vents such as those in Crater Flat, including Lathrop Wells Cone, may require the existence of related intrusive igneous bodies at some depth that could still exist as magma reservoirs.

In summary, additional geophysical data are needed to resolve the issue of what the low-velocity zone represents and whether or not it is of concern relative to potential for renewed volcanism in the Yucca Mountain area.

### 3.3.5 Silicic Volcanism in the Yucca Mountain Area

Cenozoic silicic volcanic and associated volcaniclastic rock units of the Yucca Mountain area were derived mainly from the (Miocene) Timber Mountain-Oasis Valley caldera complex (Figure 3-8) between about 16-9.5 Ma (Christiansen et al., 1977). This caldera complex is also a part of the southwestern Nevada volcanic field which is comprised by several large caldera complexes in the vicinity of Yucca Mountain (Carr, 1984). Although Carr (1984) has speculated that these caldera complexes appear to be concentrated where major right-lateral faults die out or split, studies of these volcanic centers have been too limited to clearly document specific structural control of the centers.

Large-magnitude extension generally accompanied silicic to intermediate volcanism in the Great Basin region, where Cenozoic extension started about 38 Ma in latest Eocene or early Oligocene (Wernicke et al., 1987). Waning silicic volcanism and onset of predominately basaltic (or bimodal) volcanism occurred in mid-Miocene with extension developing over a broader area (Wernicke et al., 1987). Crowe (1990) has summarized information on the basalts in the vicinity of Yucca Mountain which are associated with the waning stage of silicic volcanism, noting an age range of about 11.5-8.5 Ma for these older basalts. (See Figure 3-8 for distribution of these basalts and location of the caldera complex

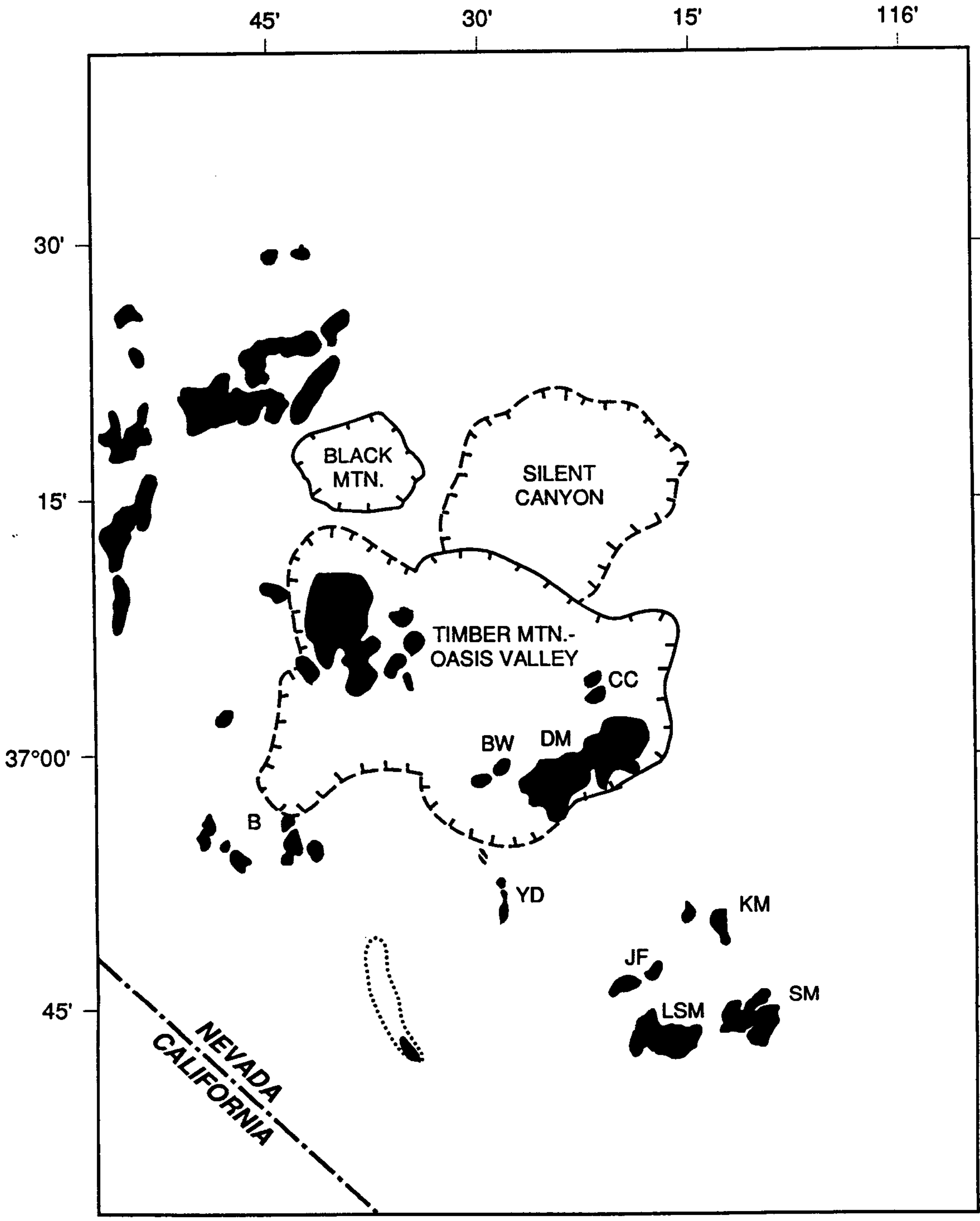


**Figure 3-8.** Caldera complex associated with the southwestern Nevada volcanic field and distribution of older basalts of the silicic episode. Age range of these basalts, which are associated with the waning stage of silicic volcanism, is about 11.5-8.5 Ma according to Crowe (1990). Legend for locations is as follows: LSM = Little Skull Mountain; SM = Skull Mountain; JF = Jackass Flat; KM = Kiwi Mesa; YD = Dike of Yucca Mountain; DM = Dome Mountain; BW = Beatty Wash; CC = Cat Canyon; B = Beatty. Figure modified after Crowe (1990).

associated with the Southwestern Nevada Volcanic Field.) Age ranges for postcaldera basalts have been delineated by Crowe (1990) and are discussed below.

## 3.3.6 Temporal Relationships of Basaltic Volcanism and Magmatism with Cenozoic Extension in the Yucca Mountain Area

### 3.3.6.1 Timing of Faulting

Scott (1990) has proposed a stepwise decreasing deformation rate model for Cenozoic (extensional) deformation at Yucca Mountain based on the following strain rates. (There is a gap in the rock record between 11.5 Ma and the present (Scott, 1990). Therefore, late Cenozoic tectonic rates at Yucca Mountain can be determined only for the 13-11.5 Ma period and the middle to late Quaternary period.)

Northeastern part of Yucca Mountain
13 Ma - 11.5 Ma — $1.4 \times 10^{-15}$/sec; 11.5 Ma - present — $8.3 \times 10^{-17}$/sec.

Northwestern part of Yucca Mountain
13 Ma - 11.5 Ma — $5.3 \times 10^{-16}$/sec; 11.5 Ma - present — $2.1 \times 10^{-16}$/sec.

Southern part of Yucca Mountain
13 Ma - 11.5 Ma — $8.7 \times 10^{-15}$/sec; 11.5 Ma - present — $5.6 \times 10^{-16}$/sec.

This stepwise decreasing rate model of Cenozoic deformation, the preferred model of Scott (1990), assumes deformation rates sharply decreased around 11.5 Ma when Bare Mountain rose along the Bare Mountain Fault and isolated the low-angle extensional fault system at Yucca Mountain from the more rapidly extending area west of Bare Mountain. This model does not directly include consideration of volcanism linked with extension and faulting. Scott (1990) does express doubt that crustal extension and volcanism have close temporal and spatial relationships at Yucca Mountain because the area of greatest extension in the Basin and Range, along the latitude of Las Vegas, is virtually free of volcanism (Wernicke et al., 1988).

Scott (1990) also discussed slip rates (dip slip) for several faults in the vicinity of Yucca Mountain which fit into his model:

Between 13 Ma - 11.5 Ma
Solitario Canyon and Paintbrush Canyon Faults = 0.19 mm/yr;
Windy Wash Fault = 0.07 mm/yr;
Stagecoach Road Fault = 0.45 mm/yr.

Between 11.5 Ma - present
Solitario Canyon and Paintbrush Canyon Faults = 0.010 mm/yr;
Windy Wash Fault = 0.026 mm/yr;
Stagecoach Road Fault = 0.024 mm/yr.

Calculated Quaternary (dip slip) rates from Scott (1990) were Paintbrush Canyon Fault = greater than 0.006 mm/yr; Windy Wash Fault = 0.0015 mm/yr; Stagecoach Road Fault = greater than 0.003 mm/yr.

Amount of extension in the northern part of Yucca Mountain is estimated at 10 percent, and 60 percent in the southern part of the Mountain (Scott, 1990).

Scott (1990) indicates that fault-movement ages fall into five periods: about 14-13.5 Ma, 13.5-13 Ma, 13-11.5 Ma, 11.5-1.7 Ma, and 1.7 Ma-present. These periods also bracket the times suggested by Carr (1984) for fault movement. However, they provide little support for another deformation rate model of faulting, an episodic model which Scott (1990) describes that attempts to temporally relate extension, faulting, and volcanism in a general way, because bracketing ages for fault displacements are not narrow enough to match with timing in the episodic model. This episodic model of Cenozoic extensional deformation is based on the assumption that some type of genetic link exists between crustal extension, fault movement, and volcanism in the Yucca Mountain area. It contrasts with the stepwise decreasing rate model which Scott (1990) prefers. In the episodic model, a hiatus in fault movement is assumed to causally coincide with a hiatus in volcanism in the Yucca Mountain area between about 10 and 4 Ma. With renewed volcanism around 3.7 Ma, fault movement is assumed to resume.

### 3.3.6.2 Timing of Volcanic Events

Timing of volcanic events in the vicinity of Yucca Mountain has been addressed by Crowe (1990). He recognized older postcaldera basalts (OPB) between 9 and 6.3 Ma, all of which occur north or east of Yucca Mountain; and younger postcaldera basalts (YPB) between 3.7 Ma to Late Pleistocene, all of which (except two sites at Buckboard Mesa) occur south or west of Yucca Mountain. Figure 3-9 shows distribution of the postcaldera basalts. No basalt units were found to occur in the age range of 3.7 to 6.3 Ma, although there is an older episode of basaltic activity between about 11.5 and 8.5 Ma (Figure 3-8) connected with termination of silicic volcanism in the Yucca Mountain region (Crowe, 1990).

In order of decreasing age, Crowe (1990) defines the following younger postcaldera basalts: basalts of southeast Crater Flat (K-Ar ages of about 3.7 Ma), basalt of Buckboard Mesa (K-Ar ages of about 2.8 Ma), 1.2 Ma alignment of central Crater Flat, basalt of Sleeping Butte (K-Ar ages of about 250,000 years on Little Black Peak and the same age on Hidden Cone with younger scoria that may be Late Pleistocene or Holocene), and Lathrop Wells (K-Ar ages on lavas of 30,000 to 500,000 years with weighted average at 135,000 years. Scoria at Lathrop Wells may be even younger. See Section 3.3.9 for a brief discussion of the controversy which exists on age and genesis of the Lathrop Wells volcanic center.)

Crowe (1990) notes at least four scoria-cone and lava centers associated with the southeast Crater Flat unit. Two sites exist at Buckboard Mesa — Scrugham Peak and a fissure extending about 5 km southeast from Scrugham Peak. These are the only basalts of the YPB group which occur northeast of Yucca Mountain. Also, the two sites contain the highest volume of material and have a chemistry different from that of the other YPB material. They are not included in the Crater Flat Volcanic Zone (CFVZ) of Crowe (1990).

Four Quaternary basalt centers comprise the 1.2 Ma alignment of central Crater Flat (Crowe, 1990): from northeast to southwest, an unnamed northeast cone (1.1 Ma from K-Ar), Black Cone and Red Cone (1.5 to 0.9 Ma from K-Ar), and Little Cones (two small scoria cones that are 1.0 to 0.8 Ma from K-Ar). These cones form a northeast-trending, arcuate alignment of vents. Sleeping Butte basalts consist of a northeast-trending alignment of two scoria cones and associated basaltic flows — Little Black Peak to the south and Hidden Cone to the north.

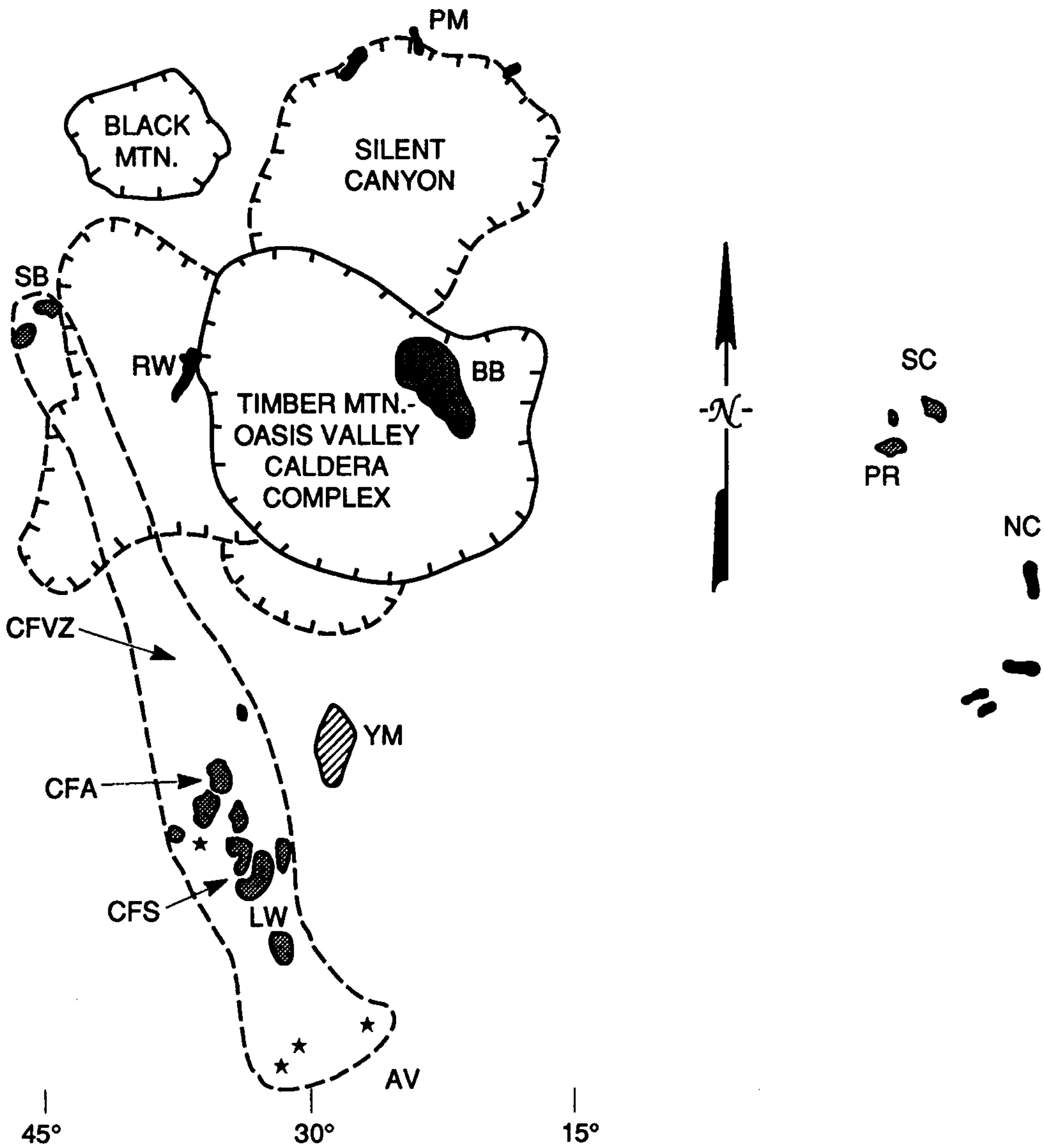


Figure 3-9. Caldera complex associated with the southwestern Nevada volcanic field and distribution of postcaldera basalts both inside and outside the Crater Flat Volcanic Zone (CFVZ) (enclosed by dashed line) of Crowe (1990). Age ranges of these basalts are about 9-6.3 Ma for older postcaldera basalts (OPB) and 3.7 to Late Pleistocene or Holocene for younger postcaldera basalts (YPB) according to Crowe (1990). The OPB group occurs north or east of Yucca Mountain; the YPB group occurs south or west of Yucca Mountain, with exception of two sites at Buckboard Mesa. Legend is as follows: PM = basalt of Pahute Mesa; RW = basalt of Rocket Wash; SC = basalt of Scarp Canyon; PR = basalt of Paiute Ridge; NC = basalt of Nye Canyon; CFS = 3.7 Ma basalts of southeast Crater Flat; BB = basalt of Buckboard Mesa; CFA = 1.2 Ma basalt alignment of Crater Flat; SB = basalt of Sleeping Butte; LW = basalt of Lathrop Wells; YM = Yucca Mountain site; CFVZ = Crater Flat Volcanic Zone. Small stars mark approximate centers of aeromagnetic anomalies inferred by Crowe (1990) to represent buried basalt centers or intrusive rocks. Figure modified after Crowe (1990).

In their latest assessment of recurrence rates for volcanism at Yucca Mountain, Crowe et al. (1992) regard $10^{-5}$/yr as an upper bound for rates of volcanic activity in the Yucca Mountain region. (See Chapter 4 for more details.) Based on data presented, and using a simple (homogeneous) Poisson model which does not consider waning or increasing volcanism, Crowe et al. (1992) constrains the recurrence of volcanic events for the Yucca Mountain region in the range of an event every few hundred thousand years and considers it implausible to assign recurrence rates that approach or equal those of other volcanic fields in the region. (For example, Lunar Crater volcanic field = between $4 \times 10^{-5}$ events/yr for vent count and $1 \times 10^{-5}$/yr for cluster count; Cima volcanic field = between $2 \times 10^{-5}$/yr for vent count and $1 \times 10^{-5}$/yr for cluster count. This is equivalent to formation of a new volcanic vent or cluster every 50,000 to 100,000 years at Lunar Crater and Cima.) This recurrence rate is comparable to that from the most recent work of Ho (1992), who determined an instantaneous recurrence rate at a 90 percent confidence interval between $1.85 \times 10^{-6}$/yr and $1.26 \times 10^{-5}$/yr using a nonhomogeneous process with Weibull intensity to account for waning or increasing volcanism. Earlier work of Ho (1991a) suggested $5.5 \times 10^{-6}$/yr recurrence rate. (See Chapter 4 for details.) Variations found in values determined for probability of disruption of a repository at Yucca Mountain between Crowe et al. (1982) and Ho (1992) are discussed in Chapter 4.

Perry and Crowe (1992) present geochemical evidence which they interpret as suggestive of waning volcanism at Crater Flat. Based on geochemical data on amounts of Sr (higher in younger lavas, related to less plagioclase fractionation and lack of plagioclase phenocrysts) and Sc (lower in younger lavas, related to more clinopyroxene fractionation) occurring in the Crater Flat basalts, deep magma chambers are suggested as sources for youngest events (i.e., less than 3.7 Ma) in Crater Flat. Lavas of the younger Crater Flat episodes have olivine phenocrysts but lack plagioclase as a phenocryst phase. Lavas of the older (3.7 Ma) Crater Flat episode contain phenocrysts of plagioclase, olivine, and clinopyroxene (Vaniman et al., 1982). Sr and Sc data suggest deeper magma chambers where clinopyroxene + olivine dominated the fractionating mineral assemblage relative to plagioclase. Perry and Crowe (1992) propose deep magma chambers may be related with waning magma flux that was unable to sustain conduits or chambers in the upper crust. Earlier, Crowe et al. (1989) presented information relating cumulative magma volume and time which also suggested waning volcanism in the Yucca Mountain region. Reduction of magma eruption rate from about 130 $m^3$/yr to 66 $m^3$/yr was noted between about 3.5 Ma and the present, although frequency of eruptions increased in that time frame.

Valentine et al. (1992) report that consequence analyses for eruptive effects on a repository at Yucca Mountain are continuing, as are studies to address understanding of the overall magma-dynamic system. Consequence analysis is being addressed mainly by studies of lithic distributions in analog volcanoes, and magma dynamics studies are concentrating on small sill geometries at present to understand physical processes and effects of magmatism in the Yucca Mountain region.

In summary, existing information does not provide sufficient detail on temporal and spatial association of volcanism with extension in the Yucca Mountain area. There are data on timing of faulting and timing of volcanism which cannot be integrated for understanding possible associations between volcanism, extension, and faulting at Yucca Mountain in space and time.

### 3.3.7 Spatial Relationships of Basaltic Volcanism and Magmatism with Structures in the Yucca Mountain Area

Crowe (1990) reports that scoria cones and lava centers for basalts of southeast Crater Flat were probably aligned and controlled by north-trending faults. At least four scoria cone and lava centers are associated with this field. The four Quaternary basalt centers comprising the 1.2 Ma alignment of central Crater Flat are, from northeast to southwest, an unnamed northeast cone, Black Cone, Red Cone, Little Cones. These centers form a northeast-trending, arcuate alignment (Crowe, 1990) which suggests control of surface location of these vents in central Crater Flat by the northeast-trending fault system at Yucca Mountain. Sleeping Butte basalts consist of northeast-trending alignment of two scoria cones and associated flows — Little Black Peak to the south and Hidden Cone to the north (Crowe, 1990).

The CFVZ of Crowe (1990) is defined by including all YPB, except Buckboard Mesa, into a northwest-elongate zone. This volcanic zone was first defined by Crowe and Perry (1989). Vaniman et al. (1982) reported basalts at Buckboard Mesa are geochemically different from those included in the CFVZ — basaltic andesite versus hawaiite of the CFVZ. Crowe (1990) and Crowe et al. (1992a) suggest structural subelements in this northwest-trending belt which are reflected in the tendency of basalt centers in the CFVZ to form northeast-trending clusters of coeval or near-coeval age within this zone. Crowe et al. (1992a) suggest the clusters may represent northeast-trending dike sets formed parallel to the direction of maximum compressive stress which is essentially the direction of dike propagation in the existing stress field. This concept relating chains of volcanic vents to stress pattern agrees with that proposed by Nakamura (1977) and Zoback (1992) where trend of the alignment should be perpendicular to minimum principal compressive stress. (Zoback (1992) draws the analogy to a natural hydrofrac experiment where the pressuring fluid is magma rather than water.) This concept may imply a temporal connection between extension and volcanism since the northeastern trend of vents described by several workers (Crowe, 1990; Crowe et al., 1992a; Smith et al., 1990; Naumann et al., 1991) parallels normal faulting in the Yucca Mountain area which is interpreted as being related to Cenozoic extension (Scott, 1990; Stirewalt et al.[3]). However, the exact relationships between volcanism and extension remain unresolved at present and no models at the Yucca Mountain scale exist to treat this relationship. Also, there are no mapped faults in the CRFZ with which the basaltic vents of this zone are colinear. The CFVZ itself is parallel to structural elements of the northwest-trending Walker Lane Belt suggesting to Crowe et al. (1992a) the basalt centers may be located along a buried structure or strike-slip fault of the Walker Lane system. Figure 3-9 illustrates the CFVZ as it is positioned relative to the postcaldera basalt group.

Smith et al. (1990) consider north-northeast, north-northwest, or north-trending high-angle normal faults to control locations of volcanic centers in the Yucca Mountain area. These normal faults reflect the northeast direction of the regional trend of the Death Valley-Pancake Range Volcanic Belt. For central Crater Flat, Smith et al. (1990) points out the following information: Black Cone has vents which occur along two subparallel zones striking about N35E and dikes also parallel this trend; Red Cone is comprised of three vent zones, two trending about N45E and one about N50W. From Black Cone to Little Cones, Smith et al. (1990) indicate vent alignments show a 15 degree clockwise rotation. Rosenbaum et al. (1991) state that paleomagnetic evidence indicates the southern tip of Yucca Mountain was rotated about 30 degrees clockwise relative to the northern part of the mountain after emplacement

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[3]Ibid

of the Tiva Canyon Member of the Paintbrush Tuff (i.e., post-13 Ma). Rotation is a product of oroflexure over a deep-seated right-lateral shear zone or shear related to differential extension in hanging wall rocks of a regional detachment system (Rosenbaum, et al., 1991).

Lathrop Wells Cone is interpreted by Smith et al. (1990) to have formed along a splay of northeast-trending Solitario Canyon Fault. Therefore, in their interpretation structures controlling location of volcanic vents in central Crater Flat and at Lathrop Wells are a part of the same northeast-trending fault system that both cuts and bounds Yucca Mountain.

All volcanic complexes in the Yucca Mountain area less than 4 Ma in age are grouped into an area of most recent volcanism (AMRV) by Smith et al. (1990). Included in the AMRV are centers in southeast Crater Flat and Buckboard Mesa, four centers in central Crater Flat, two centers at Sleeping Butte, and the Lathrop Wells cone. The AMRV encloses an irregular boundary drawn around locations of all Pliocene and Quaternary volcanic centers in the Yucca Mountain region. With the inclusion of Buckboard Mesa basalts, the ARMV of Smith et al. (1990) includes the Yucca Mountain site, rather than trending northwest and excluding it as the CFVZ of Crowe (1990) does. The AMRV of Smith et al. (1990) has no structural significance, but the above discussion indicates their observations on and interpretations of structural control within the AMRV. Figure 3-10 illustrates the AMRV of Smith et al. (1990).

Naumann et al. (1991) indicate basaltic vents at Buckboard Mesa were primarily controlled by northeast-trending faults, although the eruptions were apparently focused at the intersection of the northeast-striking fault zone and the ring fracture zone of the Timber Mountain caldera. According to Naumann et al. (1991), Scrugham Peak cinder cone and several small vents occur along a main vent zone that is 1 km long, trends northeast, and is controlled by en echelon fault segments striking N10E. Crowe et al. (1992a) reports vent zones of Buckboard Mesa are not located along northeast-trending structures, but along a 2 km long fissure oriented northwest.

Bu applying several quantitative methods (i.e., univariate analysis using cone distribution, cluster analysis, two-point azimuth analysis, and the Hough Transform), Connor et al. (1992) analyzed structural control on vent distribution in the Springerville volcanic field of Arizona where vents are numerous and patterns of structural control are less obvious. Although such an approach may be limited at Yucca Mountain because volcanic vents are not numerous, Connor et al. (1992) do reinforce the importance of understanding structural control on volcanism. It may be deemed reasonable to apply this approach in the region surrounding Yucca Mountain where appropriate data for volcanic centers exist to provide additional information on structural control of volcanism in the Basin and Range.

In summary, there is evidence of near-surface control on volcanic vents by northeast-trending (normal) faults in the vicinity of Yucca Mountain and some speculation on deeper control by strike-slip faults. However, there is little quantitative information at the scale of Yucca Mountain scale for rigorously defining these relationships. Analogs may prove useful to enhance this understanding if proper regions for study can be selected. Modeling of the normal fault-detachment system at Yucca Mountain by Stirewalt et al.[4] suggests normal (listric) faults could control volcanism only in the upper 5.6 km of the crust. More subsurface information on faulting and volcanism would be useful. There is little concrete information on structural control of volcanism in the Yucca Mountain area because of

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[4]Ibid

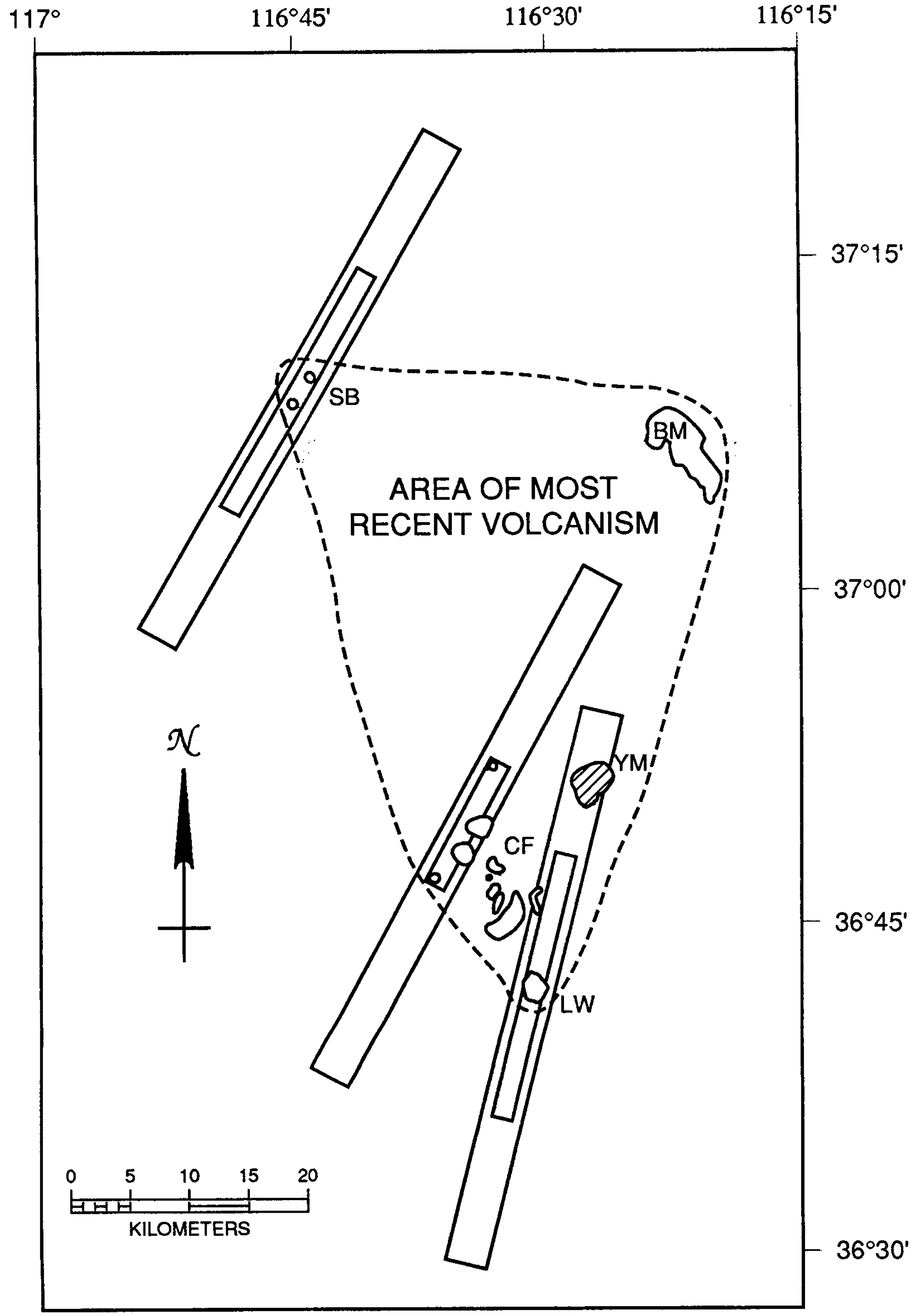


**Figure 3-10. Area of Most Recent Volcanism (AMRV , enclosed by dashed line) and rectangular high-risk zones of volcanism in the Yucca Mountain area as defined by Smith, et al. (1990). Legend is as follows: SB = Sleeping Butte; BM = Buckboard Mesa; YM = Yucca Mountain site; CF = Crater Flat; LW = Lathrop Wells. Figure modified after Smith, et al. (1990).**

the paucity of volcanic vents and events, and no subsurface information bearing on magma transport systems or magmatic processes.

### 3.3.8 Risk Assessment of Volcanism at Yucca Mountain

The latest efforts to quantify volcanic risk at Yucca Mountain are those of Crowe et al. (1992) and Ho (1991a; 1991b; 1992). These efforts are discussed in Chapter 4 of this report, along with the initial work by Crowe et al. (1982) on calculation of probability of volcanic disruption of a repository at Yucca Mountain. Smith et al. (1990) delineated high-risk zones for volcanism based on their AMRV model, as illustrated in Figure 3-10, which positions the Yucca Mountain site within a zone of risk relative to potential for renewed volcanism. However, no quantitative probability values were assigned by Smith et al. (1990) to these risk zones. As discussed in Chapter 4, Ho (1992) used the area of the risk zone encompassing Yucca Mountain to constrain his calculations of probability of volcanic disruption of a repository at Yucca Mountain.

### 3.3.9 Controversy on the Lathrop Wells Volcanic Center

Two topics of current controversy in relation to the Lathrop Wells volcanic center are genesis (polycyclic versus monogenetic) and age of the center. Wells et al. (1990) maintain the Lathrop Wells center is less than 50,000 years old (late Pleistocene or Holocene) and polycyclic based on evidence from geomorphology and soil development. Turrin and Champion (1990) and Turrin et al. (1991) argue that conventional K-Ar and 40Ar/39Ar age determinations indicate an age of 136,000 to 141,000 years. Champion (1991) suggested the center is monogenetic based on paleomagnetic evidence. Crowe et al. (1992b) believe current data indicate the center is polygenetic and admit more data are needed to resolve the chronology controversy.

### 3.3.10 Preliminary Tectonomagmatic Models for the Yucca Mountain Area

No tectonomagmatic models exist linking volcanism and extension for the Yucca Mountain area. As indicated by the discussion in Section 3.2, a single tectonomagmatic model also does not exist at a more regional scale for the Basin and Range Physiographic Province.

# 4 NONLINEAR DYNAMICS IN ASSESSMENT OF PATTERNS OF VOLCANISM AND PREDICTION OF FUTURE VOLCANIC-MAGMATIC ACTIVITY IN THE YUCCA MOUNTAIN AREA

## 4.1 INTRODUCTION

Use of nonlinear dynamics for analyzing and understanding natural systems is a relatively new approach. Until recently, studies of a natural system required either linearizing or randomizing the system dynamics to understand it. More and more these approaches are being found to be insufficient.

A linear approach requires simplifying a complex system to a simple system with simple dynamics. This type of approximation is useful for analyzing the system in a small percentage of natural systems. In general, natural systems are too complex and nonlinear to use the linear approach. Also, most natural systems have a large number of degrees of freedom, many of which may be active at any time. As a result, a randomizing or statistical approach has been the usual method for analyzing data from such a system.

A statistical approach uses no theoretical or physical description of the system. Statistical analysis of a system is predicated on the assumption that the recorded data have captured the full range of system behavior. It is then assumed the system behavior can be assigned a probabilistic distribution from the characteristics of these data and a probabilistic forecast of the future behavior can be made from the probabilistic distribution. Because statistical forecasting is based only on recorded data, the method yields the smallest amount of information of the various analysis methods. It yields only probable behavior and this forecasted behavior is limited to that which is included within the original recorded data. Hence, limited or insufficiently sampled data may give limited and possibly misleading or incomplete predictions. Statistical analyses do have a very strong attribute — with very few exceptions all field data can be analyzed statistically. However, for some natural systems statistics are neither the only nor the best approach for analyzing a data set and characterizing behavior of the system.

In recent years nonlinear dynamics has been developed to the point that, for some systems, it can usurp a statistical approach and will give a more complete description of a system's dynamics, its development, and its predictability. A data set that can be analyzed using a nonlinear dynamics approach, which may include fractals and chaos, will yield more information than can be derived from a statistical analysis. In this chapter and its associated appendix (Appendix A), nonlinearity, including fractals, chaos, associated concepts, and some alternative approaches (e.g., self-organized criticality) are discussed. These discussions are directed toward addressing the following questions:

- What approaches exist, other than stochastic, for addressing the issue of predicting the volcanism and magmatism at Yucca Mountain? Are these approaches applicable and what can they, especially nonlinear dynamics and chaos theory, contribute to addressing this issue?

- What information is derivable from the field data (e.g., eruption times, volume, location, associated seismicity)? What must a data set include to identify chaotic or other dynamical states? Can expanded or analogue data sets be used to extend or increase understanding and resolution of the prediction issue?

- Is an understanding of evolution of the dynamics of a magmatic system necessary to understand the eruptive temporal and spatial pattern?

- Is it reasonable to consider that a system with eruptive recurrences on the order of 10,000 years or greater and the spatial dimensions of the Yucca Mountain region (i.e., about 50 $km^2$) can continuously maintain being a chaotic system? Is intermittent chaos possible? Can a system have a non-fractal attractor which over time evolves into a fractal or strange attractor?

- If the system state is chaotic, what does chaos mean to predictability and reliability of predictions of intermittent eruptions? What is the compatibility between chaos and stochastics? Is a stochastic approach the best or most realistic approach?

This section is comprised of information from a review of literature pertinent to these questions. In conjunction with this section, Appendix A is included which contains a tutorial discussion of dynamics, chaos, fractals, information theory, stochastics, and the interrelations of these topics. Appendix B is a bibliography of sources of information on nonlinear dynamics which are not cited in the text. (In addition, Appendix C is a bibliographic list of information sources on geological relationships which are not cited in this report.)

## 4.2 NONLINEARITY IN NATURAL SYSTEMS

Nonlinear behavior occurs in many of the dynamic subsystems of the solid earth. Given below are summaries of studies of these subsystems. The studies are important because they demonstrate the possibility of nonlinear behavior or define characteristics of chaos measurable in volcanic-magmatic systems. The studies are divided into three categories: (i) short-term or dynamic examples, (ii) long-term examples, and (iii) spatial examples. These categories were chosen because they represent the important characteristics for the potential application of nonlinear dynamics to volcanic-magmatic systems. A number of these systems are summarized in a book by Turcotte (1992) entitled, *Fractals and Chaos in Geology and Geophysics*.

### 4.2.1 Short-Term Temporal Examples of Nonlinear Dynamics

A number of studies have examined seismicity and tectonics from a chaotic and fractal statistics standpoint. In essence, these studies show that the magnitude, space, and time distributions of seismicity have a fractal structure.

Turcotte (1992) showed the commonly accepted relationship between frequency of occurrence of earthquakes and their magnitudes, called the Gutenberg-Richter equation, is a fractal relationship. In mathematical terms the Gutenberg-Richter equation is $\log(N) = -bm + \log(a)$, where b and a are constants. The logarithm is base 10; and N is the number of earthquakes in a specified geographic area in a specified time interval, typically in years, with a magnitude greater than m. Using the standard fractal definition that the number of objects in a fractally-distributed set (earthquakes in this case) is inversely proportional to a linear dimension (the average length of the area over which the earthquakes occur) to a power D (the fractal dimension), the fractal dimension of regional or world-wide seismicity is found to be D=2b. Empirical studies typically find b to be slightly less than unity. Hirata (1989b) studied the spatial distribution of shallow (<60 km) earthquake epicenters and also found the fractal dimension of this distribution to be correlated with the b-value. Using earthquake data compiled from 1926 through 1986 for events located off the east coast of Japan, Hirata derived the relationship D = 2.3 - 0.73b.

In conjunction with investigation of the spatial distribution of earthquakes, Turcotte (1992) summarized two popular tectonic models. The first assumes a fractal distribution of faults with each fault having its own characteristic earthquakes. The second assumes the each fault has a fractal distribution of earthquakes. At present, both observation and opinion favor the first model.

Smalley et al. (1987) studied the time clustering of earthquakes and applied the resulting fractal statistics to seismicity in four regions in the New Hebrides between 1978 and 1984. The number of earthquakes varied between 44 and 1,330 and in all cases substantial deviation from random distribution (i.e., a Poisson distribution) was found. By using a Cantor set approach, Smalley et al. (1987) assumed the fraction of time intervals of length t containing earthquakes followed a $t^{(1-D)}$ distribution and found $0.126<D<.255$. Paralleling the earthquake clustering studies, Huang and Turcotte (1990) and McCloskey and Bean (1992) theoretically modeled earthquake recurrence and heterogeneous fault zones using a simple mass-spring model. Both studies provided substantive evidence that earthquake behavior can be chaotic. They found a necessary condition for chaos was spatially or temporally inhomogeneous frictional strength across the simulated fault and concluded patterns and statistics of earthquakes can be the result of faulting in a chaotic state.

### 4.2.2 Long-Term Temporal Examples of Nonlinear Dynamics

A number of studies have revealed that some long-term processes in the Earth can maintain nonlinear dynamic behavior for periods of time greater than 10,000 years and possibly on the order of tens of millions of years. Examples of these include the geomagnetic dynamo, mantle convection, and the stratigraphic column.

The Earth's magnetic field is believed to be generated by self-exciting dynamo action that couples rotationally, thermally, and/or compositionally-driven fluid convective motion in the Earth's outer core with its intrinsic electrical conductivity in a feedback loop. The result is primarily a dipole field whose principal axis aligns with the Earth's rotational axis and periodically reverses polarity. The polarity reversals can last from tens of thousands of years to a few million years. Based on theoretical modeling of coupled dynamos, Ito (1980) and Turcotte (1992) argue that geomagnetic reversals are a vestige of chaotic dynamics in the Earth's outer core.

Mantle convection, the large-scale, thermally-driven circulation of the mantle which drives plate tectonics and associated earthquakes and volcanism, is believed to take tens of millions of years for a convection cell to complete one cycle. However, despite that long time scale, theoretical studies indicate that mantle convection may be a chaotic process. Despite the very poor constraints on the crucial mantle parameters (e.g., composition, chemical phase, viscosity, thermal conductivity, expansivity) numerical studies by Machetel and Yuen (1987), Stewart and Turcotte (1989), and Kellogg and Turcotte (1990) give very strong arguments that thermal convection of the mantle is chaotic.

Besides these thermally-driven processes, the long-term natural record also indicates nonlinearity. Plotnick (1986) discusses studies that show a relationship between sedimentation rates and the time span over which they are measured (i.e., measured sedimentation rates are slow when measured over long time spans and rapid when measured over short spans). Plotnick (1986) argues this relationship is due to inclusion of more and longer hiatuses over long time spans. He presents a fractal model which estimates the relative number and duration of stratigraphic hiatuses in a given section based on an analog with the Cantor set. In a parallel type of study, Fluegeman and Snow (1989) examined the sedimentary record from core samples taken in the Pacific near the Solomon Islands. Using oxygen isotope analysis, they estimated a fractal dimension of 1.22 for the recorded climate changes over time spans from several thousand years to two million years.

In conjunction with these types of studies, Shaw (1987b) presents arguments for the periodic structure of the natural record and nonlinear dynamics. Shaw discusses some interesting and provocative issues regarding cyclicity and variation of cyclicity of geologic and paleontology phenomena, the 30-million year igneous periodicity, the solar system periodic motion through our galaxy, the periodic motion of our galaxy, and the pervasiveness of chaotic behavior. In his discussions, Shaw (1987b) uses the term chaotic to describe data that includes both periodicity and order and aperiodic disorder, and distinguishes this from random by stating that patterns of chaos are recognizable. He believes there are differing tracts of repetition in a sample of chaotic behavior.

### 4.2.3 Spatial Nonlinearity and Geological Structures

There are many spatial examples of nonlinear dynamics left as permanent records in geological features. Limiting this discussion to examples of features closely related to magmatic and volcanic processes, these include characteristics of faults, fractures, and fragmentation.

Turcotte (1992) summarized a number of studies of spatial distribution of faults and concluded the frequency-size distribution of faults is fractal, although the fractal dimension is not necessarily the same as that for earthquakes. Turcotte (1992) also showed that fractal statistics can be used to infer the three-dimensional distribution of fault sizes in a region from a two-dimensional map of fault exposures. Hirata (1989a), Merceron and Velde (1991), and Matsumoto et al. (1992) studied fault systems in Japan and the Philippines and found self-similarity or fractal statistics applied from the macroscopic scale down to the individual fracture scale. Davy et al. (1992) concurred with these findings in laboratory studies of simulated faulting and fracturing.

In connection with investigation of fracture networks in mechanically cleared surface exposures of welded tuff at Yucca Mountain, Barton and Larsen (1985) analyzed the fractal geometry of these structures. They found the fractures were self-similar over the range of scales sampled in the exposures. They quantified the spatial, trace-length, density, and orientation distributions of the fracture networks using fractal geometry. Although Barton and Larsen (1985) were able to determine the fractal dimension of the pattern of fractures in the network using an adaptation of the box method of fractal analysis where grids of various sized square cells are successively placed over the maps and the number of cells intersected by fracture traces are counted, they were unable to proceed to the next step and determine the generator for the fractal pattern represented by the fracture networks. (The fractal dimension for the fracture networks varied between 1 and 2 within confidence levels of 0.99.) The generator is the fundamental building block from which a fractal pattern is produced. In a subsequent study, Barton et al. (1986) also found the pattern of faults mapped by Scott and Bonk (1984) at Yucca Mountain to be self-similar over the range of scales that could be sampled on their map.

Turcotte (1986, 1991) has examined the relationship between fragmentation and fractal statistics. He found a fractal relationship between fragment frequency and fragment mass. This frequency-size distribution held true for a wide range of scales that included fragments produced by weathering, explosions, and impacts. He concluded fragmentation is often a scale invariant process, and pre-existing zones of weakness where failure occurs producing fragmentation exist on essentially all scales.

Studies by Hewett (1986) and Nigmatullin et al. (1992) show the scale down to which fractal geometry continues to be found. Hewett (1986) found fractal statistics described the distribution of heterogeneities in an oil reservoir and used these statistics to model the influence on fluid transport. Similarly, Nigmatullin et al. (1992) developed and demonstrated a fractal pore model for Archie's law, the empirical relationship between electrical conductivity and porosity of fluid saturated sedimentary rocks.

Power and Tullis (1991) examined natural rock surface topography and found the surfaces could not be fit to traditional Euclidean forms such as planes, spheres, or their derivatives. They found the natural rock surfaces could be described more completely using either self-similar or self-affine fractal models of surface roughness. By measuring the surfaces and calculating spectra of these data, Power and Tullis (1991) showed they could distinguish between self-similar surfaces and self-affine surfaces. The data from self-similar surfaces have slopes of -3 on log-log plots of power spectral density versus spatial frequency, while spectra from self-affine surfaces have slopes other than -3. Power and Tullis (1991) discussed how surface topography affects dynamics from scales of fluid flow through pores, fractures, and faults to scales of fault evolution and earthquake behavior.

Henderson and Main (1992) developed a theoretical model that tied together fractal fault mechanics and its evolution to active seismicity. They began with a fault model consisting of an array of individual but elastically-coupled elements and a remotely-applied stress field, and assigned random fracture toughness to each array element. By increasing the remotely-applied stress and allowing individual-element fracture toughness to evolve in a manner consistent with known material behavior and failure criteria, Henderson and Main (1992) found frequency-magnitude of the simulated earthquakes was similar to the seismic b-value data discussed earlier, and the simulated crack distribution compared with the fractal dimension of earthquake epicenters.

Scholz and Aviles (1986) also examined the relationship between faults, faulting, and seismicity. They measured the topography of natural faults and fractures over magnitudes ranging from $10^5$ m to $10^{-5}$ m. The surfaces were fractal or nearly fractal over the entire range, but fractal dimension, D, was not uniform and showed both abrupt and gradual transitions which depended upon the scale at which the surfaces were studied. This result departs significantly from prior studies, but the authors note earlier studies spanned only about two decades. The approach used by Scholz and Aviles (1986) involved combining Fourier transforms of the spatial topography and fitting the power spectrum of the transforms to functions of the form $\omega^{-(5-2D)}$, where $\omega$ is spatial frequency, to determine D. The data used split into two scales: 1 m to $10^{-5}$ m and $10^3$ m to $10^5$ m. They were no data between 1 to $10^3$ m. In terms of physical relevance, they believe the 1-$10^{-5}$ m short-wavelength band is related to fractional processes that occur during rupture, while the $10^3$-$10^5$ m long-wavelength band is related to heterogeneities in rupture propagation. For the short-wavelength band, D varied between 1.15 and 1.26. For the long-wavelength band, D was very nearly 1.0.

Scholz and Aviles (1986) recognized the results were strictly geometric and proceeded to relate the findings to earthquakes. Examining available earthquake data, they found that both large and small earthquakes were self-similar following fractal statistics or, equivalently, a power law size distribution. However, large and small earthquakes were not self-similar with each other. If statistics from small earthquakes were extended to large earthquakes, the predicted size was 1 to 1 1/2 order of magnitude smaller that what is recorded. (They described the hierarchical jump between the two families of earthquakes as a fractal tear.) These results are consistent with the variation Scholz and Aviles (1986) found in D as previously discussed.

## 4.3 Nonlinear Dynamics and Volcanic-Magmatic Systems

### 4.3.1 Nonlinear Dynamics and Hawaiian Volcanism

Shaw (1987a) discusses sources of possible periodic and nonperiodic influences in volcanism using data from Hawaiian volcanoes. It is his contention that predictability, whether exact or probabilistic, is a function of recognizing the like and unlike patterns of evolution in the data from a single volcano or volcanic system. Shaw believes these data from Hawaiian volcanoes are self-similar and there is sufficient redundancy of information in the data to recognize patterns and formulate either exact or probabilistic predictions.

Shaw presents arguments for categorical similarity or universality of volcanic characteristics (specifically, volcanic eruptions, intrusive events, and induced earthquakes) using a nonlinear dynamics (chaotic) viewpoint. He draws the premise of categorical similarity from results of investigations in four areas: (i) volumes and rates of magma supply and eruptions during evolution of the Hawaiian-Emperor volcanic chain, (ii) factors influencing thermomechanical feedback that imply oscillatory changes in conditions of magma generations, storage, and transport, (iii) theoretical examples of positive-negative feedback that illustrate methods of constructing attractor diagrams which imply oscillatory and potentially periodic behavior, and (iv) comparisons with observed patterns of volume and rate balances of intrusion and eruption for Kilauea Volcano.

For the first area, Shaw begins his discussions with self-similarity in Hawaiian volcanism. He examines volcanic products versus time at three time scales: less than 74 million years, with a resolution of $\sim 10^5$-$10^6$ years, using data from the Hawaiian-Emperor volcanic chain; less than 200 years, with an estimated resolution of about a year, using historical record data; and 30 years, with a resolution of days to months, using data from modern geophysical measurements taken by the Hawaiian Volcano Observatory . From interpretation of these data sets, he suggests volcanic systems typically evolve from smaller sizes, characterized by higher frequency events, to larger sizes, characterized by lower frequency events, at about the same overall average growth rate. He believes this proportionality represents a form of dynamic self-similarity that resembles fractal self-similarity.

Shaw then proceeds to discuss an approximate way in which some of the factors influence the variability of magma production and transport. His reason for discussing these dynamic and thermomechanical feedback processes is to show magmatic processes should be treated as systems of interacting and self-influencing mechanisms of transport that evolve in both space and time. He uses this approach to build concepts of cyclical tectonomagmatic processes that have as an outcome patterns of plutonic and volcanic behavior observed in the global record of igneous provinces where there are analogous cyclical plate tectonics processes. In this discussion, Shaw focuses on comparisons between characteristic times associated with dissipative heating, cooling by thermal conduction, and variation in viscous and elastic states of stress and on implications for timing of magma transport. He concludes from considerations of dynamical time scaling that repetitive feedback processes involving melting and magma transport are likely to occur over a range of self-determined periodicities. In addition, Shaw states that feedback interactions of complex processes converge toward limited ranges of dynamical parameters.

For the third area on theoretical examples of positive-negative feedback and methods of constructing pertinent attractor diagrams, Shaw investigates attractor dynamics and factors influencing categories of dynamic behavior for three states of behavior: fixed point or stationary, periodic, and chaotic. He also discusses concepts of sensitive dependence on initial conditions and basin of attraction (See Appendix A) as theoretically applied to dynamics of volcanic systems.

For the final area, Shaw applies data from Kilauea to an attractor dynamics analysis. In this discussion, he examines different combinations of positive-negative rate balances using the following existing data categories: (i) total magma-supply rates, (ii) total integrated volumes of magma supply, (iii) localized rates of summit supply, (iv) localized summit volumes, (v) nonsummit supply rates and volumes (representing rates and volumes of supply to rift systems), and (vi) net rates and volumes of stored magma at summit and rift localities, taking into account eruptive losses. Based on these analyses, he believes the summit-reservoir control loop may operate physically as follows. When magma volume of the summit reservoir exceeds some relatively high volume, the summit reservoir returns to the vicinity of the stationary state because of higher-than-average rates of loss of magma to the generalized rift reservoir. Conversely, when summit reservoir volume is low, the summit reservoir returns to higher volumetric levels because of lower-than-average rates of loss of magma to the rift reservoir. These rate variations do not appear to be dominantly eruption-controlled, since eruptions occur at times of either higher or lower-than-average rates of return to the stationary states. That is, if eruptions were controlled only by rate, they would presumably occur mainly at times of higher-than-average volumetric states.

He further states that the summit reservoir tends to buffer the rate of shallow magma supply by adding to the inertia of the magma system. Fluctuations in rate of magma supply from depth are damped at the surface by summit reservoir effects. When rate of magma supply from depth is low, eruptions can still be fed by magma stored in the reservoir. When magma-supply rate is high, eruptions can be damped by increased subsurface storage of magma. Whereas eruptions of magma evidently can occur at almost any volumetric state of the summit chamber, large eruptions occur at times near the locus of stationary states. This observation indicates the eruption mechanisms themselves may be controlled by summit-rift reservoir balances in amount of magma. A high net inflation state of the summit reservoir seems to require adjustments by increasing net transfer to the rift reservoir from the summit reservoir before optimal conditions for eruptions can recur. That is, if values of magma-supply volume and rate are both too high, the resistance to eruptions appears to increase until summit storage returns toward the stationary states by a shift to increased rift storage. If both reservoirs increase together, rift earthquakes may be more likely than eruptions. Conversely, if the summit reservoir is operating at much lower volumes than the stationary states, the eruptive head may be too low to overcome the net viscous dissipation associated with inflation. Consequently, eruptions appear most likely at values near the stationary states when magma volumes of the summit reservoir and the rift storage system are properly balanced, and perhaps at slightly higher volumes, regardless of net magma transport rates.

In conclusion, Shaw states patterns of volcanic phenomena which he presented for Hawaiian volcanoes are chaotic and existence of chaotic behavior severely alters the nature of prediction of future volcanic activity although it does not preclude prediction. He implies attractor dynamics and analysis should be used in volcanic studies where an adequate amount of recorded data are available particularly for active volcanic centers under surveillance and requisite data for this type of analysis should be recorded as a standard procedure of volcanic surveillance.

Following is a summary of other articles in which nonlinear dynamics are coupled with specific aspects of volcanic-magmatic systems. The discussion is divided into three categories: (i) volcanic seismicity, (ii) lava and magma transport, and (iii) volcanic eruption sequences. With exception of the lava flow measurements of Bruno et al. (1992), all the studies discussed deal with exceptional and recently-recorded data sets from active volcanic systems.

### 4.3.2 Volcanic Seismicity

Local seismicity is a characteristic of volcanic provinces and is believed to be an indicator of magma transport and eruptive activity. This seismicity is characteristically different from that related to intra- and inter-tectonic plate earthquakes. Volcanically-related seismicity is specifically called volcanic tremor. As noted by Chouet and Shaw (1991) volcanic tremors are much longer in duration and have a much more limited frequency than typical and comparably-sized intra and inter-plate earthquakes.

Shaw and Chouet (1989) used a method called fractal singularity analysis to study a 22-year record of deep volcanic tremor (30-60 km depth) in the vicinity of Kilauea Volcano, Hawaii. They assumed magma transport and fracture could be treated as a system of coupled nonlinear oscillators with each oscillator acting as an individual source of seismic radiation resulting in long-period seismic events. Each recorded tremor was then viewed as a succession of individual long-period events, and each long-period event was assumed to average 20 seconds in duration. Their data, recorded between 1962 and 1988, consisted of 577 events which ranged in episode duration from about 1 to 100 minutes or, equivalently, 3 to 300 rupture increments. The fractal singularity analysis of Shaw and Chouet (1989), whose specifics are beyond the scope of this summary, is a method to decompose the multifractal content of a complex data set. It is based on using fractal statistics to determine the probability of the time duration of the next tremor based on the duration of the previous tremor. Assuming four possible dynamic regimes for the coupled nonlinear oscillators: (i) chaotic, (ii) mode-locked, (iii) periodic-doubling, and (iv) white noise, Shaw and Chouet (1989) were not able to uniquely define the dynamic regime of the tremor data. However, they indicated evidence for the transition between mode locking, the nonlinear interactions of a dynamical system that produces periodic behavior which persists for a range of parameters (Rasband, 1990) and chaos (period doubling). They attributed the uncertainties in the results to paucity of data.

Chouet and Shaw (1991) continued their work on volcanism-associated seismicity at Kilauea Volcano and studied the fractal properties of individual shallow volcanic tremor and gas piston events associated with magma degassing. Recognizing the lack of adequate data on the details of the tremor process, they tried a more generalized approach of looking for universal properties of the tremor process in the seismic data. This approach resulted in a search for attractor dynamics and finding evidence for a low-dimension strange attractor. Chouet and Shaw (1991) found an upper bound on the fractal (correlation) dimension of a strange attractor common to both tremor and gas piston events in the range of 3.1 to 4.5 with a mean of 3.75. Using data from an array of more than 60 seismometers, individual events were analyzed using the embedding space approach to identify the strange attractor and extract its correlation dimension from the recorded time series. Chouet and Shaw (1991) recognized two concerns: the first was the number of data points; the second was the data sampling rate and the embedding analysis method. While specifics of this concern are beyond the scope of this summary, the number of data points is a very important issue. Chouet and Shaw (1991) used 10 seconds of data per event recorded at a sampling rate of 200 samples per second, or 2000 data points. They believed this number was at the low end of the accepted range of data volume needed to stably determine the attractor dimension. Chouet and Shaw (1991) cite a study where 100,000 data points were used. They also cite a study claiming to use 500 points and extracting a stable, reliable dimension. In this later study there is some evidence of a simple attractor structure. In light of their concerns, Chouet and Shaw (1991) indicated confidence in their method and belief that their findings represented an upper bound on the strange attractor dimension.

### 4.3.3 Lava and Magma Transport

Bruno et al. (1992) studied the fractal nature of the plan-view shapes of lava flows in Hawaii, Idaho, and the Galapagos Islands and on Venus, Mars, and the Moon. They used the same self-similar or scale-invariant assumption as Mandelbrot (1989) used when measuring the length of the British coast line. They determined the apparent length, L, of the lava flow margin by walking rods of different lengths, r, along the margin and then using the data to determine the fractal dimension, D, from the relationship $\log(L) = C + (1-D)\log(r)$, where C is a constant. They found scale-invariance from 0.5 m through 2.4 km. Their data indicates fractal dimension of 1.05 to 1.09 for aa flows and 1.14 to 1.23 for pahoehoe flows. Bruno et al. (1992) concluded these data were indicative of nonlinearity in the fluid dynamics producing the lava flows.

Extending their earlier work (Shaw and Chouet, 1989), Shaw and Chouet (1991) created a hierarchical model of magma transport in Hawaii using the deep and intermediate-depth (5-15 km) volcanic tremor. They found two kinds of spatial distributions of magma fractions at depths below 5 km, defined by the fractal dimension from an embedding space analysis of seismic data and seismic hypocenter locations. One dimension, 0.28, was from focused hypocenters interpreted by Shaw and Chouet (1991) as reflecting conduit-like structures where the magma flow converges toward a summit magma chamber with a fractal dimension tending to zero (i.e., non-chaotic motion). The other dimension, 1.52, they interpreted as resulting from a dispersed hypocenter distribution. They believed the distribution reflected multifractal clustering of dendritic fractures where the hypocenters represent subsets of fractures within spherical domains of average radius about 1 km. They interpreted the geometry as representing a percolation network of clustered intermittent fracture and magma transport. They developed a tremor model of magma transport using mass balance of percolation that was proportional to tremor duration. Predictions of the models and measured data sets gave reasonable agreement and appeared to indicate a high degree of self-organization of the nonlinear dynamics of fracture percolation and coupled tremor processes.

In extended analysis, Shaw and Chouet (1991) noted logarithms of concentrations of frequencies of high-amplitude tremor (a 1-second period), mean tremor duration (a 28-minute period), and mean onset interval (a 14-day period) gave values of 0, -3.2, -6.1, respectively. They believed these data to be a sequence in which the next number, a 32-year period or a logarithmic value of -9.0, corresponded to eruptions and shallow intrusions and was comparable to the average eruption interval (about 20 years) of Mauna Loa Volcano during the last 150-year period. Shaw and Chouet (1991) interpreted these data as a spatial-temporal universality that extends from small to large scales in Hawaiian and other magmatic systems. They speculated this apparent universal scaling of bundles of frequencies may extend over 15 decades in time (1 second to 60 Ma) and 10 decades in length (9.1 mm to 1,000 km). However, there is insufficient data to firmly substantiate this assertion and Shaw and Chouet (1991) offered no physical basis for their conclusions.

### 4.3.4 Volcanic Eruption Sequences

Dubois and Cheminee (1991) used a fractal analysis method to study the distribution of quiescent or repose time periods between eruptions for four basaltic volcanoes: Piton de la Fournaise on la Reunion, Mauna Loa, Kilauea, and Etna. The repose time is defined as one of the four periods of the eruptive cycle of a volcano. In order, the periods are repose, persistent activity, intermediate eruption, and final eruption. The authors contrast their work with traditional statistical approaches which assume a random eruption model and a constant probability of eruption in an interval of time that does not depend on prior eruptive history.

Using a Cantor set model in the time domain for the repose data, Dubois and Cheminee (1991) fit their data to a fractal relation, $\log(N) = -D*\log(t)$, where N is the number of time periods of length t and D is the fractal dimension. In this type of statistics, the fractal dimension, D, lies between 0.0 and 1.0 and describes strength of clustering of data. The more isolated the clustering, the smaller the value of D. The main result they obtained for the eruptive activity of hotspot volcanism (Piton de la Fournaise, Mauna Loa, and Kilauea) over a period of about 60 years was evidence for a double-regime process. They found strong clustering ($D=0.3$) of eruptions occurring over short intervals (i.e., months) and more regular occurrences ($D=0.7$) of eruptions on large intervals (i.e., years). They found a single regime at Etna ($D=0.75$) which characterizes regular activity. Dubois and Cheminee (1991) offer two interpretations of their results. One is related to fractional crystallization in a shallow reservoir, which they do not favor. The second, which they support, deals with magma replenishment in which the two time scales of the fractal analysis suggest magma reservoirs are fed and drained at different rates. They believe the data indicate a two-fold magmatic system: a deep subcrustal system connected to large calderas and a shallow reservoir (3 km depth) feeding eruptions. They interpret the two regimes as two different "rhythms" of magmatic extrusion. The more irregular one is characterized by the small D ($D=0.3$) and appears to correspond to a superficial mechanical response of the edifice to volatile over-pressure due to cooling of the magma in a shallow reservoir. The second, more regular rhythm with $D=0.7$ is believed to correspond to eruptions in 17-year cycles attributed to the disruption of fractionated olivine. It is important to note this study showed the regime is not a simple Poisson process.

Sornette et al. (1991) specifically addressed the question of whether sequences of volcanic eruptions are chaotic and found strong evidence indicating chaos. They analyzed the same repose time sequence data from Piton de la Fournaise, Mauna Loa, and Kilauea as Dubois and Cheminee (1991). Computing the attractor fractal dimension using an embedding space analysis for the 72 repose periods at Reunion in the last 60 years, they calculated the attractor dimension to be approximately 2. For the nearly 100 periods of the Hawaiian system, they found the dimension to be approximately 4. They were confident with the Reunion value since smaller dimensions can be found with smaller a data set, but were less confident with the Hawaiian results since the dimension is larger and it substantiation requires a larger data volume. The authors attempted to further analyze Reunion data to explain the deterministic dynamics of the eruptions. These analyses corroborated the embedding space analysis of low dimensional chaotic dynamics, but were plagued by problems that prevented further insight.

## 4.4 Other Approaches Applicable to Yucca Mountain

### 4.4.1 Stochastics and Chaos

Prior to discussion of other approaches which have been applied, or may be applicable, at Yucca Mountain, it is appropriate to discuss relationships between stochastic approaches and chaos. As is the case for Yucca Mountain, if a data sequence is to be used for prediction of future volcanism, it is very important to determine if the sequence is deterministic, random (i.e., stochastic), or semi-deterministic (i.e., chaotic). Ignoring deterministic data sequences since these are not applicable at Yucca Mountain, if the data are truly random, then a stochastic analysis is justified. If the data are not random but result from chaotic behavior, then use of a stochastic approach may give misleading results. If the chaos is low-dimensional, a stochastic approach will give incorrect results; while if the chaos is high-dimensional, a stochastic approach is justified and may give reliable results. However, if the data are insufficient to capture the full range of system dynamics, then no approach, including stochastics, will give reliable results for prediction of future volcanism.

All data analysis methods assume stationarity in the data. This means a sufficient volume of data has been recorded and a full range of system behavior is included in the data. It also means the range of behavior included in the data is indicative of the long-term behavior of the system. If these two assumptions are not met in the data, then as stated above, reliability of any prediction method is questionable. If a data set is stationary then the analysis can proceed. The first test of the data is to determine whether or not they are random.

Checking the nature of randomness in a given sequence requires many different tests since some pseudo-random sequences of numbers have successfully passed some tests and failed others (Sornette et al., 1991). Randomness implies both the existence of a limiting probability distribution and the absence of correlations. Thus, tests for randomness are divided into two general categories: one for checking if the events are distributed consistent with a well-defined probability distribution and a second that detects correlations. However, it should be noted that Sornette et al. (1991) reported two classes of deterministically dynamic systems passed all the usual statistical test for randomness. The first type of system is one with many degrees of freedom which are intimately coupled and develop random-like dynamics as a result of the complexity created by the superposition and coupling of the different evolutions of each degree of freedom. In this case, evolution of the system is indistinguishable from a suitable random process and use of a stochastic analysis is acceptable. The second type of system is a chaotic system. Time sequence data recorded from chaotic systems pass all traditional tests of randomness. However, the divergence of states and the creation of new information in chaotic systems preclude the use of statistics that apply to random, non-deterministic sequences, unless the chaos is of high dimension. Lower dimension chaotic systems allow short-term predictions based on an adequate catalog of past patterns in the time series data, but predictability necessarily degrades for longer time periods. In contrast, once the probability distribution of the random variable of a stochastic system has been established, its predictive reliability does not degrade unless the driving force(s), physical system, or some other related component are altered. For a more complete discussion see Appendix A.

### 4.4.2 Stochastic Predictions and Volcanism at Yucca Mountain

Crowe et al. (1982) used a stochastic approach to analyze volcanism in the vicinity of Yucca Mountain. They modeled eruptive history as a random (Poisson) distribution, assuming rate of eruption,

$\lambda$, was constant over time and the individual eruptive events occurred independently. Data used by Crowe et al. (1982) came from 14 basalt flows at four vent areas (i.e., Lathrop Wells, Crater Flat, Sleeping Butte, and Buckboard Mesa). From geochronologic data, they concluded that no distinct patterns or periodicity to basaltic volcanism in the late Cenozoic were suggested. In addition, sparseness of the data precluded analysis for interval patterns and calculation of future rates of volcanic activity. As one approach, Crowe et al. (1982) estimated rate of eruption, $\lambda$, by counting the number of Quaternary surface vents which occurred in a given time period and determined rate of volcanism during Quaternary time as follows: for the Nevada Test Site, $9.4 \times 10^{-6}$/yr; for Buckboard Mesa, $6.4 \times 10^{-6}$/yr. In conjunction with calculating estimated rate of eruptions, Crowe et al. (1982) determined the probability of volcanic disruption of a repository as $10^{-8}$ to $10^{-10}$ for probability of one disruptive event per year. They pointed out precautions in connection with the calculations related to accuracy, precision, and paucity of data, limitations of a stochastic approach, and the assumption of a Poisson process which assumes volcanism is a random process.

Ho (1991a), recognizing that a simple Poisson model may be inadequate, expanded the stochastic approach to risk forecasting volcanism near Yucca Mountain. Specifically, he argued a simple Poisson model (i.e., a fixed recurrence rate throughout the entire life of volcanic activity) does not allow for the possibility of a change or waning volcanic time trend. In addition, Ho pointed out that the limited amount of data on volcanic events in the Yucca Mountain area makes justifying a simple Poisson model for calculation of recurrence rate difficult.

Calling a simple Poisson process a homogeneous Poisson process, Ho (1991a) examined the utilization of a nonhomogeneous Poisson process (Ho, 1991b). In this type of model, the recurrence rate, $\lambda$, is no longer assumed constant but is assumed to be changing with time. In the analysis, Ho (1991a, 1991b, 1992) used a nonhomogeneous Poisson process with Weibull distribution (see Appendix A) to estimate recurrence rate from the existing data, which he then combined with a homogeneous Poisson process to assess future disruption. The Weibull distribution assumes the rate of occurrence follows a power law (i.e., is proportional to time to an exponent). By varying the exponent, random (i.e., homogeneous Poisson process), waning, and developing rates of volcanism can be modeled.

Although Ho (1991a) states that data from the Yucca Mountain area are very sparse (a fact also clearly recognized by Crowe et al., 1982), he points out some important results. His time trend analysis of post-6-Ma volcanism near the Yucca Mountain region shows a moderate developing time trend of volcanic activity. He finds a similar trend for the post-3.7-Ma data. Based on these findings, he believes a simple Poisson model would give an oversimplified assessment of the volcanic risk to the proposed repository site. Based on the Quaternary data, which allows a linearized calculation of risk (i.e., probability of at least one major eruption), Ho gives a value of $5.5 \times 10^{-6}$ for the estimated instantaneous recurrence rate for a future window of $10^4$ years or less. He stresses caution in interpreting this probability that based on this value, the estimated risk for an isolation time of $10^4$ years is about 5 percent. However, because of the time trending found in the analysis, Ho (1991a) believes the estimated risk increases to 42 percent if $10^5$ years is the required isolation time. In conclusion, Ho points out his time trend analysis does not completely take into account such possibilities as polygenetic and polycyclic volcanism.

In his most recent work, Ho (1992) determined a value of $1.0 \times 10^{-3}$ to $6.7 \times 10^{-3}$ for probability of a disruptive volcanic event for an isolation time of 10,000 years (C.I. = 90 percent) based on a homogeneous Poisson (random) process similar to that applied by Crowe et al. (1982). Ho (1992) used information on area of the AMRV from Smith et al. (1990) to select the area over which the potential for volcanic disruption was evaluated.

Crowe et al. (1992) used the most current data from site characterization studies to generate revised probability calculations. They now calculate the probability of magmatic disruption using a Bayesian tripartite probability: the product of the probability of volcanism at the Yucca Mountain region, times the probability that the future magmatic event intersects the repository, times the probability that the magmatic disruptions of the repository causes release of radionuclides to the accessible environment. The new calculations of Crowe et al. (1992) use mean values for geologic data, whereas past studies (e.g., Crowe et al., 1982) used conservative data assumptions. Crowe et al. (1992) define conservative data as "numerical assignments that, because of uncertainty in data distribution, are skewed toward estimates which produce a higher level of risk." They believe a conservative approach is useful in creating probability bounds and introduce a bias toward higher probability values.

Crowe et al. (1992) states the primary problem in defining volcanic recurrence rate is the small number of Pliocene and Quaternary volcanic centers in the region of interest: 7 Quaternary centers and 13 to 16 Pliocene and Quaternary centers. They concluded it is impossible to develop and test conceptual or statistical models with this scarcity of data. Accepting the consequences and uncertainty from such a sparse data set, Crowe et al. (1992) discuss the problem of volcanism at Yucca Mountain in relation to three questions: (i) What are reasonable time-distribution models of volcanic events that can be used with the small data set? (ii) Can those models be structured to guarantee not to underestimate volcanic risk? (iii) Can the uncertainty of a small data set be bounded by comparison with analogue studies of more active volcanic fields in the southwestern United States?

To the first question they conclude the simple homogeneous Poisson process is the most direct and reasonable approach to a probabilistic assessment based on a small data set. To the second question they also conclude, whether the volcanic activity is increasing, steady state, decreasing, or complex/chaotic, the simple Poisson models offer the best overall approach, again, given the paucity of data. Crowe et al. (1992) recognizes a Poissonian approach for an increasing recurrence rate may underestimate future recurrence rate, which is not an acceptable forecast of risk. For steady state, a Poissonian approach is appropriate. For decreasing recurrence, the Poissonian approach would overestimate future recurrence, which is acceptable given the risk is still within regulatory guidelines. Finally, they argue that a Poissonian approach to a complex/chaotic pattern of recurrence is more difficult to assess. They point out that if the observation period of the recorded data captures the full range of chaotic behavior (i.e., the limits of the strange attractor) then the range of possible changes is bounded.

For two reasons, Crowe et al. (1992) believe the volcanic activity is either decreasing or chaotic and can be mathematically bounded with acceptable assurance. First, they argue the post-Pliocene time-volume-compositional patterns of basaltic volcanism in the Yucca Mountain region are consistent with a waning system of volcanism. Second, the formation pattern of small volume, spatially isolates basaltic volcanic centers has persisted in the region for almost 10 million years. This period equals and exceed the lifetimes of most basaltic volcanic fields in the southwestern United States.

To the third question they examined data from the Cima volcanic field in California (Mojave Desert) and the Lunar Crater field in central Nevada. From these data they concluded volcanic events are relatively long compared with the isolation period of radioactive waste (10,000 years) and the recurrence rates at the field are reasonable upper bound ($10^{-5}$/year) on maximum rates of volcanic activity in the Yucca Mountain region.

In addition to posing and answering these questions, Crowe et al. (1992) make four conclusions regarding the number of recurrence models and the lack of consensus concerning the most applicable model for different volcanic systems. First, the primary problem is paucity of data. Second, modeling of volcanic events by analyzing the limited data sets may be an oversimplification of the complexity of the systems. Third, generalizing patterns of observation at one volcano or a volcanic system are not easily applied to other volcanoes or systems given the wide spectrum of behavior. And fourth, utilization of nonlinear dynamics analysis (i.e., fractals, chaos, etc.) is appealing and may explain the differences in interpretations of eruption patterns derived from standard statistical approaches.

The basic conclusion of Crowe et al. (1992) is that application of a simple Poisson model is the most reasonable approach to estimating the recurrence of volcanic events in the Yucca Mountain region. In this regard the authors further state that although they have improved and updated their data and calculations, after a decade of considerations there have been no significant changes in the recurrence rate calculations for volcanic events in the Yucca Mountain region. Calculations by other workers (Ho, 1991a) using different approaches were consistent with their results.

### 4.4.3 Other Nonlinear Methods

In addition to nonlinear dynamics and stochastic approaches, there are two other nonlinear approaches that warrant discussions with regard to volcanic recurrences in the Yucca Mountain region. One is self-organized criticality and the other precursor monitoring. Both methods are still being developed and may warrant further evaluation for application at Yucca Mountain.

#### 4.4.3.1 Self-organized criticality

A concept which may be useful in understanding and possibly predicting catastrophic events like volcanic eruptions is self-organized criticality.

Bak and Chen (1991) describe self-organized criticality as a theory that describes how a composite system with many degrees of freedom naturally evolves to a critical state in which a minor event starts a chain reaction that can affect any number of elements in the system. Although composite systems produce more minor events than catastrophes, chain reactions fractal through all sizes are an integral part of the dynamics of these systems. In this theory, the mechanism that leads to minor events is the same one that leads to major events. In addition, the system never reaches equilibrium but instead evolves from one metastable state to the next.

Bak and Chen (1991) further describe self-organized criticality as a holistic theory in which the global features, such as relative number of large and small events, do not depend on microscopic mechanisms. As a result, the global features of the system cannot be understood by analyzing the parts separately. An important element of the theory of self-organized criticality is its relationship to chaos theory. In chaotic behavior, a small initial uncertainty grows exponentially with time. As one attempts to make predictions further and further into the future, the amount of information needed about the initial condition or state also increases exponentially with time. In practice, this exponential growth precludes long-term predictions because of the associated uncertainties.

In contrast with a chaotic system, Bak and Chen (1991) determined the uncertainty in a critically self-organized system grows much more slowly. They found uncertainty grows according to a power law of time, not as an exponential function. They believe the system evolves on the border of chaos and coined the term weak chaos for this behavior. Weak chaos differs significantly from fully chaotic behavior. It lacks a time scale beyond which it is impossible to make predictions and so long term-predictions are possible.

Although self-organized critically is still new and relatively undeveloped, it has been used in a few studies. Bak and Tang (1989) and Bak and Chen (1990) believe that earthquakes are a self-organized critical phenomenon and argue that with further development the method can be used to predict earthquakes. Shaw and Chouet (1991) used the concept to argue their analysis indicating fractal hierarchies in magma transport also indicates an aggregation of scale-independent feedback processes that move the system from metastable state to metastable state, a type of critical self-organization.

#### 4.4.3.2 Precursor monitoring

Aki (1981) unifies various areas of earthquake prediction research using the concept of probability gain. The concept may have application to volcanic eruption predictions. Probability gain is predicated on identifying event-precursory phenomenon. Once the precursory phenomenon is identified, the concept of probability gain is the quantitative change or, equivalently, the increase in prediction capability as a result of the precursory information. For example, if the risk of a large seismic event in a region is normally placed at 1 per thousand years but precursory information (e.g. a marked increase in pre-seismic events) places the risk at 1 per several hours, the probability gain is about $10^6$.

Aki (1981) states probability gain can be applied to long-term, intermediate-term, short-term, and imminent predictions. For many independent precursors, the Bayesian theorem of conditional probability (Aki, 1981) shows that the total probability gain is approximately the product of the individual gains. Along similar lines, Voight (1988) discussed a method for predicting volcanic eruptions. His method is based on using a general nonlinear differential equation which normally describes the behavior of material in the terminal stages of failure to model individual eruptive precursor phenomenon. He applies the approach to a limited sets of precursory data from Mount St. Helens, USA, Bezymyanny Volcano, Kamchatka, Russia, and Mount Toc, Italy. Included were geodetic data (line lengths and tilts), seismic data (magma-activated faults and earthquakes), and data on volcanic debris avalanches and direct-blast volcanism. Using these data with his method, Voight (1988) was able to predict volcanic eruptions only for a period of time not exceeding three months.

## 4.5 SUMMARY

At the beginning of this chapter are a number of key questions regarding relevance and utility of nonlinear dynamics. The literature survey and appendix showed the means, motivation, and benefits of a program to answer these questions and determine if Yucca Mountain volcanism is nonlinear and chaotic. Based on findings of the literature study, the nonlinear dynamics approach can be fruitful and should be continued if expanded along the lines of the guidelines presented in Chapter 5 for the next stages of work.

# 5 DATA ASSESSMENT AND RECOMMENDATIONS

## 5.1 GENERAL ASSESSMENT OF AVAILABLE DATA

The primary technical focus of this literature review is to assess sufficiency of data on, and determine current understanding of, middle to late Cenozoic (< 55 Ma) extensional deformation of the Basin and Range region and spatial and temporal patterns of associated magmatism and volcanism. The impetus for this focus is recent developments in application of space geodetic methods to analysis of present day tectonic deformation. It is now possible to directly measure relative and absolute velocities of precisely located base stations thereby deriving displacements and the contemporary strain field. Certain key questions which can now possibly be addressed more directly using these data are: Is recent to modern volcanism in the Basin and Range region caused by or otherwise directly associated with accumulation of extensional strain? If so, to what extent are eruptive centers influenced by faults and the faulting process, especially active or recently active faults or fault systems? To what extent are eruptive style, frequency, and volume of specific volcanic centers influenced by local finite strain and strain rate?

At this time, available data bearing on association of extensional strain and late Cenozoic volcanism appear sufficient primarily for interpretations and conclusions related to broad, regional correlations between deformation and volcanism. Data in the literature are sufficient to establish general associations of strongly extended terrains (core complexes) with regions of crust which were subjected to roughly syntectonic silicic magmatic intrusion and in some areas subsequent large-volume silicic eruptions.

Strong regional geographic and temporal correlations of late Neogene (6.0 Ma - 1.64 Ma) and Quaternary (< 1.64 Ma) basaltic and silicic volcanism with regions of Quaternary faulting and areas of modern seismic and aseismic strain accumulation are also well-documented. Indeed, Yucca Mountain is situated within a tectonically active corridor of basaltic, and some associated silicic, volcanism, Quaternary faulting and modern strain accumulation. However, regional information on subsurface magmatic processes and magma transport is sparse, and a single, widely-accepted regional tectonomagmatic model does not exist at present.

Considering the Yucca Mountain area specifically, although data exist on location and timing of faulting and basaltic volcanism, volcanic vents are few, structures are not rigorously linked to volcanism, strain partitioning has not been extended to this finer scale, and there is no information on local subsurface magmatic processes and magma transport. Consequently, construction of a tectonomagmatic model for the Yucca Mountain area is as difficult as construction of a more regional model for the Basin and Range. At an even smaller scale, available data from the Yucca Mountain area are sparse and may not be sufficient to establish highly reliable models which can be used to estimate probability of magmatic disruption of a potential repository at Yucca Mountain.

Notwithstanding the paucity of data for the Yucca Mountain area, sufficient data may be available from existing sources to allow useful application of stochastic or nonlinear dynamics methods of data analysis, including chaos theory, that are potentially pertinent to assessing patterns of volcanism in the Basin and Range and at Yucca Mountain. If specific select localities characterized by late Cenozoic (< 6.0 Ma) and particularly Quaternary volcanism in other parts of the Basin and Range are analyzed as analogs for possible patterns of basaltic volcanism, results may be used for understanding patterns of volcanism at Yucca Mountain. However, it must be understood that nonlinear dynamics approaches (e.g., determination of attractor characteristics of observational data) generally require numerous data points. Also, compilation and assessment of absolute age dates of volcanic rocks from eruptive events at the select localities will be required to determine whether a sufficient number of data points exists for effective time series (stochastic) analyses of the events.

The initial focus of this review was to examine literature on volcanism and tectonics throughout the entire Basin and Range region for the entire period of regional extensional deformation (about the last 55 Ma). Based on results of this review, it is recommended that data compilation be concentrated on the region comprised by the trends of coincident Quaternary volcanism and faulting along the western margin of the central Basin and Range region.

Considering the general paucity of existing data on volcanism in the Yucca Mountain area (because the number of discernable eruptive events is small) and the regional concerns stated above, the following information provides guidance for directing future efforts in remaining tasks of the Volcanism Research Project.

## 5.2 SILICIC VOLCANISM AND CALDERA SYSTEMS

Yucca Mountain consists of a sequence of (silicic) ash flow tuffs erupted from the (Miocene) Timber Mountain caldera complex between about 16 - 9.5 million years ago. Regionally, Yucca Mountain is part of a highly-extended core complex system that includes Yucca Mountain, Crater Flat Valley, Bare Mountain and the Bullfrog Hills. Yucca Mountain is locally situated in a relatively weakly extended part of this system. Extension is about 10-12 percent across the north end of the mountain and up to 60 percent at the south end, while extension across the Bullfrog Hills segment of the system ranges from 100 to 275 percent locally. Most of the fault slip at Yucca Mountain accumulated from about 14 Ma through the Quaternary into the Holocene. Initiation of the Yucca Mountain extensional fault system is approximately synchronous (starting about 13 Ma) with eruption of the Timber Mountain caldera complex, although numerous faults in the Yucca Mountain area have experienced Quaternary displacement.

Throughout the Basin and Range, large-volume silicic ash flow systems, such as the Timber Mountain system, are not exclusively or simply associated in time or space with localized areas of large-magnitude (core complex) extension. However, large-volume regional intrusion of magma into the crust may be necessary to provide heating and resultant increased ductility of the middle and lower crust, thereby allowing development of highly-extended terrains (i.e., core complex type extension systems). Strongly extended core complex systems are geographically broadly coincident with regional-scale magmatism.

Magma intruded into the lower and middle crust during Neogene extension of the Great Basin region was erupted during core complex extension in some areas. However, plate margin and subcontinental mantle conditions related to both geometry and rate of tectonic plate deformation suitable for widespread silicic magmatic arc volcanism during the Neogene (23 Ma - 1.6 Ma) appear to have fundamentally changed to conditions less conducive to large-volume silicic melt generation within the central Basin and Range region. That is, the convergent subduction dominated margin required for widespread arc magmatism has been replaced by a transform margin evidenced by evolution of the San

Andreas fault system. Modern subduction related arc magmatism in the western United States is largely restricted to latitudes north of the Mendocino triple junction (i.e., the Cascade Range).

### 5.2.1 Recommendations Related to Silicic Volcanism

Compilation of data on silicic eruptive centers should be focused on temporal evolution, eruptive style and volumes, composition, and tectonic setting of late Neogene and Quaternary complexes within selected regions of Quaternary (especially Holocene) faulting, extensional strain, basaltic volcanism, and modern strain accumulation in the Basin and Range region. Special attention should be given to volcanic complexes for which Quaternary, particularly Holocene, silicic volcanism is synchronous with or postdates basaltic eruptions. It has been determined from this literature review that an appropriate tectonomagmatic domain for this focused data compilation is the north-northwest-trending Mojave-Death Valley-Sierra Nevada-Central Nevada tectonic corridor.

It is further recommended that a relatively decreased level of effort be applied to compilation of data on the silicic eruptive systems that are older than about 6 Ma. Compilation of data on silicic systems associated with Neogene core complex extension throughout the Basin and Range should be a secondary focus at this time because ages and temporal relationships between volcanism and extensional deformation are not resolved at scales immediately useful to assessment of potential recurrence of volcanism at Yucca Mountain. Furthermore, it is anticipated that compilation of data on silicic centers older than 6 Ma would reinforce the concept that silicic volcanism was an early stage of volcanic development in extensional terranes of the Basin and Range which was followed by bimodal and basaltic volcanism.

## 5.3 BASALTIC VOLCANISM

Small-volume basaltic volcanic fields, including cinder cones, spatter cones, lava flows, and associated fissure and dike systems, largely characterize the Quaternary eruptive style of most of the Basin and Range region, and particularly the central Basin and Range (i.e., the southern Great Basin) which encompasses the Yucca Mountain area. Quaternary basaltic volcanism correlates well with the regional linear trend of modern strain accumulation, earthquake seismicity, and Quaternary faulting comprised by the combined Mojave shear zone, greater Death Valley-Owens Valley Fault system, the faulted eastern flank of the Sierra Nevada Range, and the central Nevada seismic belt. Quaternary basaltic and associated silicic eruptive complexes are geographically associated with seismically active fault zone trends within the Mojave shear zone-Owens Valley Fault system. Within Crater Flat at Yucca Mountain and adjacent to major fault-bounded range blocks (Reveille-Pancake Range and Fishcreek Range) in interior regions of the Great Basin, basaltic eruptive centers are geographically coincident with Quaternary fault zones or trends of fault zones. However, data available in the literature may not be sufficient for developing useful models of structural control of basaltic magma eruptions applicable directly to Yucca Mountain.

### 5.3.1 Recommendations Related to Basaltic Volcanism

Review of the literature has not yielded sufficient data on ages and styles of faulting and volcanism, genesis and migration of magma, and coupling of faulting and eruption processes to rigorously model or forecast recurrence or behavior of specific Quaternary basaltic eruptive complexes either in the

Basin and Range Province or in the Yucca Mountain area. A compilation of data focused on specific local-scale eruptive complexes is needed.

Consequently, recommendation is made to compile data on specific Quaternary eruptive complexes from the region of the north-northwest-trending Mojave-Death Valley-Sierra Nevada-Central Nevada tectonic corridor. This focused compilation will collect information bearing specifically on tectonic setting, geodetic strain measurements, and structural control of eruptive centers, as well as geophysical, geochemical, and geochronological data, for a suite of selected Quaternary (primarily basaltic) eruptive complexes. Special attention will be given to eruptive complexes active through the Holocene. This compilation would concentrate on materials acquired and reviewed for Task 1, with new material being reviewed and incorporated as required. Therefore, Task 2 (Data Compilation) of this research project should focus on compilation of data on age, composition, eruptive style and volumes, surface and subsurface distribution and geometry of feeder-dike systems, tectonic setting, and strain history of selected Quaternary (especially Holocene) basaltic eruptive centers in this tectonic corridor. It is anticipated that compilation of data on basaltic volcanism will assist with analysis of regional relationships between extension and basaltic magmatism and local relationships between extensional faulting and basaltic vents. These data can be used to assess petrologic evolution and longevity of aligned volcanic vents, and may provide information for understanding more about vent alignments in the Yucca Mountain area. Based on these data, it may be possible to begin development of preliminary models concerned with spatial and temporal patterns of volcanism in the Basin and Range which can be used to understand patterns in the Yucca Mountain area.

In addition, comparison of patterns in evolution of aligned vents and longevity of those vents between locations in the tectonic corridor and other areas affected by extensional tectonism may be useful for assessing evolutionary history of vent alignments which can be applied at Yucca Mountain. Alternatively, vent alignments may prove to have evolved differently in different basaltic fields. Regional vent alignments such as those discussed by Connor et al. (1992) in the Springerville field of east central Arizona (marginal Colorado plateau) are characterized by complex histories of volcanic activity with long periods of quiescence and petrologic affinities which are not easily related to simple magmatic fractionation models. Although preferred vent alignment in this field may be related to extension resulting from uplift of the Colorado Plateau, and to a lesser extent to Basin and Range extension (Connor et al., 1992), this location still may be useful for comparison of vent alignment patterns and assessment of magmatic and volcanic processes because considerable data on structural control of the field already exist.

## 5.4 TECTONOMAGMATIC ANALOG FOR YUCCA MOUNTAIN

A carefully chosen natural tectonomagmatic analog of the Yucca Mountain area would be of significant value in understanding geometry, distribution, relative timing, intrusion processes, and near-field environmental effects (thermal alteration, structural deformation, hydrologic effects) of magmatic systems that feed basaltic eruptive complexes.

### 5.4.1 Recommendations Related to a Tectonomagmatic Analog

It is recommended that areas be identified within the Basin and Range Province that are similar to Yucca Mountain in overall late Cenozoic tectonic setting and magmatic evolution. Potential areas of interest would be mountain range-scale fault blocks within the Death Valley region that have been tectonically uplifted and eroded deeply enough to reveal the magmatic plumbing system. These areas would allow detailed examination and description of the pattern of dikes intruded below correlative eruptive features as well as a view of how the dike systems interact with faults in the subsurface. If appropriate data already exist for potential analog areas, it is anticipated that conceptual tectonic models based these data may shed additional light on processes of magma intrusion, eruption and fault control applicable to Yucca Mountain. Based on these data, it may be possible to begin development of preliminary models for magma genesis and transport in the Basin and Range.

## 5.5 APPLICATION OF NONLINEAR DYNAMICS AND CHAOS THEORY

The existing volume of absolute age data for Quaternary eruptive events throughout the central Basin and Range appears insufficient for anything but a stochastic analysis, and even that approach may be questionable given sparseness of data for the Yucca Mountain area. If a nonlinear dynamics approach is to be directly applied to Yucca Mountain, a larger volume of data is necessary. Compilation of data from specific eruptive centers and tectonomagmatic analog areas of the Basin and Range as previously discussed provides a means of expanding the database, potentially to a size large enough that nonlinear dynamics approaches (and perhaps more detailed stochastic time series analyses) may be applied.

Self-similarity may be used to relate data compiled over a larger, regional-scale area to the more local scale of the Yucca Mountain area. That is, a fractal dimension may be found relating spatial and temporal volcanic eruptive histories and extensional deformation histories at various regional scales for a suite of specific eruptive locales distributed over a wide region. A characteristic regional fractal dimension could then be applied across temporal and spatial scales to the Yucca Mountain area to determine factors like expected evolutionary trends of volcanism (developing, waning, random, or extinct) in the Yucca Mountain region. In addition, a large data volume could be analyzed for attractor characteristics. These analyses may make it possible to determine whether repose periods on the order of those at Yucca Mountain are compatible with continuous or intermittent chaotic behavior.

There appears to be two basic data types that may be available in sufficient volume to analyze for chaotic behavior (i.e., for occurrence of a strange attractor). Analyses of compositional and geochemical characteristics of volcanic rocks may reveal chaos in individual or tectonically-domained magmatic-eruptive systems. Initially, iterative and phase-space mapping of time-series geochemical data for individual flows within complexes or from suites of complexes within selected tectonic domains would be an appropriate exploratory approach. It is not clear whether the available data are suitable for such an approach. Also, analyses of earthquake seismic data may reveal chaos in the overall tectonic system.

At this time, searching for chaotic behavior of the late Cenozoic to modern tectonic-magmatic system of the Basin and Range is strictly an exploratory exercise. Furthermore, it is not clear how this knowledge may impact assessment of recent and future volcanism at Yucca Mountain. It may be that the most which can be accomplished with chaos theory is a determination that the tectonomagmatic system is or may have been chaotic. Direct application of chaos methods to estimation of magmatic recurrence may not be possible. However, an indication of chaotic behavior should be considered as an important condition with respect to use of probabilistic methods for assessing likelihood of volcanic and magmatic activity and probability of magmatic disruption of a repository at Yucca Mountain.

### 5.5.1 Recommendations Related to Use of Nonlinear Dynamics or Other Methods

Geochronological, compositional, and geochemical data on Quaternary basaltic, and associated silicic, eruptive centers compiled for tectonic-magmatic correlations should also be analyzed for chaos and fractal statistics. This approach may reveal temporal-spatial patterns of volcanism applicable to Yucca Mountain. In addition, it is recommended that the earthquake seismicity time series recorded throughout the Basin and Range, and specifically by the Southern Great Basin Seismic Network in the Yucca Mountain region, be analyzed for chaos and spatial clustering of hypocenters be examined for fractal statistics. The purpose of these analyses is to look for indications of chaotic behavior in the tectonic-magmatic system.

A substantial conceptual problem in analyses of natural systems for chaos is that observational data give an incomplete and uncertain view of the total system. The extent to which eruptive history is representative of total magma system dynamics is probably an important consideration. Therefore, it is also recommended that a theoretical (mathematical) model of magma intrusion and eruption be developed to determine dynamic characteristics necessary for a volcanic system to generate a chaotic eruptive history and what the important temporal and spatial scales may be. A reasonable theoretical model may indicate the dynamic conditions (e.g., magma and heat flux) and time periods required for a volcanic system to maintain a chaotic regime, or whether equilibrium processes (i.e., energy dispersion and attenuation) may dominate at time scales indicated by field data.

Self-organized criticality is still a new approach to understanding system dynamics. It may prove fruitful and should be investigated especially in light of an expanded regional data set as was discussed. Again, direct application of this approach to assessment of recent and future volcanic eruptions specifically at Yucca Mountain is problematic. Indeed, it is not at all clear how to analyze complex natural systems with sparse data for self-organized criticality. However, as with chaos, it seems probable that existence of this type of dynamic behavior would be an important condition to be considered in application of probability theory. Consequently, it is recommended that data compiled for analyses of magmatic and tectonic correlations also be examined for this type of dynamic behavior. The analyses of correlations should be facilitated by looking at data from volcanic fields in similar tectonic settings where large numbers of eruptive events have occurred and large geochronological and geochemical data bases already exist. The San Francisco volcanic field of central Arizona may be an amenable location since more than 600 volcanic vents are located there (Tanaka et al., 1986).

## 5.6 SUMMARY STATEMENT

The general conclusion drawn from this literature survey is that middle to late Cenozoic ($<$ 55 Ma) volcanism in the Basin and Range region is broadly correlative with extensional strain in both time and space, although there is as yet no single, universally accepted, regional tectonomagmatic model for quantifying this correlation. Also, this review of pertinent literature did not determine immediately useful relationships between Quaternary volcanism, extensional tectonic strain, and concomitant faulting at time and space scales (0.01-0.1 Ma, $10^2$-$10^4$ km$^2$) appropriate for assessment of magmatic hazard at Yucca Mountain. Although the current literature review does not determine definitive local-scale relationships between Quaternary volcanism, strain, and faulting, the regional-scale correlations are strong and support the following recommendations for local-scale focus of data compilation.

Due to strongly diachronous occurrence and uncertain age determinations of episodes of associated Neogene volcanism and extensional deformation at the scale of the entire Basin and Range region, compilation of data from the entire Basin and Range region is not considered the best approach at this time. Also, data from the literature suggest plate tectonic and crustal-scale magmatic and structural conditions extant during the period of large-magnitude, Neogene extension and silicic volcanism are no longer operative for the central Basin and Range region. Although Neogene (23.3 Ma - 1.64 Ma) silicic eruptions are broadly correlative with strongly extended regions within the Great Basin, data from recent literature do not establish definitive cause and effect relationships between Neogene extensional strain and large-volume, caldera-forming silicic eruptions. Consequently, an exhaustive study of available literature and data on Neogene and older silicic volcanism in the Great Basin will probably not yield significant insight applicable to assessment of recurrence of volcanism in a specific location such as Yucca Mountain.

This literature review identifies an appropriate tectonic-magmatic domain — the north-northwest-trending Mojave-Death Valley-Sierra Nevada-Central Nevada tectonic corridor — within which to conduct a more focused data compilation. An approach is recommended to concentrate data compilation on specific episodes of volcanic eruption within this tectonic corridor that are similar in style and age to late Neogene (approx. 6.0 Ma - 1.64 Ma) and Quaternary (< 1.64 Ma) volcanism at Yucca Mountain. Yucca Mountain is located in this corridor which may be absorbing a large proportion (8-10 mm/yr) of the Pacific-North America relative motion that is distributed east of the San Andreas Fault. Quaternary volcanism within this corridor is largely basaltic but silicic and basaltic volcanism occur in complexes associated with the Owens Valley-Sierra Nevada zone of faulting. Therefore, continued study should focus on late Neogene (approximately 6.0 Ma - 1.64 Ma) and Quaternary (< 1.64 Ma) volcanism, both silicic and basaltic, and correlative recent tectonics.

Accordingly, it is concluded from this literature review (Task 1 of the Research Project on Volcanism in the Basin and Range) that the data compilation phase (Task 2) should be focused on description and characterization of individual eruptive complexes in the age range of 6.0 Ma to present, within the Mojave-Death Valley-Sierra Nevada-Central Nevada tectonic corridor. Specifically, data pertaining to temporal evolution, eruptive style, magma genesis and movement, and tectonic setting should be compiled for computer-assisted mapping and correlation. Special attention will be given to correlation of Holocene (< 0.01 Ma) eruptive centers and modern, geodetically determined, crustal strain and faulting. This data compilation will provide a basis for assessment of variations in temporal and spatial patterns of volcanic eruptions in the tectonic corridor, and may provide information useful for assessing likelihood of volcanic activity in extensional terranes. Comparison of data from the corridor and from other volcanic fields in similar tectonic settings may also be useful for understanding the significance of the variations and for aiding interpretations of temporal and spatial patterns of volcanism in the Yucca Mountain area. This comparison with other volcanic fields where considerable data exist may help to derive the common aspects of vent distribution, repose periods, and petrologic evolution of basaltic volcanic fields.

Compiled and integrated data of the variety and volume necessary to determine tectonomagmatic relationships at the scale of individual eruptive complexes and synoptic views of all available data do not exist at appropriate temporal and spatial scales in the literature. Consequently, these data must be collected from the available literature, compiled into databases, and plotted together on common base maps. After compilation, plotting, and appropriate review and analysis of the maps produced, additional judgments can be made about sufficiency of available data for assessing likelihood of occurrence of volcanism at Yucca Mountain. It is considered that the suggested approach should prove fruitful for fulfilling this goal. The literature search and acquisition of materials for this literature review has resulted in identification and collection of most key references needed to conduct a focused review and compilation of pertinent data.

In connection with analytical treatment of coupled crustal-scale tectonism and magmatism as a discrete nonlinear system, compilation of a sufficient amount of data may make it possible to analyze selected data types for strange attractor and fractal characteristics. It is recommended that data compiled for Task 2 of this project be analyzed for attractor and fractal properties during Task 3 data analysis and that these data be used directly to constrain theoretical tectonomagmatic models of magma intrusion and eruption developed in subsequent Task 4 modeling. The data and the models should provide important input for performance assessment analyses in relation to volcanism, magmatism, and tectonism. It is anticipated that this input will include information related to spatial and temporal patterns of volcanism and definition of disruptive scenarios for volcanism and magmatism.

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# APPENDIX A

# DYNAMICS, CHAOS, FRACTALS, AND STOCHASTICS

# APPENDIX A
# DYNAMICS, CHAOS, FRACTALS, AND STOCHASTICS

## A.1 DESCRIPTION

This appendix presents a summary of pertinent topics in dynamics, chaos, fractals, information theory, stochastics, and related subjects. Aspects of these topics are used, but not explained, in Chapter 4, and the intent of this appendix is to give an explanation of these topics to make this report self-contained.

Treatment of topics in the appendix has been maintained at a general level. Articles and books with additional explanation are cited herein or can be found in the bibliography of Appendix B. The recent text by Turcotte (1992) and the short course notes from the Geological Association of Canada (Middleton, 1991) are of particular interest for nonlinear dynamics in the geosciences. Of more general interest, not necessarily directed toward the geosciences, are publications by Crutchfield et al. (1986), Devaney (1990), Gleick (1987), Hofstadter (1991), Lauterborn and Parlitz (1988), May (1976), Moon (1987), Peitgen and Richter (1986), Rasband (1990), and Ritman (1989).

Excluding this descriptive section, there are nine sections on the following topics:

- Dynamics — basic concepts
- Chaos
- Fractals
- Stochastic methods
- Chaos and fractals
- Chaos and information theory
- Chaos and recorded data
- Chaos or stochastics
- Conclusion

The first four sections (A.2–A.5) are independent tutorials. The next four sections (A.6–A.9) examine some implications and intricacies of chaotic dynamics. The final section (A.10) provides brief concluding remarks.

## A.2 DYNAMICS — BASIC CONCEPTS

### A.2.1 Introduction

Dynamics is that branch of mechanics that deals with energy, forces, bodies, and the resulting movement or changes. Conceptually, a dynamicist attempts to understand the state of a system from the causes and effects producing development, evolution, or changes of the system with time. Heuristically, dynamics consist of two parts (Crutchfield et al., 1986): the state or essential information about a system and a dynamic or rule(s) describing how the state evolves with time. In this context, chaos is one class of states in which some systems can exist.

A dynamic system is defined as any entity, body, grouping of particles or bodies, piece of a body, continuum, etc. whose evolution, change of state, movement, development, etc. is of interest. In the study of a dynamic system, time may be viewed either as a continuous or a discrete variable.

### A.2.2 Types of Studies

For categorization relevant to this study, dynamics can be divided into two general classes: theoretical and laboratory studies, and field studies. Although the distinction between these classes is obvious, it is worth discussing since the distinction also categorizes capabilities, benefits, and utilities of the studies. For example, in field studies, natural systems are evaluated for seeking ground truth, but are frequently limited in data. System access is usually restricted, and enough data cannot be extracted to develop a picture of the system as complete as that from controlled theoretical and laboratory studies.

For theoretical studies, an attempt is made to understand a particular system by formulating and investigating mathematical relationships that describe salient features of the system. For laboratory or field studies, researchers both monitor and record system data and then interpret the data to understand the system. The critical difference between laboratory and field studies is the availability and accessibility of useful data. Theoretical and laboratory studies are designed to generate the requisite data for as complete a picture of the system as possible. Field studies are also so designed, but are limited to data supplied by nature, which may not be sufficient to draw a complete picture.

In practice, successful studies combine both theory and field data. Understanding the behavior of a system usually means using the measured data to determine parameters that are explicit in a theoretical model. However, the capacity to use data to uniquely determine physical parameters or fit a model is not always possible. Understanding the limitations and accessible information content of data — its invertability, interpretability, and its uniqueness — is very important.

In field studies, many of the real systems are extremely complex. Many, and perhaps all, of the parameters needed to understand the system cannot be accurately measured either directly or indirectly. For example, in the study of a volcanic-magmatic system, most investigations are undertaken at or near the surface, and only data manifest there can be obtained. Consequently, the system is probably under-sampled. Part of the reason for careful design of field studies and analysis of data is to overcome these limitations.

### A.2.3 Definitions

Following is a list of definitions of certain terms and concepts which occur in nonlinear dynamics.

#### A.2.3.1 Degrees of Freedom

Degree of freedom is essentially the number of parameters needed to completely describe a particular type of behavior of the system. Degrees of freedom represent the individual avenues of behavior available to the system. For example, if one wishes to study the change in configuration of a body of $N$ particles, then $3N$ parameters (e.g., the $3N$ Cartesian coordinates) are required. If the system behavior is somehow constrained and the constraints are represented by $M$ equations, then the number of degrees of freedom of this system is reduced to $3N-M$.

If the parameters chosen to describe system behavior represent the minimal number of parameters needed (i.e., the $3N-M$ discussed above), the family of parameters is termed generalized coordinates or state variables. Frequently, generalized coordinates are not limited to the location coordinates, but, depending on the system, may include characteristics such as momentum, energy, temperature, permeability, porosity, and time intervals.

For a complex system, like a volcanic-magmatic system in which solid and fluid dynamics, thermodynamics, chemical dynamics, material behavior, and other factors are involved, the number of state variables and their interrelationships become very large, essentially approaching infinity, and very complicated. To study this type of system one tries to reduce the number of degrees of freedom by considering only the most salient elements of behavior. As will be discussed later, the lower the number of degrees of freedom of a system, the higher the capacity for predictability of development of that system.

### A.2.3.2 Linear Versus (Nonchaotic) Nonlinear Dynamics

Although all natural systems are treated as either linear or nonlinear, no real system is purely linear: all natural systems possess factors which make them nonlinear to some degree. However, many systems can be very effectively approximated as linear, which makes solutions of these systems substantially easier. The definition of linearity of a system is borrowed from a concept in differential equations called superposition. Superposition states that if $S_1$ and $S_2$ represent two solutions to a linear differential equation, then $\alpha(S_1 \pm S_2)$, where $\alpha$ is an arbitrary constant, is also a solution for all $\alpha$. The same is true for a linear physical system. The sum, difference, etc. of possible states of a linear system are possible states. An example is an idealized simple pendulum. If $S_1$ is the solution (i.e., amplitude of oscillations) for one force, $F_1$, and $S_2$ is the solution for a second force, $F_2$, then the force $F_1 + F_2$ gives a solution $S_1 + S_2$.

The same is not true for nonlinear systems, either chaotic or nonchaotic. The combinations or superpositions of solutions for nonlinear systems are not necessarily system solutions. This concept is important since it implies that nonlinear systems are much more difficult to characterize and understand. Nonlinearity is particularly important since it is a necessary prerequisite for chaotic behavior.

For later reference, we introduce a theoretical concept regarding solution characteristics of linear and nonlinear systems. The generalized coordinates and associated generalized momentum (i.e., the time derivative of the generalized coordinates) of a system can be plotted on a multidimensional graph, called a phase-space plot, where each pair of axes of the graph corresponds to one pair of generalized coordinates. This type of plot results in the multidimensional equivalent of a trajectory which describes the evolution of a system. As will be discussed later in greater detail, this trajectory is called an attractor. Any point of this trajectory represents the complete state of the system at a certain time and may represent the initial state of the system when an investigation was begun. For a linear system, distance between any two or more points on this trajectory remains a constant or goes to zero as the system evolves. The same is true for nonchaotic nonlinear system trajectories: two points remain at a fixed distance or get closer as the system evolves. As will be discussed, for chaotic nonlinear systems the attractor points separate or diverge at an exponential rate, stretching the attractor. This is a crucial characteristic of chaotic behavior.

Chaos in a system requires a number of factors, one of which is nonlinearity. A linear system cannot become chaotic. The requisite nonlinearity necessary for chaotic dynamics can arise in a number of different ways (Moon, 1987):

- Kinematics — for example, convective fluid acceleration and turbulence, Coriolis and centripetal accelerations

- Constitutive relations — for example, nonlinear stress-strain relationships

- Boundary conditions — for example, free surfaces and bound surface interactions with fluids

- Nonlinear body forces — for example, magnetic or electric forces

- Geometric nonlinearities associated with large deformations in solids — for example, plasticity and fracturing

With the exception of nonlinear body forces, each of these effects can be present in a volcanic-magmatic system.

#### A.2.3.3 Deterministic and Nondeterministic Systems

Two important issues of determinism and nondeterminism are predictability and reliability of predictability of future system behavior. As the name implies, a deterministic system is one in which the behavior or evolution of the system can be precisely predicted or simulated to an acceptable degree of accuracy through a set of mathematical relations. By stipulating a set of initial conditions and mathematical relations, future behavior can be theoretically stipulated for all time. Typically, relations are used to synthesize or predict data, which then simulate measured data to the accepted degree of accuracy if measurements can be made. The mathematical relations are a model of the system.

A nondeterministic system is one in which prediction of future behavior cannot be specifically stipulated. Typically, this is a result of having too many degrees of freedom or equivalently nondeterminable generalized coordinates or an intrinsic random character to the system. The best, and perhaps only, approach here is a stochastic, or time-based, statistical approach in which measured data are assumed to follow a probability distribution. The distribution is then used as a basis for a probabilistic prediction of future behavior.

The concept of chaotic behavior of a system falls between the implications of determinism and nondeterminism. Chaotic systems may be called semi-deterministic. In theory, chaotic systems are deterministic, but nonpredictable or semi-predictable. In practice, only a small number of natural systems can be modeled theoretically and, hence, are deterministic. Most chaotic systems cannot be modeled and must be understood by analyzing complex data sets.

The term semi-predictable means that if a chaotic system can be modeled with exact, mathematical relations (usually differential equations), then these relations cannot synthesize data that continue to accurately describe or predict the system as it evolves. Depending on the system, equations may be used to make short-term predictions. However, these predictions will begin to diverge and continue to diverge from actual system behavior. The only way to continue predicting is to abandon the original prediction, record more system data, and reformulate a subsequent prediction based on the new data (i.e., new set of initial conditions). This scenario must be repeated to maintain predictability. The continued divergence of system states represents the creation of new system states as time increases (i.e., the continued separation of points on the system attractor) and is one characteristic that uniquely identifies a system in chaos.

#### A.2.3.4 Autonomous and Nonautonomous Systems

One important distinction in dynamics is the one between autonomous and nonautonomous systems. An autonomous system is one in which real time is not an explicit function of the data (synthetic or real) describing the system. An example is an experiment in which the time between drips of a faucet are measured (Shaw, 1984). Here real time was not a factor. A nonautonomous system is one in which time is an explicit parameter of the system behavior. In mathematical terms, an autonomous system involves relationships in which time does not appear explicitly but may be implicit. For a nonautonomous system, time appears explicitly.

#### A.2.3.5 Hamiltonian and Dispersive Systems

Another way of categorizing dynamics systems is based on what happens to the energy of the system as a function of time. If the system has energy absorption mechanisms, the system is termed dispersive. In reality, all systems are dispersive (i.e., they are not perpetual motion machines). If, however, energy absorption mechanisms are insignificant, as in the motion of the planets around the sun, then the system is called a Hamiltonian system. This distinction is quite significant since the dynamics of a Hamiltonian system can continue indefinitely, while the dynamics of a dispersive system must have an infusion of energy to continue.

Without continued energy infusion, a dispersive system will grind to a halt. Energy infusion and dispersion rates are very important aspects of ascent to and maintenance of chaotic behavior.

### A.2.4 Basic Modeling Methods

Mathematical analysis and models of dynamic systems generally take one of three forms: (i) differential equations, frequently called flows; (ii) discretized or difference equations, frequently called maps; and (iii) symbolic equations. Symbolic equations are not applicable here and will not be discussed.

A differential equation description of a system is a theoretical description of system dynamics. It usually means that the system can be viewed as continuous in either or both space and time, and the variations in space and time can be mathematically modeled by continuous evolution implied in a differential equation. For some systems, the differential equations can be solved to give closed-form solutions comprised of known or well-tabulated mathematical equations. For deterministic systems, the solutions coupled with a set of initial conditions describe or equivalently predict exactly the evolution or flow of the system.

For most nonlinear systems, the differential equations cannot be solved in closed form and can only be approximated. This is usually done with a discretizing scheme (e.g., finite difference, finite element, boundary element methods) which results in a mapping. Typically, a mapping gives the values of system parameters at a particular time and location based on values from previous time and neighboring locations. The mapping evolves by iterating. Once the present values of the system are found, they become the previous values and are put in the mapping scheme for the next iteration to determine the next set of values.

If the system or the data set being modeled is nonautonomous, the iteration step will most likely involve time. If the model is autonomous, time will not be explicit. In either case, an important aspect of the mapping (and flows, in general) is the amount of information about the present state of the system being transmitted to the next state with each iteration. It is important to understand that even though a mapping (or flow) is deterministic, its prediction capability is very much involved with the amount and state of new information (i.e., new states) which the system generates as it evolves.

Besides use in theoretical settings, mappings are a central aspect of the analysis of experimental data. Mapping experimental data and examining the trajectory is one means of identifying categories and characteristics of the behavior of the system. For example, if a system is being investigated and only one parameter, $X$, is or can be recorded, then a common mapping is to create a plot in which the $(n+1)$th data point, $X(n+1)$, is plotted against the $n$th data point, $X(n)$, for the entire volume of data recorded. This type of plot is something like a phase diagram and is discussed in the next section. In this type of plot, the shape of the resulting trajectory indicates how the $n$th state is related to or affects the $(N+1)$th state. The nature, strength, and quality of the relationship between $X(N+1)$ and $X(n)$ is indicative of the type of evolution of the system. For example, if the system is random, then there will be no definite relationship and the data will be scattered. If the relationship is deterministic, the resulting trajectory will be a well-defined curve. If the behavior is chaotic, the relationship will be fractal. Specifically identifying the relationship for a limited data set can be a very difficult problem.

Although an $X(n+1)$ versus $X(n)$ plot may describe the system, if the system is nonautonomous, the time interval between the $n$th and the $(n+1)$th data point may not have been gratuitously chosen to give the best and clearest picture of the evolution of the system. For example, if the system is evolving at a rate commensurate with the monthly cycles of the moon, recording data once a minute and plotting$X(n+1)$ versus $X(n)$ will not give much information. Sometimes a clearer picture can be derived if $X(n)$ is plotted against $X(n+m)$ where $m$ is an integer greater than one. As will be discussed later, this is part of an embedding analysis and is a very important method for determining if a data set indicates that a system is chaotic.

### A.2.5 Phase Space, Attractors and Poincaré Plots

In the study of dynamic systems, phase-space diagrams are a very useful tool for understanding the characteristics of system evolution. They are one of the best and most common means of describing the time-based evolution of the system.

Assume that a system is characterized by $N$ generalized $x_i$ coordinates. Each generalized coordinate has a first-order time derivative, $\dot{x}_i$, which is called the conjugate or generalized momentum. If $x_i$ is a position, then strictly speaking, $\dot{x}_i$ is the velocity. A plot which pairs $x_i$ coordinates to their first-order time derivative $\dot{x}_i$ is called a phase-space plot or a phase plot. Phase-space plots can vary from two-dimensional to multidimensional depending on the system being studied, but each degree of freedom of a system produces two dimensions of a multidimensional plot. It is possible for a system, specifically a chaotic system, to have half degrees of freedom. Hence, phase-space plots do not need to have even dimensions. Strictly speaking, a phase-space plot involves position and velocity (or momentum). The term is also used loosely by some authors for any space defined by a set of state variables related by first order differential equations. If the variables are not those of position and velocity, such a space should be more properly called a state space. In this appendix, phase space will be used for both phase and state space.

For an example of a phase plot, consider a simple pendulum with small amplitude oscillations. Here the generalized coordinate is the position relative to the resting location, and the generalized momentum is the associated velocity (i.e., the time derivative of position). If the pendulum is dissipative, and it was given an initial push and left alone, its motion dampens to zero, and the phase plot gives a trajectory that is a curve which spirals down to a single point at the origin. The single point to which the system moves is called a fixed or equilibrium point and represents a state in which the system will remain unless forced out. If the system is Hamiltonian (i.e., nondissipative) then motion maintains its periodicity, and the phase plot trajectory of this pendulum is an ellipse centered about the origin (see Figure A-1).

In classic dynamics (i.e., nonchaotic) there are three types or categories of dynamic behavior of a system: (i) equilibrium motion, (ii) periodic motion or limit cycle motion, and (iii) quasiperiodic motion. Each is characterized by a unique and specific set of points or trajectory in phase space. The term for this trajectory is an attractor. Attractor is used because, after any transients of the system die out, the trajectory is that locus of states to which the system tends or is attracted in the course of its dynamic evolution. In its most common use in dynamics, the term attractor implies the state to which a dissipative system tends to converge.

As stated, each type of dynamic behavior has a specific type of attractor geometry. The attractor of an arbitrary linear system with one degree of freedom in equilibrium motion is a single point. The two-dimensional attractor for periodic motion is a circle or ellipse. Limit cycle motion is similar to periodic motion. In periodic motion, the motion in phase space is on the attractor. In limit cycle motion, the system moves toward the attractor as the limit of its motion, and the attractor is a closed curve, a circle, or ellipse, as in periodic motion.

Quasiperiodic motion or almost periodic motion must be characterized in a minimum of three dimensions, and its attractor trajectory is a spiral which appears to be wrapping around a toroid (i.e., a doughnut). As an example, quasiperiodic motion occurs in a system with a natural period of oscillation and a driven period of oscillation. If the ratio of these two periods is irrational, then the two periods compete, and the motion will never be truly periodic quasiperiodic. The important feature of quasiperiodic motion is, in spite of its complexity, it is predictable.

All the classical attractors have common characteristics. Close orbits remain close to one another. Small errors or inaccuracies remain bounded. The behavior is predictable; although, if the system is very complex and has many degrees of freedom, its predictability may be purely academic and its interpretation may require a stochastic approach. Like classical motion, chaotic motion has an attractor. It is called a strange attractor, and it has totally unique characteristics that distinguish it from classical attractors. (Refer to section A.1.3.4 for additional information on strange attractors.)

A concept that is very much a part of phase diagrams and attractors is the Poincaré plot or section. A Poincaré plot is a group of points on an attractor sampled at discrete time intervals, like a stroboscopic recording. It is a means of simplifying an attractor trajectory, especially for a system with many degrees of freedom. Conceptually, a Poincaré plot is created by placing a two-dimensional plane

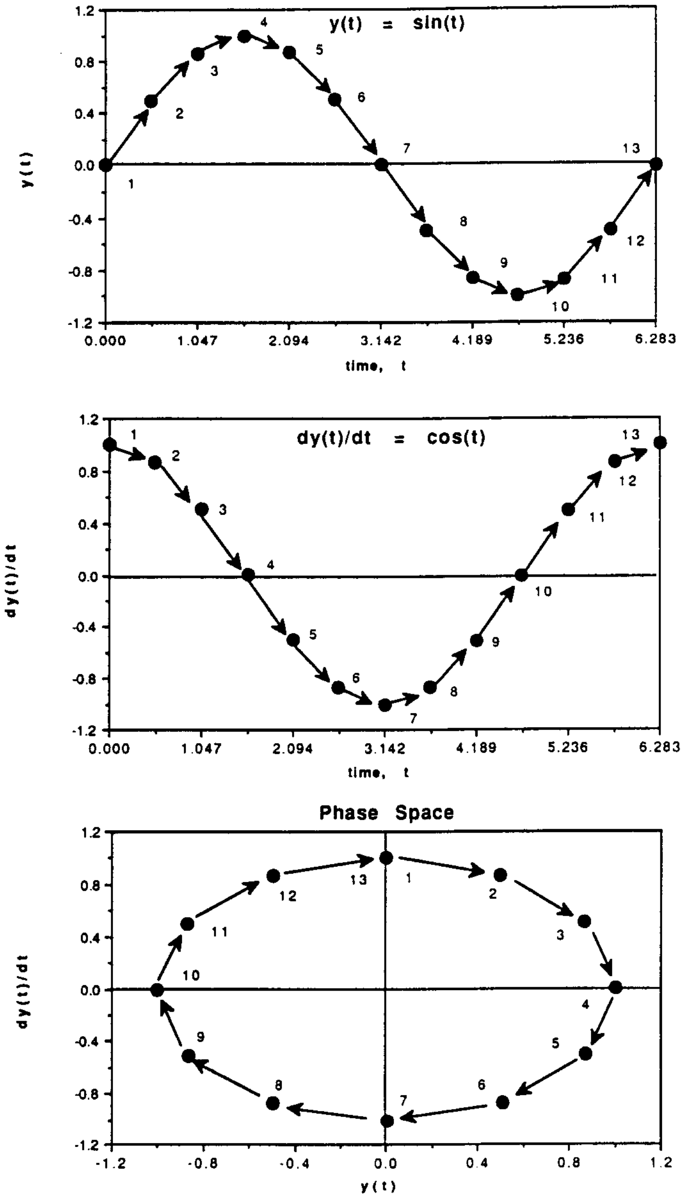


**Figure A-1. Example of a phase space plot. Illustrated is a periodic motion attractor. While a very simple source function is used to characterize a possible system motion, the lessons it offers are essential for understanding the phase-space behavior of more complex data sets. In the top figure, sinusoidal motion has been plotted as a time versus displacement *y(t)* plot. In the middle figure, time versus velocity *dy(t)/dt* is plotted. In the lower plot, a phase space plot is generated: data from the first two figures are plotted parametrically, or *y(t)* versus *dy(t)/dt* — time being explicitly extracted. The ellipse in the phase space plot is the specific attractor for this periodic system. Phase space plotting is an established method of illustrating and analyzing system dynamics. These plots are especially useful in nonlinear dynamics for identifying and characterizing chaotic behavior and its onset. All categories of motion have characteristic trajectories or attractors in phase space.**

at some location in the phase space of the system. Then, each time and at each location where the attractor crosses this plane, a point is placed on the plane. The cumulative trajectory of points on the plot is the Poincaré plot. For example, the continuous and tortuous toroidal spiral of quasiperiodic motion would create two circles (i.e., the intersection of the torus and the plane), and the ellipse of periodic motion would create a point on a Poincaré plot.

Moon (1987) gives the following table of classifications of Poincaré maps. Some of the terms needed to understand these classifications are defined in the following list.

- Finite number of points — periodic or subharmonic oscillation
- Closed curve — quasiperiodic, two incommensurate frequencies present
- Open curve — suggest modeling as a one-dimensional map; try plotting $x(t)$ versus $x(t+T)$ where $T$ is a fixed delay time that is usually determined empirically
- Fractal collection of points — chaotic motion strange attractor in three-phase space dimensions
- Fuzzy collection of points — (i) dynamic system with too much random or noisy component; (ii) chaotic motion, strange attractor but system has very small dissipation — determine Lyapunov exponent to confirm; (iii) chaotic motion, strange attractor in phase space with more than three dimensions — try multiple Poincaré maps (not discussed); and (iv) quasiperiodic motion with three or more dominant incommensurate frequencies

# A.3 CHAOS

## A.3.1 Introduction

In nonlinear dynamics, chaos is sometimes referred to as deterministic chaos or dynamical chaos, to distinguish from the typical dictionary definition of chaos (i.e., state of utter confusion or disorder). The identification and study of a coherent class of motion called chaotic has developed mainly in the last 25 years in an interdisciplinary arena. It was found that complex dynamic behavior, previously considered to be purely stochastic, could be diagnosed and understood in greater detail than could be accomplished from a statistical standpoint alone. One of the very interesting and perhaps ironic elements of nonlinear dynamics is that even the simplest of numerical and mechanical systems is capable of becoming chaotic and will if circumstances warrant. The essences of chaotic behavior and many of its facets can be understood through two simple but very illustrative examples. One is an experiment called the water drop experiment. The other is a theoretical mapping of a very simple nonlinear relation called logistic mapping.

### A.3.1.1 The Water Drop Experiment

The experiment consists of examining the time interval between drips from a dripping faucet. Although not of great scientific significance, the experiment shows characteristics of a complex physical system with many degrees of freedom compressing down to a system that evolves from simple to chaotic behavior and is characterized by a single parameter (Shaw, 1984; Martien et al., 1985; Wu and Schelly, 1989).

It was found that for very slow flow rates, the dripping interval was a period with a single frequency. (Although time is an integral element in this experiment, time interval or recurrence was being measured, making the system autonomous.) As the flow rate (i.e., input or driving energy) was incrementally increased, the system abruptly changed behavior, and the drip recurrence rate jumped. The drips became faster, as expected, but now at two distinct and interwoven or equivalently alternating frequencies. The original frequency split into a pair of frequencies. In the vernacular of chaos theory, the behavior bifurcated from a single solution to a doubly periodic solution. As the flow into the faucet was further increased, behavior again abruptly changed and each solution (i.e., the new bifurcation pair) bifurcated, giving rise to two pairs or four recurrence frequencies with a repeat periodicity or cyclicity 4.

There is a universal relation between parent and daughter frequency pairs. The process of periodic-doubling bifurcation, 2→4→8→16→32...., would probably have increased if the effects of noise and sensitivity did not obscure measuring. At a still faster or increased flow rate, the recurrence behavior ceased and behavior become nonperiodic. This new behavior had an almost random-like character. However, mapping successive time intervals against previous intervals showed a well-defined trajectory and not the scatter of a stochastic process. The system was now behaving chaotically. That is, further increases to the flow rate showed that different types of chaotic behavior could be instituted. The initial or lowest flow rate chaos was very simple (i.e., low-dimensional) chaos. It fits a theoretical chaotic model called logistic mapping, which will be discussed later. At higher flow rates the chaos became more complex and was found to be similar to other known mappings. The experimenters did not attempt to find any correspondence between these mappings and the physics of their experiment. They did attempt to universalize their results by introducing concepts in information theory into the discussion of predictability of future states of the system.

The water drop experiment is quite interesting and serves to illustrate a number of characteristics common in chaos studies.

- A very complex system with many degrees of freedom can show simple behavior that becomes more complex as the input or driving energy is increased. As input energy increases, more of the degrees of freedom will assert their presence. In addition, the rate at which the system was operating increased.

- A complete description of the physical parameters may not be necessary to understand and categorize the behavior(s) of a system. There are universals in the dynamics of many continuous systems, especially at simple, low-dimensional chaos.

- The behavior of a single solution undergoing periodic-double bifurcations and becoming chaotic is very common and is one example of the evolution of system, termed the route to chaos.

- Once a system is acting chaotically, the character of the chaos is not fixed and can change with changes in the dominant parameter(s) of the system.

- Since the system begins with a single stable solution and evolves to behavior which changes, the information retained by the system after each drop falls must change as the driving energy is increased. There must be a feedback system operating in the system.

#### A.3.1.2 Logistic Mapping

Logistic mapping is probably the most common mapping used to illustrate some of the theoretical concepts of chaos. There are many extensive discussions of this mapping (e.g., May, 1976; Hofstadter, 1981; Moon, 1987; Rasband, 1990). A truncated discussion is given here. It is intended to illustrate a simple chaotic mapping and the characteristics that are modeled.

The logistic mapping is an autonomous iterative mapping given by the nonlinear equation $X(n+1) = \mu X(n)[1-X(n)]$ where $X(n)$ is the $n$th data point and $\mu$ is a parameter which can be varied in the range 0 to 4. Outside this range, repeated iterations [i.e., putting the output value $X(n+1)$ back into the equation on the right and generating the successive $X(n+1)$ or $X(n+2)$] of the equation do not remain bounded, but increase in size without bound. We ignore the ranges less than 0 and greater than 4 because they are not indicative of realistic dynamic behavior. For the accepted range of $\mu$, the value of $X$ remains between 0 and 1. That is, in this interval the logistic mapping maps values in the interval $[0,1]$ into the same interval.

It is very easy to examine the logistic equation, and, because it is deterministic, expect it to be a predictable model. One could easily expect that the $X(n+1)$ is uniquely and predictably determined by $X(n)$. It will be shown that this is not necessarily the case. Although simple, logistic mapping shows a number of classical symptoms of chaotic behavior.

The logistic equation has been used in a number of disciplines where the dynamic behavior of a system can be viewed in one dimension. The character of the logistic equation changes drastically as a function of $\mu$. Following is a discussion of logistic mapping solutions as a function of $\mu$, without reference to any physical system.

A solution to an iterative mapping means a stable solution found after a sufficient number of iterations. Iteration for the logistic mapping begins by picking an initial and arbitrary value $X(0)$ in the interval $0 < X(0) < 1$, taking the output $X(1)$, inputting it back into the mapping to find $X(2)$, etc. until a final value has been calculated. The final value or values are identified when either a classical (i.e., a constant or equilibrium, periodic, or quasiperiodic result) or a chaotic solution is identified.

$X(0)$ is arbitrary in the mapping because it is simply a starting point and does not effect the final result. The final result here, for example, is purely a function of $\mu$. After a sufficient number of iterations, the transients resulting from the difference between the initial value and the final result damp to zero.

In logistic mapping, subranges of the full range of $\mu$ determine the final outcome of the solution (see Figure A-2). For $0 < \mu < 1$, iterations of all initial values of $X$ converge or are attracted to 0. $X=0$ is termed an attracting fixed point or a stable fixed point for the logistic equation in this interval.

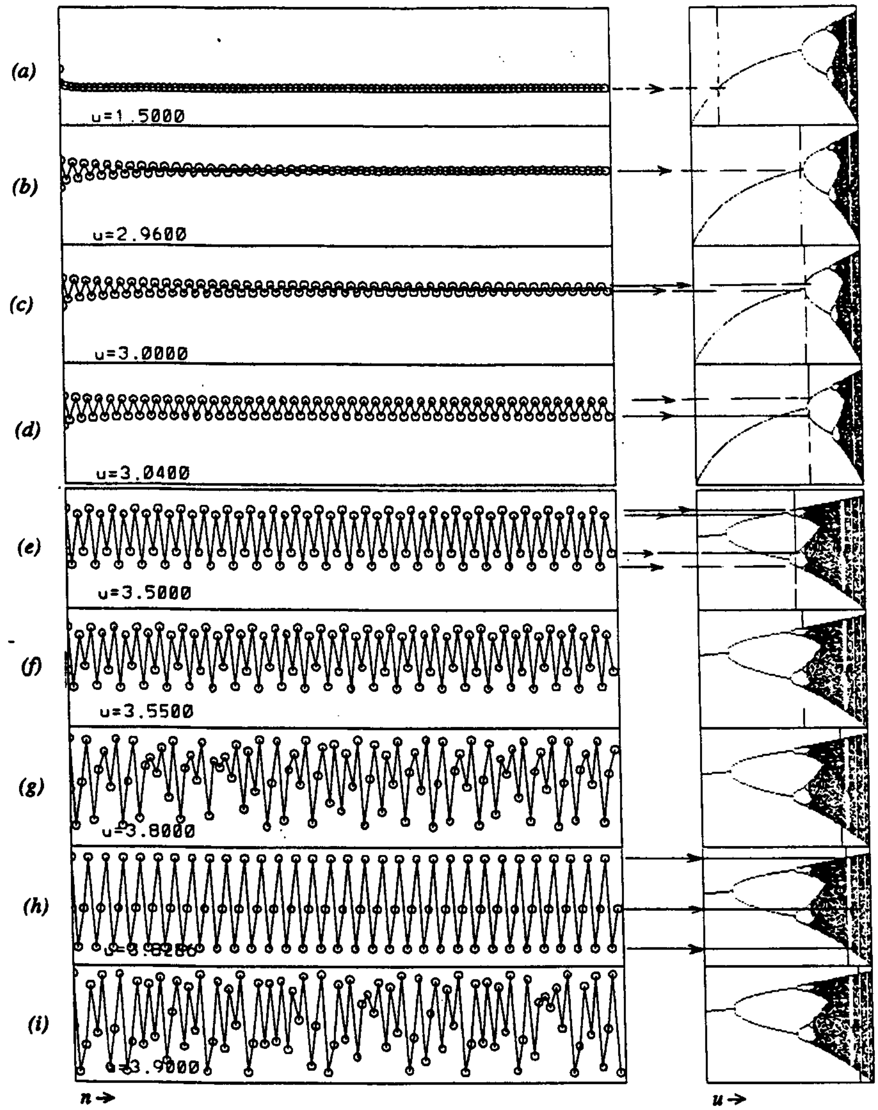


**Figure A-2. Sequences of iterated solutions to logistics equations. Left side: sequence of solutions to the logistic equation, $x(n+1) = \mu * x(n) * [1-x(n)]$ as a function of iteration number $n$, for different values of $\mu$. Right side: Solutions to logistic equation as a function of $\mu$. Tick marks in figures at the right indicate value of $\mu$ used in iteration solutions on the left. In each strip, (a) through (i), $\mu$ is increased. In strip (a), $\mu=1.5$, and the population decays down from its initial value, $y(t=0)=0.5$, to a lower population value. This is true for all $\mu<3.0$, in strips (b) and (c), where an oscillatory initial behavior damps out to a constant value. For $\mu<3.0$, strip (d), a two-state, oscillatory condition sets in. Increasing $\mu$ to 3,5000, strip (e), drives the system harder, and results in a bifurcation of bifurcations — a four-state, oscillatory condition, as noted for $\mu=3.5$. In strip (f) further bifurcations can be noted, $\mu=3.55$, an eight-state oscillatory condition is shown. In strip (g), $\mu=3.8$, and population values never settle down to a finite number of states. The system population is in chaos. In strip (h), $\mu$-3.8286, the system population has transitioned from a chaotic, unsettled state, to a regular tri-state rhythm. Windows of simple states such as this one occur throughout the chaotic regime. For the final $\mu=3.9$, the population is again chaotic. (In the strip chart transition from $\mu=3.04$ to $\mu=3.5$, the horizontal scale of the accumulation series was increased from $0<\mu<4$, to $2.5<\mu<4$ to reveal further detail.)**

In the interval $1 \leq \mu \leq 3$, solutions are single-valued and attracted to the stable point $X = X^* = (\mu - 1)/\mu$. It is interesting to note that although $X=0$ is also a solution, it is in this interval a repulsing or unstable fixed point, since any arbitrary point different than $X=0$ is repulsed and attracted to $X^*$.

At values greater than $\mu=3$, a new class of behaviors not evident in the smaller values of $\mu$ begins to appear. The first of these behaviors is bifurcation. That is, now the results from the mapping stably oscillate or alternate between two solutions. This is termed a stable period attracting cycle of 2 for the mapping. Mathematically, $X(n+2 = X(n)$ or equivalently $X(n) = X(X(n))$ where $n$ is an integer large enough that transients have damped out. A bifurcation of solutions happens again at $\mu=3.449490...$, giving a four-cycle solution or $X(n+4) = X(n)$. It continues to happen in a doubling sequence — the four-cycle becomes 8 which becomes 16, etc. This is periodic-double bifurcation and is one of the routes or ways a system can evolve to chaos as a single or a set of parameter changes. Incidently, although both $X = 0$ and $X = X^*$ are solutions to the mapping, in this interval they become and remain unstable fixed points.

The periodic-double bifurcations continue effectively to infinity, but the difference between the $\mu$ values at which the bifurcations occur shrinks. The last $\mu$ is $\mu_\infty=3.5699456....$ The sequence of $\mu$ values has been studied and found to have some properties that hold universally for all systems undergoing a periodic-double bifurcation route to chaos, independent of the specific mapping or the physics of the system (Feigenbaum, 1983).

Letting $\mu_n$ denote the value of $\mu$ at which a $2^n$-cycle periodic solution doubles to become a $2^{n+1}$-cycle periodic solution, then as $n$ becomes large the following ratio is found to hold universally that

$$\left(\mu_n - \mu_{n-1}\right) / \left(\mu_{n+1} - \mu_n\right) = 4.669201...$$

This is quite a significant finding and very important to identifying chaotic motion.

In addition, Feigenbaum (1983) found a universal relationship between parent and daughter solution pairs that occur during bifurcation. Denoting the pair of solutions after a bifurcation as twins, Feigenbaum (1983) found that as $n$ the period number increased, the ratio of the difference between daughter twins to the difference of its parent with it own twin approached 2.502907....

In the interval between $\mu_\infty$ and 4, solutions of the logistic equation become truly chaotic. That is, a sequence or cyclicity for solutions generated by the mapping no longer exists. Without additional analysis or appreciation for the means by which the data were generated, these data are indistinguishable from stochastic data. In light of the previous discussion, this mapping example demonstrates how chaos can be described as deterministic but not predictable. A more complete discussion of the particular characteristics and criteria which qualify to be called chaotic behavior is given in the next section. Logistic mapping has been found to satisfy all these criteria.

One particularly interesting aspect of the chaotic interval of the logistic equation is that not all $\mu$ values in this interval generate chaotic data. That is, in this interval there are appearances of a large number of small windows or sub-intervals where the behavior becomes stable, specifically periodic.

These windows are characterized by what are called periodic $p$-cycles with $p = 3,5,6,...$ The appearance of stable, periodic motion with a change in $\mu$ has been likened to mode locking where the interaction of nonlinear, nonperiod elements in a system can result in periodic motion. Unlike the double bifurcations cycles, periodicities in these stable regions can be both odd and even. Another interesting characteristic of these stable windows is their self-similarity or fractal nature (see Figure A-3). Self-similarity is a property common to chaotic attractors.

### A.3.2 Routes to Chaos

As has been discussed and illustrated, chaos is one characteristic state in which a nonlinear system can exist. It typically arises because of a high input energy flux. In a heuristic sense, the system becomes overloaded with the input or driving energy. Studies (e.g., Moon, 1987) have shown that ascent to this state can occur with a number of different characteristics.

In all cases, the route to chaos from equilibrium, periodic, or quasiperiodic states requires an increase in driving energy to a level where some of the output energy remains accessible, flows back into the system, and interacts with the continuing dynamics and driving energy of the system. Sometimes the increase in driving energy is not obvious and is hidden in a scaling phenomenon such as simply increasing a parameter, as in the logistic equation. Where the logistic equation has been used to describe system behavior, the parameter $\mu$ always corresponds to some type of flux in the system. Increased energy input is quite easy to see in the dripping faucet experiment.

The periodic-double bifurcation route to chaos has already been illustrated. This is one type of bifurcation in which solutions split — becoming pairs of solutions or states. There are other types of bifurcation, and each may give rise to a distinct route to chaos (Lauterborn and Parlitz, 1988). A pitchfork bifurcation occurs when one equilibrium solution splits into three solutions and is sometimes categorized as a periodic-doubling bifurcation. Another is a saddle-node or tangent bifurcation which occurs when one limit cycle becomes a second limit cycle. This type of behavior is seen when a system has two driving frequencies and at some point one of the frequencies looses it stability and jumps to the other. It is also possible that new frequencies are introduced into the system (i.e., subharmonics). Another type is a Hopf bifurcation-transition which occurs when a fixed point (e.g., the stable spiral of a damped pendulum) becomes a limit cycle oscillation. This type of route to chaos is frequently called the quasiperiodic route to chaos.

Another route to chaos is called intermittency. Here, long time windows of periodic motion are followed by bursts of chaotic motion. With increasing input energy or its equivalent, the chaotic bursts become more frequent and longer until the motion becomes completely chaotic.

Sometimes chaotic behavior appears from a change in some system parameter but eventually dies down into periodic or quasiperiodic motion after a short time. This category of chaos is termed transient chaos.

Chaotic behavior also can be identified when a system with well-defined and specific frequencies, as found in a spectral analysis of motion, abruptly acquires a band or bands of new frequencies of motion. These new frequencies are identified as broad bands or as a continuous broad band that replaces the well-defined frequency spikes in the prechaotic spectrum.

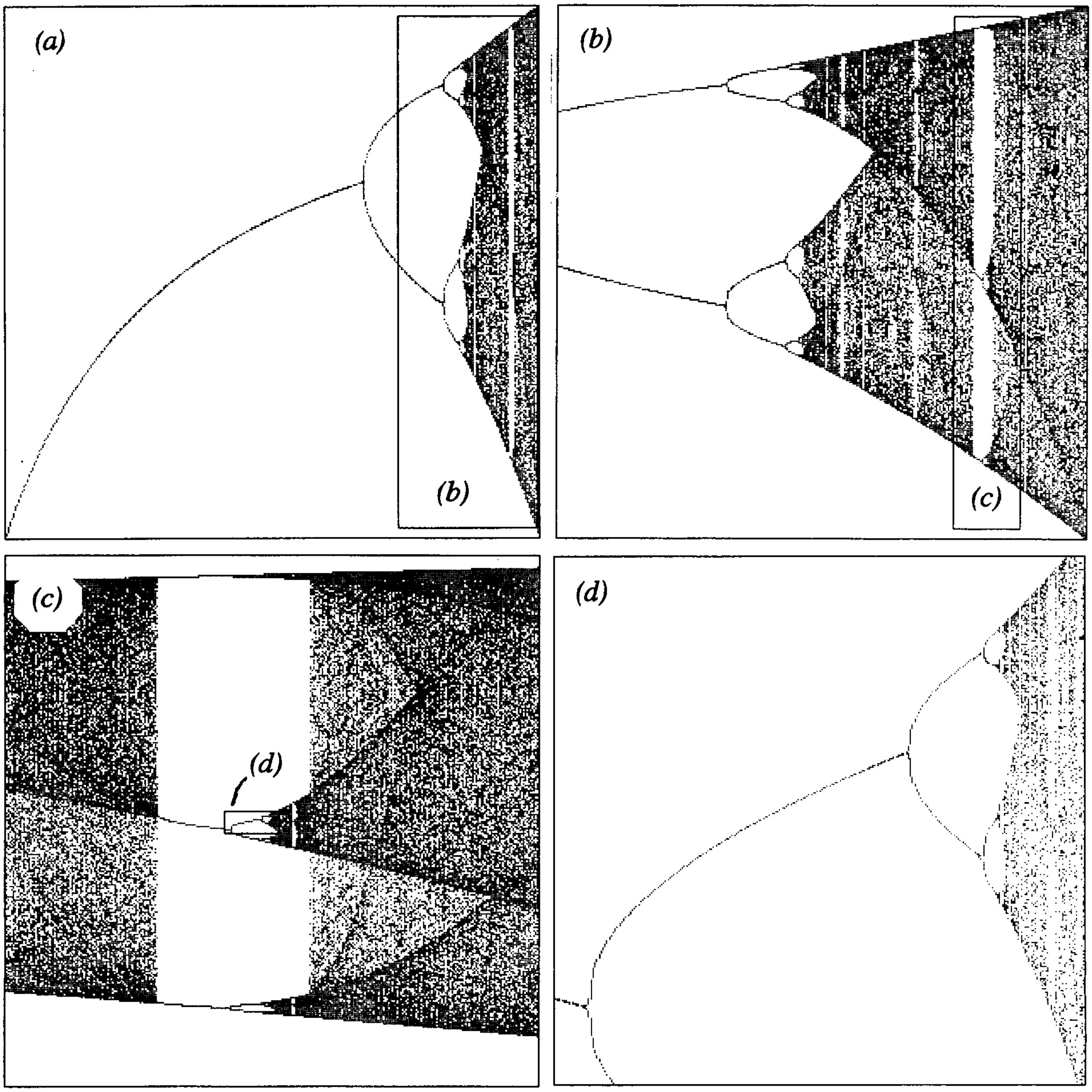


**Figure A-3. Self-similar solutions in the logistic equation. Figure shows solutions to logistic equation $x(n+1)=\mu^*x(n)^*(1-x(n))$ for iteration number $n>125$. Abscissa values are $\mu$ for $1<\mu<4$; ordinate values are solution $x$ with a range $0<x<1$. Plot (a) is the full solution space. Plots (b), (c), and (d) are zooms as indicated. Different zoom panels illustrate a fractal attribute: self-similarity or similarity across scale. Each subsequent figure shows more detail of the structure. The onset of chaos in the logistics equation occurs at $\mu$=3.56... In the last frame, $\mu$ has been expanded to examine the region between $\mu$=0.8409 and $\mu$=0.8510 (a factor of almost 400 in the horizontal direction). At this scale, the structure of figure (a) is repeated. This is an example of similarity across scale, a characteristic of fractals. In phase space, fractal structure differentiates ordinary attractors from strange attractors.**

### A.3.3 Criteria

> Chaotic states "possess three ingredients: unpredictability, indecomposability, and an element of regularity. A chaotic system is unpredictable because of what is now recognized as a sensitive dependence on initial conditions. It cannot be broken down or decomposed into two subsystems.... And, in the midst of this random behavior, we nevertheless have an element of regularity, namely the periodic points which are dense." (Devaney, 1989)

Although this description is terse, it gives the basic qualities of chaotic behavior that cumulatively separate it from random motion.

The sensitive dependence on initial conditions is probably the most commonly noted characteristic of chaotic behavior. E.N. Lorenz called it the butterfly effect (Gleick, 1987).

Lorenz attempted to numerically model weather and discovered that differential equations approximating its behavior generated data indicating a chaotic state. He recognized the futility of trying to predict weather and presented a paper titled "Predictability: Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?" from which the name, butterfly effect, originates.

The characteristic of sensitive dependence on initial conditions has a number of very profound implications which make chaotic behavior unique in the study of dynamics. Consider a system in a chaotic state that is being modeled theoretically or numerically. Assume that, at some initial but arbitrary time in the evolution of this system, two distinct phase-space states are noted. Then, as these two states evolve, the distance or separation between them increases and continues to increase as the system continues to evolve.

There are a number of definitions for distance or separation based on the mathematical concept of a norm. For simplicity, we will assume the construct similar to physical distance between points in space.

It has been found (e.g., Moon, 1987) that if a system is chaotic, the divergence of states occurs at an exponential rate. Actually, theoretical studies (e.g., Rasband) have shown that only one variable of the system must be diverging for the system to be in a chaotic state. A test for chaotic behavior associated with the divergence of states is based on determining a parameter, called the Lyapunov exponent of the system.

Calculating the Lyapunov exponent for a system tests the sensitivity of the system to changes in initial conditions. Conceptually, it can be viewed as placing an imaginary small sphere around two neighboring points in phase space and watching the deformation the sphere must go though to continue to contain the points. For chaotic trajectory, the sphere becomes an ellipsoid. If $d$ is the maximum length of the ellipsoid and $d_o$ is the initial size of sphere — for a continuous system, the Lyapunov exponent $\lambda$ is defined by the equation

$$d = d_o 2^{\lambda(t-t_o)}$$

where $t$ and $t_o$ are time when $d$ and $d_o$ are found, respectively. For a discretized system of mapping, the $(t-t_o)$ is replaced by $n$, the iteration number of the mapping. Without going into specifics, one measurement of the Lyapunov exponent is usually not sufficient, and calculations must be averaged over different regions of phase space.

The primary importance of the Lyapunov exponent is its sign. If this parameter is positive, then the states are diverging. If the parameter is zero or negative, the system is in regular or traditional motion. It should also be noted that the Lyapunov exponent is not only a theoretical tool for identifying chaos. With sufficient data volume, it can be found and used to analyze experimental and field data.

The sensitive dependence on initial conditions or a positive Lyapunov exponent has additional implications. It means that small perturbations do not stay small, but propagate through the system and can become very important. It also means that errors or inaccuracies in the system, no matter how small, will grow eventually to detectable levels. The exponential growth of small errors precludes long-term predictions or forecasting without continuously updating the data from which the predictions are based.

The long-term nonpredictability of a theoretical system in a chaotic state is a statement of reality. If one had infinitely precise (i.e., unrealistic) information, then predicting exact system behavior for infinite time would be possible. The divergence of states would not apply since a single state would be identified and tracked through its trajectory. However, infinite precision is not possible. Measurements have intrinsic error and inaccuracy. Computer memories and computations are finite. Hence, nonpredictability is, in part, a coupling of chaos to reality.

A positive Lyapunov exponent is a means for distinguishing chaotic and stochastic behavior. Although stochastic behavior cannot be predicted, the probability distribution which describes the random variables of the system are assumed fixed throughout the life of the system. For a chaotic system, new states are constantly being produced.

The positive Lyapunov exponent means that the state of at least one variable of the system is diverging and continues to diverge at an exponential rate. In order to continue to diverge, the phase-space trajectory must be expanding over a greater and greater volume. This is not the case. The trajectory is expanding, but within a fixed space. This is accomplished by a stretching and folding of the trajectory similar to the stretching and folding of taffy candy. The trajectory grows in length, but continues to occupy the same volume of phase space. As stated, this means the increased distance between states is measured along the phase-space trajectory, not across the trajectory. It also means that where the amount of taffy candy is fixed and the added length is created by thinning of the volume as it is pulled, the length of a chaotic phase-space trajectory is the result of the creation of new states. The distance between neighboring states is filled with new states; hence, new information is being generated by the system. The creation of new states is unique to chaotic behavior and not a characteristic of stochastic dynamics.

Quantifying the creation of new information is another characteristic of the Lyapunov exponent. For the continuous system, units of the Lyapunov exponent are bits/second; for discretized mapping, the units are bits or iteration. The Lyapunov exponent quantifies the time window or iteration number beyond which all information about the state of the system at time $t_o$ (i.e., the initial state) has been lost. This is equivalent to giving a limit beyond which the system dynamics cannot be predicted from an initial state. A more complete discussion of the Lyapunov exponent, information, and prediction follows.

The second criterion given by Devaney (1989) is indecomposability. This means that if one examines the system with closer scrutiny, it retains its characteristics. It also means that, unlike many systems where one can understand the whole by breaking down and studying the parts, this cannot be done to a chaotic system.

Indecomposability is in part an implication of the stretching and folding of the phase-space trajectory previously described. It also means the phase-space trajectory of chaotic behavior is a fractal. That is, the phase-space trajectory of the system maintains an average characteristic of self-similarity or self-affinity. Identification of the fractal characteristic, called fractal dimension, is one of the means by which data are tested for chaos. The fractal dimension and ways it is determined will be discussed.

Devaney's third criterion is an element of regularity. This is equivalent to periodic windows described in the chaotic regime of the logistic equation. The appearance of regular, periodic motion within the chaotic range of behavior is an enigma, but is a unique characteristic of chaotic behavior. The various explanations of the appearance of periodic windows within the chaotic regime is beyond the scope of this appendix (May, 1976; Moon, 1987).

## A.3.4 Strange Attractors

The family of phase-space trajectories for chaotic motion represents the fourth class of attractors, the strange attractor. As just discussed, strange attractors have characteristics which make them unique in the family of all attractors. They have at least one positive Lyapunov exponent. They never intersect themselves (i.e., a state would be repeated or the motion would be periodic). They are fractal. In addition, strange attractors can occur in groups which lead to the concept of basins of attraction.

Being fractal is an attribute of the attractor trajectory stretching and folding over on itself as it develops. This results in a layered structure with pieces of nonattractor phase space trapped between attractor layers. It also means that folding results in an attractor within a finite volume of phase space with an infinite length.

### A.3.4.1 Basins of Attraction

A dynamic system may possess several types of attractors simultaneously. This includes the coexistence of classical and strange attractors. Each attractor is reached by starting at a different initial location in the phase or state space of the system. The space of initial conditions available to a system is then divided into different areas, the basins of attraction, each of which belongs to a specific attractor. If a system has more than one chaotic attractor, then the boundary between the basins of attraction which are chaotic are fractals. This has important implications on the predictability of systems to be discussed.

## A.3.5 Chaotic Categories

Based on Moon (1987), the following list gives classes and complexity of dynamics of nonlinear deterministic systems:

- Predictable Classic Motion — Equilibrium, periodic oscillations, quasiperiodic motion, not sensitive to change in parameters or initial conditions

- Unpredictable Classic Motion — Multiple regular attractors (e.g., more than one periodic motion possible): long-time motion sensitive to initial conditions

- Transient Chaos — Motions that look chaotic and appear to have characteristics of a strange attractor (as given by Poincaré maps) but that eventually settle into a classical motion

- Intermittent Chaos — Periods of regular motion with transient bursts of chaotic motion; duration of classical motion interval unpredictable

- Limited or Narrow-Band Chaos — Chaotic motions whose phase-space orbits remain close to some periodic or regular motion orbit; spectra often show narrow or limited broadening of certain frequency spikes

- Weak, Large-Scale or Broad-Band Chaos — Dynamics can be described by orbits in a low-dimensional phase space (i.e., $3 \leq n \leq 7$; 1–3 modes in mechanical systems) and usually one can measure fractal dimensions of attractor (i.e., $< 7$); chaotic orbits traverse a broad region of phase space; spectra show broad range of frequencies especially below the driving frequency, if one is present

- Strong, Large-Scale Chaos — Dynamics must be described in a high-dimensional phase space; large number of essential degrees of freedom present; difficult to measure reliable fractal dimension; dynamical theories currently unavailable

## A.3.6 Examples

Many systems have been investigated and found to be capable of having and sustaining chaotic states. In many cases, governing equations, usually a set of first order differential equations, have been developed and confirm the existence and characteristics of the chaos.

Probably the most famous and influential example of a theoretical study of chaos was done by Lorenz (1963). In attempting to predict weather by approximating the Navier-Stokes equations applied to atmospheric flow, he found that the sensitive dependence on initial conditions was an intrinsic characteristic of his system of equations.

Chaos and chaotic attractors are found or used in a wide variety of science and engineering pursuits (Moon, 1987). Chaotic dynamics are used to investigate fluid flow and turbulence. The application has ranged from microscopic motion through studies of the mysterious red spot on Jupiter. Chaos, as it applies to Hamiltonian systems, is used to study planetary and heavenly body motion. It has been used to study the dynamics of magnetically levitated vehicles, vibrations in elastic material, buckling of material, nonlinear pendulum motion, nonlinear electrical circuits, animal population dynamics, and biological systems, in addition to the geoscience applications described in Chapter 4.

#### A.3.6.1 Software

Many of the theoretical approaches and common attractors can be examined and manipulated using canned or easily programmed software. Devaney's book (1990) is a very elementary tutorial on chaos and fractals and includes a number of BASIC programs for examining both. Rollins (1990) gives what he calls a chaotic dynamics workbench consisting of a wealth of common strange attractors and Lyapunov exponent calculations for an IBM personal computer (compatible)(PC) computer system. The uses of this workbench can do an extensive amount of manipulations to the attractor equations and examine the results. In a similar way, Autodesk (1991) offers a PC software package that has nice graphics and allows some manipulation of examples of chaotic attractors and fractals. In all cases the available software is purely tutorial. None of these software packages can be used for direct analysis of an independently acquired data set.

## A.4 FRACTALS

### A.4.1 Introduction

The descriptions, analyses, and interpretations of chaotic behavior are strongly coupled to fractal characteristics. The study of fractals has grown into a vast field. A survey of those aspects germane to chaotic dynamics will be presented in this section.

Fractals, fractal geometry, and fractal sets represent sets whose members all satisfy certain scaling symmetry. For example, many physical objects look essentially the same when enlarged, as in a photographic enlargement, or when reduced. This feature is termed self-similarity under an isotropic change of scale, or simply self-similarity. The term fractal, credited to Benoit Mandelbrot, is the generic term for objects or members of a set that possess self-similarity over a wide range of viewing scales or lengths. In this regard, self-similarity is equivalent to scale-invariance. That is, there is no specific scale or size of which all the objects are integer multiples.

### A.4.2 Fractal Geometry

Mandelbrot (1967) first identified the concept of a fractal, or fractal geometry, when studying the coastline of Britain. He found when attempting to measure its length that, unlike typical geometric objects which have fixed lengths independent of the viewing scale, the length of the coastline was a function of viewing scale. The length increased at enlarged or more detailed scales, which is equivalent to measuring the length using a smaller measuring scale (i.e., ruler). Mandelbrot found a fixed relationship between the length of the coastline and the length of the measuring scale. This relationship defines the coast line as a fractal curve. A fractal curve is defined as a curve whose length or perimeter $P$ is related to the measuring rod length $l$ by the relation $P \sim l^{1-D}$ where $D$ is called the fractal dimension. $D$ is also sometimes called the Hausdorff dimension.

To better visualize the idea of a fractal dimension, we will put the concept of fractal geometry into a Euclidean geometry context. In three-space (i.e., *xyz*-space) Euclidean geometry, there are four basic families of objects: points, lines, planes, and solids. Each of these families is associated with an intrinsic dimension: zero for the point, one for the line, two for the plane, and three for the solid. One way, a somewhat unusual way, of viewing dimension is in terms of self-similarity properties of these objects.

Consider a line cut into equal pieces so that each piece if magnified, say using a camera and the same magnification, resembles the original line of length $L$. The ratio of the number of pieces to the amount of magnification that gives a length $L$ to the pieces gives the dimension of the object. Actually, as will become evident, the ratio is the ratio of the logarithm of the number of pieces to the logarithm of the magnification. For example, if the line is of length $L$ and divided into two pieces each the same length, $L/2$, then in order for either segment to appear to be a length $L$ a magnification of 2 is needed. Hence by this definition, the dimension of the line is log(number of line segments, 2)/log(magnification,2) = 1. A moment of contemplation or a hand-held calculator will show the logarithms could be to any base (e.g., natural or common) as long as only one type is used.

A square is used to demonstrate the concept for a plane. The square is subdivided into four equal squares. By the previous definition, the dimension of the square is then log(number of squares, 4)/log(magnification, 2) or 2. Similarly for a cube, subdivided into 8 equivalent cubes, the dimension is log(8)/log(2) = 3. This unusual definition of dimension becomes very important when the object does not have an integer dimension, which is the definition of a fractal object or fractal set. This definition of dimension was presented for illustrative purposes and cannot always be applied to all fractals. Alternate definitions will also be discussed.

To further illustrate a fractal dimension, consider the following operation, which will produce a fractal set called the Cantor set. Take a line of length $L$. Divide the line into three equal segments. Remove and disregard the middle segment. The remaining two segments are both of length 1/3 and go from 0 to 1/3 and 2/3 to 1. Repeat the operation for the two segments. Now there are four segments, each of length, 1/9 (0 to 1/9, 2/9 to 3/9; 6/9 to 7/9; and 8/9 to 1). If this operation is repeated on remaining line segments $n$ times, then the number of segments remaining will be $2^n$ and each will be of length $(1/3)^n$. Using the dimension definition given above gives the dimension of the Cantor set: log(number of pieces, 2)/log(magnification, 3) = log(number of pieces, $2^n$)/log(magnification, $3^n$) = 0.6309.... This dimension shows that the Cantor set lies somewhere between a point and a line. It partially fills more of a space than that filled by a point, but fills less of a space than that filled by a line.

It can be shown that in the limit as $n \to \infty$, the Cantor set becomes a perfectly disjointed set; that is, no two points which are adjacent remain after a finite number of operations. Each point eventually becomes isolated. This gives rise to the term Cantor dust for describing the set. The repetitive iteration leading to a dust is known as curdling.

The transformation creating the Cantor dust (i.e., continued removal of a piece under a specific rule) can be generalized into two and three dimensions. In two dimensions, a square can be divided into 9 equal squares in a $3\times3$ matrix and each of side 1/3 the original square. The middle square of the matrix is removed. Each of the remaining 8 squares is again subdivided into 9 equal squares and again the middle one is removed leaving 64 squares and so on. The resultant, holey geometric object is called a Sierpinski carpet and is a fractal of dimension $D=\log(8)/\log(3)$.

A similar transformation can be done in three dimensions. Subdivide a cube into 27 equivalent sub-cubes which are stacked like the original cube. Remove the middle sub-cube and the middle sub-cube of each face of the original cube (i.e., 7 sub-cubes are removed). Repeat the process on each sub-cube. The result is called a Mengor sponge and it has a fractal dimension $D = \log(20)/\log(3)$.

The concept of a noninteger dimension is the basis of fractals. All fractal objects or fractal sets have noninteger dimension. It is half of the definition of a fractal. The other half of the fractal definition is self-similarity (or as will be discussed self-affinity). Conceptually, the noninteger dimension can be viewed as a description of the extent to which an object fills the geometric or Cartesian space it occupies. The closer the dimension is to an integer dimension, the more the fractal is like the objects of that dimension.

The concept of filling is an abstraction. However, it can be understood if recognized that the length, area, or volume displaced or filled by a fractal object can only be determined by knowing the self-similarity of the objected as viewed at higher and higher magnification.

Cantor dust is an example of transforming a line into a fractal with a dimension between a point (0) and a line (1), by removing some of the line. The Koch set or Koch curve is a fractal formed by transforming a line into a fractal with a dimension between that of a line and a plane (2) by adding to the line. The Koch curve can be formed by taking a line of length 1, for convenience. Divide the line into three equal segments. Each segment will be of length 1/3. Remove the middle segment. In the gap of the removed segment place a $\wedge$ which was made of two lines, each of whose length is equal to the removed middle segment, 1/3, and whose open end just fits the gap made by the removal of the middle segment. This creates a continuous curve. The curve that now remains is made of four segments each of length 1/3 and has a total length of 4/3. To get the Koch curve, repeat the process for each of the four segments and so on. The total length of the curve increases by 4/3 with each transformation, and the total length approaches infinity. After many steps, the curve begins to look fuzzy. In a sense, this operation is an apparent paradox of a continuous curve that has some of, but not all of, the properties of an area. Hence, it is no surprise that a dimension between 1 and 2 is found for this curve. Using the definition given above, the dimension is log(number of segments, 4)/log(magnification, 3) = 1.26186.... The fractal dimension of the Koch curve between 1 and 2 can be viewed as a measure of the tortuosity of the curve.

If, instead of subdividing a straight line into three segments and following a middle-segment-removal-and-replacement-with-an- $\wedge$, readjust the original three segments into an equilateral triangle with side length 1/3. Now, remove the middle segment of each side and replace with the $\wedge$ and repeat for each resulting smaller segment (see Figure A-4). This is a figure called a Koch snowflake which has the same dimension as the Koch curve. Being a closed curve, the Koch snowflake has interesting geometry: its area is finite, but its perimeter is infinite!

### A.4.3 Fractal Sets

Although conceptually there is no difference between fractal geometry and fractal sets, a distinction is made here for illustrative purposes and for ease in understanding the use of fractals in the analysis of time series and chaos. Fractal sets are a generalization of the concepts introduced in the preceding section.

A fractal set is a set in which the number of objects $N_n$, which possess some characteristic $r_n$, are related to that characteristic by the relationship $N_n = C/r_n^D$, where $C$ is a constant of proportionality

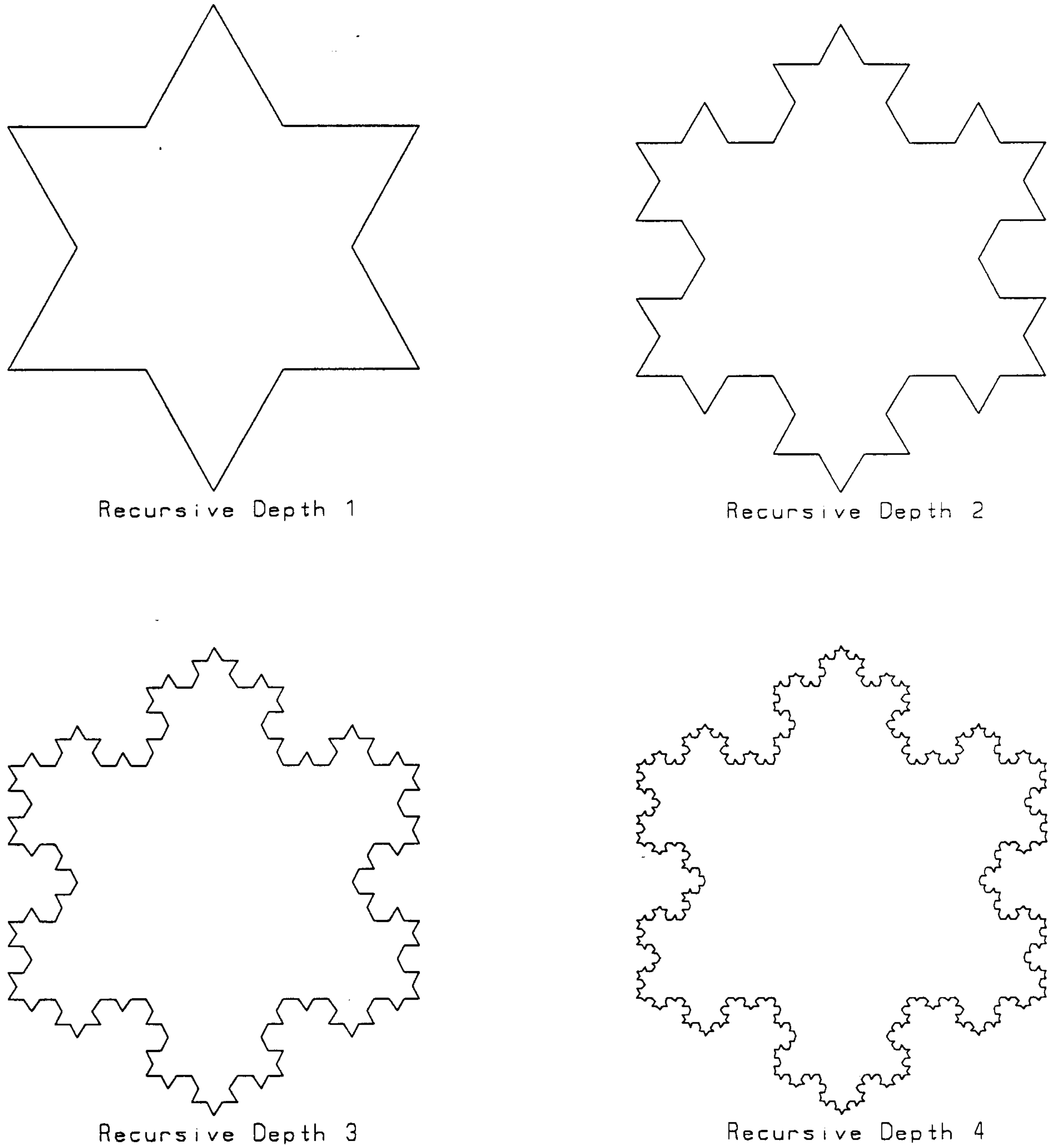


**Figure A-4. Iterated rendering of Koch snowflake. Figures show examples of the construction of the Koch snowflake after one, two, three, and four iterations of a recursive relationship. Patterns generated in this manner have the attributes of finite area, yet infinite perimeter length.**

and $D$ is the fractal dimension. Some examples of $r_n$ are geometric, like length, as in fractal geometry, frequency of occurrence, and time interval.

The concepts of fractal geometry and fractal sets combine very easily. The set of measures used in the study of the perimeter, area, or volume of a fractal object is a fractal set. The perimeter or length $L$ of a fractal object, using a measuring rod of length $r$, is defined as $L = Nr$, where $N$ is the number of measuring rod lengths. From the definition of fractal sets $N = Cr^{-D}$, then $L = Cr^{1-D}$. Generalizing, for area $A = Cr^{2-D}$ and for volume $V = Cr^{3-D}$. Conversely, data from objects that show these types of relationships over given ranges are necessarily indicative of fractal geometry.

### A.4.4 Fractal Statistics, Probability, Cantor's Method, and Data

Fractal statistics is the study of data to determine if the data are fractally distributed as a function of some parameter. If the distribution is fractal, then the number of objects with a specific value of the characteristic, say $r$, must satisfy or fit the relation $N = C/r^D$, where $D$ is again the fractal dimension. If this is found to be true, the distribution is said to follow a fractal statistical distribution or simply fractal statistics.

As in fractal geometry, where the noninteger filling of a space is modeled, fractal statistics modeling has been used extensively to analyze data from processes that appear to exhibit scale invariant clustering. Fractal dimension describes the strength of clustering or how space is filled — the more isolated the clusters, the smaller the value of $D$. Clustering may be in time, as in a series of intervals between events, or in spaces, as in the spacial location of events. The fractal dimension $D$ is determined from plots of log($N$) versus log($r$).

The extension of fractal statistics to probability (and prediction) is directly parallel to the extension of conventional statistics to probability. However, fractal statistics result in predictions that frequently differ from predictions of conventional statistics, which are much more commonly used. The difficulty in applying fractal statistics is usually the result of insufficient data volume. To understand fractal probability, consider the following example.

Take a line of unit length and perform the Cantor transformation (i.e., removing the middle third segment repeatedly). After $n$ applications of the transformation, there will be $2_n$ line segments, each of length $(1/3)^n$. The spacial distribution of these segments will not be uniform; it will be clustered. If one starts at one end of what was the original line and walks the path of the original line in steps of size $(1/3)^n$, what is the probability that at any step you will be standing on a line segment and not an empty region? The answer is $(2/3)^n$ or the number of segments times the length of a segment. If in this exercise one keeps a running sum of the probability as the line is traversed from 0 to 1 and plots this cumulative probability versus location, the resulting curve is called the Devil's Staircase (Bak, 1986) and is itself a fractal with some utilities not germane to this discussion.

Generalizing, if $p_n$ is the probability of occurrence, then $p_n = N_n r_n$, where $N_n$ is the number of occurrences of a parameter of size, length, dimension, etc. $r_n$. Taking $C = 1$ and using the definition of fractal distribution given, $p_n = (r_n)1-D$, where now $0<D<1$, which describes the nature of the clustering of the probability. The application of this equation to a data set is called Cantor's method.

This method can be generalized to more that one dimensional data, in which case $p_n = (r_n)^{d-D}$, where $d$ is the dimension or number of parameters germane to the data.

Independent of the dimension or number of parameters contributing to the data, the Cantor method attempts to examine how the data clusters (i.e., how it is distributed in a zero-to-one dimensional space). Viewed in another way, the Cantor method does this by dividing the space of the data into a series of smaller and smaller intervals and examining the probability or the fraction of intervals in which there are data. If the fraction of intervals $P$ is related to the size $s$ of the interval by a power law (i.e., $P \sim S^D$) a fractal relation is established and a dimension $D$ is determined. If the Cantor method is generalized into two or three dimensions, the basis for analysis becomes the Sierpinski carpet and the Mengor sponge, respectively.

### A.4.5 Self-Affine Fractals

Up to this point the discussion has centered around one type of fractal, specifically, self-similar fractals, and in one dimension all fractals are self-similar. However, in two dimensions or greater, there is a second type or class of fractals, self-affine fractals. These fractals are quite similar to self-similar fractals but show a slight generalization on the self-similarity characteristic.

Self-similar fractals are by definition isotropic. In two dimensions (i.e., *xy*-space), a self-similar transformation (i.e., magnification) transforms both directions or coordinates by equal amounts. Mathematically, a function $F(x,y)$ is statistically equivalent to $F(rx,ry)$, where $r$ is the scaling factor.

A self-affine fractal is not isotropic. In two dimensions, the transformation in each dimension is not the same. A physical example is surface topography as a function of longitude or the topography of a fault or fault surface as a function of location. In both cases the self-similarity of the topography is at a much different scale than the location scale. Mathematically in two dimensions, a self-affine fractal surface $F(x,y)$ is statistically equivalent to $F(rx,r^H y)$, where $H$ is known as the Hausdorff measure. Self-affine fractals are important in time series data where the time sampling does not scale in the same manner as the amplitude of the corresponding recorded data. The analysis of self-affine fractals will be discussed.

### A.4.6 Fractal Dimensions and Measures

The concept of a fractal dimension is quite straightforward when it is limited to the number-parameter mathematical relation previously presented. When the mathematical relationship or transform by which the fractal set is generated is known, it uniquely determines the fractal dimension. Moon (1987) formally defines the fractal dimension as "a quantitative property of a set of points in an *n*-dimensional space which measures the extent to which the points fill a subspace as the number of points becomes very large." The fractal dimension increases as the data become more irregular or more tortuous.

The determination of a fractal dimension becomes nonunique when there is no established or fixed number-parameter relationship but only a recorded data set. In practice, there are a number of different but closely related methods for determining if a data set is fractal and the dimension of the set.

Four methods are discussed for determining fractal dimension. In using any of these methods, it is assumed a substantial data volume (i.e., >500 data points) is present.

### A.4.6.1 Capacity (Hausdorff, Hausdorff-Besicovitch) Dimension

This dimension, also called the box counting dimension, is a very intuitive or geometric definition of fractal dimension. It is typically used to determine the dimension of points along a line or distributed on some area. The line-fitting or divider measurement Mandelbrot first used to measure coastline length is a one-dimensional example of this method.

To determine the capacity dimension $D_{cap}$, the question of how many small cubes of side $\epsilon$ (or spheres of radius $\epsilon$) it will require to cover the set of data points is answered. As $\epsilon$ diminishes, one expects the number of cubes $N(\epsilon)$ to increase. If for small $\epsilon$, $N(\epsilon)$ increases according to the relation $N(\epsilon \propto \epsilon^{-Dcap}$, then $D_{cap}$ is the capacity dimension of the data set. Capacity dimension is determined by the relation

$$D_{cap} = \log[N(\epsilon)]/\log[1/\epsilon] = -\log[N(\epsilon)]/\log[\epsilon] ,$$

in the limit as $\epsilon \to 0$. Intuitively, as $\epsilon \to 0$ more of the detail (i.e., the self-similarity) of the data are identified by the cubes which show how self-similarity and dimension are coupled.

The capacity dimension also encompasses Euclidean geometry: for a data set consisting of a single point, $N(\epsilon) = 1$ independent of $\epsilon$; for a line of data of length $L$, $N(\epsilon) = L/\epsilon$; and, for a surface of data of area $S$, $N(\epsilon) = S/\epsilon^2$. In these cases $D_{cap} = 0,1,2$, respectively.

The capacity dimension is also called the box counting dimension because, in practice, one can make a physical map of the data and cover the trajectory with a series of boxes. The number of boxes is counted and the operation is redone with boxes of a different size. The number of boxes versus the logarithm of their size (i.e., $\epsilon$) is then plotted. The slope of the plot converges to the capacity dimension for smaller $\epsilon$. Typically, the whole box overlay and counting operation is done by a computer algorithm, but in the case of a physiographic map like a coastline, it can be done by overlaying templates.

### A.4.6.2 Pointwise Dimension

The pointwise dimension $D_p$ is found in a substantially different manner than the capacity dimension. First, a large number of data points (e.g., $10^3 - 10^4$) must be present in order to thoroughly cover the fractal geometry. Then a cube or sphere of length or radius $r$ is centered at a data point and the number of data points within the cube or sphere $N(r)$ is counted. The probability of finding a point in this sphere is found using the formula $P(r)/N_o$ where $N_o$ is the total number of data points. The pointwise dimension is then found using the formula

$$D_p = \log[P(r)]/\log[r] ,$$

in the limit as $r \to 0$. In some cases, points will be distributed with gaps like the Cantor set. In these situations, $D_p$ is calculated by averaging either a number of $D_p$ calculated from a number of points or from a number of *P(r)*, which are themselves averages.

### A.4.6.3 Correlation Dimension

The correlation dimension $D_{corr}$ is a very common dimension in calculations of attractor (fractal) dimensions of experimental data. It is calculated in a similar manner to the pointwise dimension. As with the pointwise dimension, a substantial number of data points, which thoroughly cover the fractal, must be present. The distance $s_{ij}$ is then calculated for all pairs of data points $x_i$ and $x_j$. Using this distance, a count is made of the number of points whose distance is less than some distance *r*. Mathematically, a correlation function *C(r)* is defined using the formula

$$C(r) = [\text{Number of pairs } (i,j) \text{ with distance } s_{ij} < r]/N^2 ,$$

where *N* is the number of data points. The correlation dimension is then calculated using the formula

$$D_{corr} = \log[C(r)]/\log[r] .$$

The correlation dimension takes into account the population density of the fractal data.

### A.4.6.4 Information Dimension

Intuitively, the dimension of a space (e.g., a point, a line, an area, a volume) or set is the amount of information necessary to specify a location in that space. Similarly, there is no compelling reason the information must be discretized into integer groups. This is the basis of the information dimension of a fractal — the amount of information necessary to specify the fractal to within an accuracy of $\epsilon$. For future reference, if the fractal is a chaotic attractor, then the information dimension is based on the amount of information necessary to specify the state of the system to within an accuracy $\epsilon$.

The information dimension $D_I$ is a fractal dimension that is similar to the capacity but tries to account for the frequency or probability with which the trajectory of the fractal visits each covering cube. As with capacity, calculations begin by covering the set of data points with a set of N cubes of size $\epsilon$. Then the number of points $N_i$ in each of the *N* cells is counted, and the probability of finding a point in that cell $P_i$ is calculated, where $P_i = N_i/N_o$, with $N_o$ being the total number of points in the data set. Using probability, the information entropy $I(\epsilon)$ (discussed in more detail later) is calculated using the formula

$$I(\epsilon = -\sum P_i \log[P_i] ,$$

where the sum $\sum$ is taken over $N$ the number of cells. When the log function is in base 2, $I(\epsilon)$ has units of bits. In information theory, $I(\epsilon)$ represents the amount of information necessary to specify the data to within an accuracy $\epsilon$. It is the amount of information gained by making a measurement that is uncertain by an amount $\epsilon$.

Using the definition of $I(\epsilon)$, the information dimension is then found by the formula

$$D_1 = I(\epsilon)/\log[1/\epsilon] = -I(\epsilon)/\log[\epsilon] .$$

In the capacity dimension calculation, each cube counts equally regardless of probability of points in the cube. The information dimension takes into account relative probability of the data being in the cube. If the probability for each cube is the same, then the capacity dimension equals the information dimension.

Choice of which dimension or dimensions to calculate is mitigated by a number of factors, some of which include data type, data volume, and experience. Trial and error is probably the most common discriminator.

Grassberger and Procaccia (1983) found a relation between the correlation, information, and capacity dimension. They found

$$D_{corr} \leq D_1 \leq D_{cap} .$$

And, when calculating the fractal dimension of many attractors, these dimensions are nearly equal.

### A.4.7 Self-Affine Fractals and Spectral Analysis

If the data set being analyzed is potentially a self-affine fractal (e.g., a time series or surface topography), then other direct methods of determining fractal dimension are not applicable unless properly scaled. Determination and interpretation of the fractal dimension of self-affine fractals are generally done quantitatively using spectral techniques.

The basis of spectral analysis is the Fourier transform, the transformation which determines the frequency content of a data set. Since the Fourier transform and the Fast Fourier Transform (FFT) for discretized data are well-established and extensively understood and utilized methods, they will not be discussed here. However, a Fourier transform is used because there are established relationships between directly determined spectral properties, fractal dimension, and their mutual interpretation.

Although its development is beyond the scope of this appendix, it can be shown that fractal dimension $D$ of dimensional data $d$ is related to the Hausdorff measure of the fractal by the relationship $H = d - D$. This relationship is the basic definition of fractal dimension of a self-affine fractal data set in two dimensions, as in a time series. The Hausdorff measure can be determined from the power spectrum of the data if the distribution of the data is fractal.

For a two-dimensional data set like a time series that has a fractal distribution, the power spectrum $S$ (i.e., the square of amplitude or FFT spectrum of the data) shows a power-law dependence on frequency $f$ or

$$S(f) \sim f^{\beta} .$$

It can be shown that power $\beta$ is related to $H$ by the formula $\beta = 2H + 1$. Hence, by determining $\beta$ from a power spectrum plot, usually by fitting to the data, the fractal dimension $D$ can be determined from the relationship $D = (2d + 1 - \beta)/2$.

The inverse of these results is that natural phenomena which give continuous power-law spectra over a specific range are scale invariant (i.e., do not have characteristic or fundamental frequencies with overtone) and hence are fractally distributed. This means the data subscribe to fractal statistics and their implications.

### A.4.8 Multifractals

Multifractal is a generalization of the concept of a fractal (Stanley and Meakin, 1988; Mandelbrot, 1989). A multifractal describes a set or object which has nonuniform fractal properties. For example, the fractal dimension may not be constant but may be mathematically or spatially distributed. A physical object may have different fractal dimensions over different physical regions or may have different dimensions superimposed over each other in the same region. Similarly, a data set may have more than one fractal dimension. Mathematically, the general fractal relationship $N = C/r^{D}$ has the added feature that there is a function $F(D)$ which shows how the fractal dimension $D$ is distributed.

## A.5 STOCHASTIC METHODS

The term stochastics implies a statistical description of a system in which time is an integral part of the description. Stochastic predictions are probabilistic predictions made on a time-based statistical or stochastic model — a specific mathematical expression that describes in terms of probabilities how values of a random variable or variables are spread over an acceptable range(s) of values, as a function of time. Random variables are also called chance variables, stochastic variables, and variates. Roughly, a random variable is the observable quantity which was either measured and used to develop the model or whose probabilistic appearance is being predicted. Random variables are considered either completely random or their average properties are postulated as random, resulting from the summing of the actions of many separate variables that are individually unknown and perhaps unknowable.

The categorization of a stochastic model is usually based on the type or name of the process (i.e., probability distribution) describing the random variable. A white noise process is one where the probabilities of all possible values of the random variable (i.e., data) usually within a given range are equal. Two other distributions are the Poisson process and the Weibull process.

### A.5.1 Poisson Process

In a Poisson process: (i) the time between events is exponentially distributed, and (ii) the probability of $N$ events (i.e., the random variable) occurring in a time interval from arbitrary time 0 to time $t$ is described by the expression:

$$\text{Probability}\{N = r\} = \left[(\lambda t)^r e^{-\lambda}\right]/r!$$

where $\lambda t$ is the mean of the distribution, $\lambda$ is the mean rate of the probable occurrences of events (i.e., the average number per time) over a long period of time, and $r!$ means r-factorial. From this expression, it is not difficult to show the probability of $N$ events occurring in a time period $t$ to $t + \Delta t$, or $N(t, t + \Delta t)$, is given by the expressions:

$$\text{Probability}\{N(t, t + \Delta t) = 0\} = 1 - \lambda\Delta t + o(\Delta t) = e^{-\lambda\Delta t},$$

$$\text{Probability}\{N(t, t + \Delta t) = 1\} = \lambda\Delta t + o(\Delta t),$$

and

$$\text{Probability}\{N(t, t + \Delta t) \geq 2\} = o(\Delta t),$$

where $o(\Delta t)$ is a function that very rapidly goes to zero as $\Delta t \rightarrow 0$.

The main features of the Poisson process are as follows:

- Probabilities of $N(t, t + \Delta t)$ given in the previous expressions do not vary in time, meaning there is no trend in the time series or conditions of the process remain constant for all time with the probability of event occurrence(s) increasing linearly with time

- Chance of two simultaneous events is negligible

- Chance of an event in the time interval from t to t+$\Delta$t is independent of what has happened prior to time $t$. (Unlike chaotic behavior, no information is transmitted between events or sequences of events and the chance of occurrence is not affected by the time elapsed since the last preceding event.)

### A.5.2 Weibull Process

In a Poisson process, also known as a homogeneous Poisson process, the rate of occurrences $\lambda$ is assumed to be independent of time $t$. If events occur according to a Poisson process, the repose times between consecutive events are independent exponential variables with mean $\theta = 1/\lambda$. If the constant $\lambda$ is replaced with a function of $t$, denoted $\lambda(t)$, then another type of Poisson process, called a nonhomogeneous Poisson process, results. A common choice is the Weibull distribution.

A Weibull process, based on a Weibull distribution, assumes recurrence rate is defined by the function

$$\lambda(t) = (\beta/\theta)\,(t/\theta)^{\beta-1}$$

where $\beta$ is parameter whose value determines the characteristic of the system being modeled. If $\beta$ is greater than 1, the rate of occurrence increases with time (unbounded); if $\beta$ is less than 1, rate of occurrence decreases with time (to zero); and if $\beta$ equals 0, rate of occurrence is constant (random, a homogeneous Poisson process). The major use for the Weibull process model is as a time-to-failure model, since by the proper choice of $\beta$, lifetime characteristics (waning, random, or developing) can be modeled. In typical practice, the Weibull process is used to model the first *n* occurrences of a failure and then a subsequent distribution is used (called failure-truncation). Or, it is used for a fixed time period and, similarly, a subsequent distribution is used to model the remaining observations (called time-truncation).

## A.6 CHAOS AND FRACTALS

### A.6.1 Fractal Attractors

A chaotic state in a system is identified by two requirements. First, the system must be nonlinear and deterministic, not statistical, with specified initial or boundary conditions. The second requirement is that solutions that are initially infinitesimally close diverge exponentially as the system evolves (i.e., the Lyapunov exponent>0). The second of these, sensitive dependence on initial conditions, binds chaotic behavior to fractal geometry and fractal statistics.

As was discussed, the evolutionary development of a system in chaos continually stretches and folds the attractor on to itself while maintaining it in a fixed volume of phase space. This necessarily results in a self-similar or fractal geometry for the attractor. Chaos is categorized in part by the fractal dimension of the strange attractor if a fractal dimension can be determined.

Given a data set whose attractor is fractal and can be determined (i.e., a confirmed chaotic system) the meaning or significance of the fractal dimension and associated characteristics are not fully settled issues. However, the dimension of an attractor is the first level of knowledge necessary to characterize its properties.

The higher the dimension of the attractor, the greater the number of active degrees of freedom of the system and, probably, the more complex the system dynamics. Dimension gives the amount of information necessary to specify the position of a point on the attractor to within a given accuracy. Dimension is also the lower bound on the number of essential variables needed to model the dynamics.

### A.6.2 Chaotic Basins of Attraction

In most linear systems, there is just one possible motion or state for a variety of input. In nonlinear systems, it is possible that the state of the system can vary drastically depending on the value of initial conditions or state and, hence, the system can have more than one attractor. The range of values of certain input or control parameters for which the motion tends toward a given attractor is the basin of attraction of the attractor. If there are two or more attractors for a system, the transition from one basin of attraction to another is call the basin boundary.

It has been discovered (Moon, 1987) that basin boundaries for many nonlinear systems are fractal — termed fractal basin boundaries. The existence of fractal basin boundaries has fundamental implications for the error and uncertainty of initial conditions and predictability.

The actual technique for determining dimension of the fractal basin boundaries is beyond the scope of this appendix. However, the technique differs from that for fractal trajectories since the boundary points are never given but are formed from the set of points that lie in neither of two attracting sets. Such fractals have been labeled fat fractals.

### A.6.3 Chaos and Natural Fractal Systems

Chaos and fractals are intimately involved. The presence of fractals in chaotic dynamics is noted throughout this appendix. Chaos necessarily requires fractals in its description. However, does the presence of a fractal(s) in a naturally occurring system necessarily require chaos? At present there is no clear answer to this question. For example, earthquakes show fractal statistics and may imply transient chaotic dynamics during eruptions. In other cases, like fractured surface roughness, chaotic dynamics is much less obvious, if at all present. What is required for the existence of fractals is nonlinearity and scale independence.

## A.7 CHAOS AND INFORMATION THEORY

If a system is chaotic, how chaotic is it? One measure is the dimension of its attractor. A second measure is related to the rate of stretching and folding of the attractor, or the average rate at which new system states or system information is produced. The basis for this approach is information or communication theory.

Information theory is a mathematically based discipline for quantifying communication. It was first formalized by Shannon (Shannon and Weaver, 1962). Its formal study is quite complex and predicated on applying probability and statistics theory to communication chains. Its quantitative description is beyond the scope of this appendix. However, some of the general concepts in information theory are applicable to the study of chaos and lend great insight into chaotic behavior and the information gleanable from a chaotic data set.

### A.7.1 Introductions and Definitions

The concept of information transmission or communication is based on a combination of probability, statistics, and a conceptual system. In its simplest form, the system consists of three elements: a transmitter, a receiver, and a channel. In operation, the transmitter sends information to the receiver through the channel. These elements are generic and are not limited to electrical components. Because of real-world factors like noise, instrument insensitivities, imprecision, and inaccuracies, etc. transmitters, receivers, and channels have intrinsic statistical or probabilistic properties. That is, at any given time these elements can be in any of a number or range of states.

A transmitted signal $x$ is described by a distribution of possible transmitted signals, P($x$). Similarly, a received signal $y$ is described by a distribution of possible received messages, P($y$), and the channel connecting the two distributions is a conditional distribution $P(x|y)$, the probability of receiving message $y$ given that message $x$ was transmitted.

Another way of viewing these parameters is that the $x$ are the possible values of the quantity to be monitored, the $y$ are the possible outcomes of the measuring operation, and $P(x|y)$ is again the probability that measurement $y$ originated from $x$ state.

The set of possible transmitted and received messages or quantities can be in many forms and is not limited to language. The messages can include finite sets of entities likes letters or symbols in the analysis of language. It can also include continuous distributions like voltage levels where $x$ represents possible values to be measured and $y$ represents outcomes of the measuring operations.

As demonstrated by computers, the fundamental unit when information is quantified is the common binary digit or bit. The measure of necessary information is defined as the minimum number of bits or the number of yes-and-no questions required to uniquely specify the particular outcome. For example, what is the information necessary to determine a specific outcome out of $N$ equal possible outcomes? This example is exemplified in the following problem.

Using the least number of questions, uniquely identify a selected integer in the range of integers from 1 to 128. The optimal way of doing this is by halving or asking yes-and-no questions like, Is the number greater than 64? and thus eliminate half the possibilities. It turns out that by decreasing by half, the number of questions needed to identify the selected number is $\log_2(128) = 7$, where $\log_2$ is the logarithm to the base 2. Generalizing, the information associated with the identification of one outcome of $N$ equally probable outcomes, each of which occurs with probability 1/N, is $-\log_2(1/N)$ bits.

In this example, the total information required was $-\log_2(1/128)$ bits. After the first halving or answer to the first question has been received, information yet to be obtained is $-\log_2(1/64)$ bit. The information conveyed from the first answer is then $\log_2[(1/64)/(1/128)] = 1$ bit.

Generalizing this example gives the definition and measure of information transmitted. Given the definitions of P($x$) and $P(x|y)$, information about $x$ obtained from the observation of $y$ or $y$ from $x$ is called the mutual information, or simply the information I($x$,$y$) and is defined by the expression:

$$I(x,y) \equiv \log_2\left[P(x|y)/P(x)\right], \text{ bits .}$$

One interpretation of this expression is that given $x$, how much information is required to specify $y$? This interpretation is useful for understanding the situation when $I=0$, which is the situation that given $x$ or $y$, no additional information is needed to obtain $y$ or $x$, respectively. The outcome is uniquely specified by the input, leading to the definition of self-information.

If the state of the source is completely certain upon observation of the state of the destination (i.e., communication is perfect: no noise, no accuracy, etc.), then $P(x|y)$ is equal to 1, and the self-information associated with the state $x$ is given by the expression:

$$I(x) \equiv -\log_2[P(x)] \text{, bits .}$$

The measure of self-information has two interpretations. First, it is the amount of information about $x$ that must be provided to specify it uniquely. This follows from the fact that the mutual information between $x$ and another event, say $y$, becomes equal to the self-information only when the probability $P(x|y)$ is equal to 1 or $x$ uniquely specifies $y$. The second interpretation of I is the maximum amount of information that can be provided about $x$ by $y$.

Another important element of information theory is the concept of information entropy or simply, entropy H. Information entropy is the measure of the uncertainty in a message or recorded data set. It is defined as the average information content of a message. For self-information, this translates mathematically to the expression

$$H(x) \equiv -\sum P(x)\log_2[P(x)],$$

where the summation is over all possible states. Besides defining the uncertainty, H defines the amount of information on the average which must be provided to specify or maintain a state. Note that when I and H are 0, no information or no new information is being provided. This means the system was completely specified from the start and it is not changing as the information is being transmitted. This is very significant in the study of dynamics and prediction. Zero information for a dynamic system means it is predictable and not chaotic. Nonzero information means chaotic or stochastic.

For mutual information, the entropy is similarly defined as

$$H(x|y) \equiv -\sum\sum P(x|y)P(x)\log_2[P(x|y)/P(x)],$$

where the summations are over the possible states of $x$ and $y$. Note that the entropy of a situation with no uncertainty is again identically zero, implying a fixed state and no new information being transmitted.

As just discussed, an unchanging or completely specified state or variable communicates no information into the future. Although a static state is predictable and establishes continuity through time, it is part of the fixed time-independent system description. Information, as defined, measures a property of dynamic systems, and the transmission of information requires the possibility of change.

Entropy or average information transmission is also called the rate of transmission of information for a continuous channel or system. This rate can vary up or down depending on $P(x)$, the distribution of input. Channel capacity is defined as the maximum rate which can be found by varying $P(x)$ over its possible distributions.

### A.7.2 Information Theory and Chaos

The application of information theory to chaos is quite direct. The problem of predictability of dynamic behavior can be cast into an information theory format. A dynamic system communicates some but not necessarily all the information about its present state into the future. The larger the volume of change, the greater the rate of information transmission.

In conventional deterministic motion, I and H are both zero. The system is uniquely specified at the start. This is not surprising. When cast in a framework of equations of motion and initial conditions, a system's evolution is known or totally predictable.

In a chaotic state, I and H are not zero and new information is constantly being generated as the system evolves. New information here is equivalent to the generation of new dynamic states. In this regard, Shaw (1984) and Martien et al. (1985) give a very extensive discussion of chaos and information theory and relate it to the results and interpretation of the water drop experiment.

In their discussion, Shaw (1984) and Martien et al. (1985) generalize on the concepts of channel rate and channel capacity to define a parameter particularly applicable to dynamic systems. This parameter is the information stored in a system (i.e., information in the system transmitted from past to future states). They show that the information stored and the entropy, or rate of loss of this information, are two quantifiable invariants of a dynamic system.

Although the particulars of their analysis are beyond the scope of this appendix, Shaw (1984) and Martien et al. (1985) use these invariants as their model for the water drop experiment and calculate values of the stored information and the entropy for a number of postulated values of $P(x)$. The most important result they found, and which seems to be universal for chaotic systems, is that the maximum entropy, or loss of predictability, occurs when the stored information is a maximum. Put into the context of attractor dynamics, the rate at which the attractor is stretched and folded (i.e., its loss of predictability) is related to the rate at which stored information is produced. In context of energy and feedback, the maximum entropy or loss of predictability occurs when energy feedback is maximum and interacting with incoming or source energy. Heuristically, the system has a memory of past event(s) which interacts with the present dynamics.

Another important element of information theory and chaos is through the Lyapunov exponent and the loss of system knowledge and predictability. Recall that information transmission within a dynamic system is a function of the probabilities of the system accessing new states given a previous state. Hence, the number of accessible states of a system is a crucial parameter in understanding the predictability of a system. If the number of states accessible to a system is increasing, as it is for a chaotic system, then information content of the system is growing while predictability is necessarily decreasing as the system evolves.

The quantitative measure of the rate at which new system states are being produced or the rate at which information is being lost is given by the Lyapunov exponent $\lambda$. This can be demonstrated as follows: for a continuous system, $\lambda$ is given in units of bits or time; for a discretized mapping, it is given in units of bits or iteration. Assume the initial condition of a system is known to an accuracy of $n$ bits. Then simply dividing $n$ by $\lambda$ or $n/\lambda$ gives a number in either units of time (continuous) or number of iterations (discrete) in which all the knowledge about initial conditions are lost. That is, $n/\lambda$ represents the absolute limit of the predictive window in either time or iterations for a chaotic system with a Lyapunov exponent $\lambda$.

An example of this calculation can be found in the logistic mapping discussed beforehand. As noted, the logistic mapping became chaotic for $3.57 < \mu < 4$. Over this range, the Lyapunov exponent increases to a maximum of $\lambda=\ln(2)=0.691...$ at $\mu=4$. For calculations on a computer with 16-bit resolution, the number of mapping iterations which can be performed before the total loss of initial condition information at $\mu=4$ is 16/0.691 or about 23.

## A.8 CHAOS AND RECORDED DATA

### A.8.1 Measurable Chaos Characteristics

In general, chaotic motion has five unique attributes (Moon, 1987):

- Sensitivity to changes in initial conditions, as measured by the Lyapunov exponents and fractal basin boundaries
- Broad spectrum of frequency components when motion is generated by a single frequency, as determined by an FFT
- Fractal properties of the motion in phase space which denote a strange attractor, as measured by Poincaré maps
- Increasing, but mappable, complexity of regular motions as some parameter is changed, as described by routes to chaos
- Transient or intermittent chaotic motions — nonperiodic bursts of irregular motion (intermittency) or initially random-like motion that eventually settles down to a regular motion (transient)

The essence of data analysis for a system suspected of being in a chaotic state is to uniquely identify and exploit one or more of these characteristics.

#### A.8.1.1 Chaos Identification in Data

Shaw (Middleton, 1991) states

> "In a sense, *tuning* is the central issue of nonlinear dynamics. Attractor states are tuned, sometimes robustly and sometimes with excruciating sensitivity, by the relationships between forcing functions and the strength of coupling among parameters of the system, such as its natural frequency modes and/or those which may be (i.e., a probability density function in phase space) imposed on or induced in the system by external (e.g., heating) or internal (e.g., thermal feedback) mechanisms. It is easy to fall into the habit of speaking of this or that 'attractor' as though it were characteristic of a particular system. As this discussion indicates, even the simplest systems potentially have an infinite number of attractor states."

At present there are four principal and one emerging measures of chaos (Moon, 1987) — the first four have already been discussed:

- Extended Fourier distribution of the frequency spectrum

- Fractal dimension or dimensions of the chaotic attractor
- Positive Lyapunov exponent(s)
- Positive Information and entropy
- Invariant probability distribution of the attractor

The fifth method, invariant probability distribution of the attractor, is based on the idea that, since a time history of chaotic motion diverges, a probabilistic approach of finding locations on the attractor will give at least a statistical measure of the chaotic dynamics. The method utilizes fractal statistics to determine a probability density function of the attractor in its phase space. The implementation of this method is quite computer intensive, requiring super computers, and is still very much in infancy. In all five measures, large data sets are required to assure any reasonable reliability in the results.

### A.8.2 Data Volume

Attractor trajectories, fractal dimensions, Lyapunov exponents, etc. must be determined if a chaotic system is to be identified and characterized. Typically, these parameters are found from either discretized continuous data or naturally discrete data. When data are recorded, whether from a laboratory, field experiment, or a numerical experiment, enough data must be recorded to uniquely characterize the dynamics of the system. Users of chaos analysis vary in their opinions as to the amount of data required. Consensus seems to indicate that a minimum of 500 accurate data points will give reliable results. Below this number, results can become suspect, especially for higher-dimension chaos and less accurate data. In practice, data sets with populations on the order of tens of thousands are preferred.

### A.8.3 Data Acquisition

Data acquisition, whether experiment or numerical, can be categorized as either active or passive. In active acquisition, the experimenter dictates and is able to acquire a complete data set. Sampling rate, volume, the number of and location of sensors, etc. can be affected in part or *in toto* by the experimenter. In active acquisition, the experimenter has enough knowledge of the system to know the dimension of the phase space wherein the attractor lies, and therefore has the ability to measure the complete or nearly complete requisite state variables to construct the attractor.

In some data acquisition setups, a completely active acquisition is not possible, and only a partial set of state variables is recordable. If the variables that the experimenter can record are truly a subset of the system variables or generalized coordinates, then the experimenter can possibly create a Poincaré map or section. For low-dimension chaos, the dimension of the complete attractor can be determined from the dimension of the Poincaré map.

In most field operations as done in the geosciences, even a partially active acquisition setup is not possible. Here the data acquisition is totally passive.

In passive acquisition, the system dictates. Data acquisition is limited to what the system is willing to give. In many passive studies the targeted system is of such complexity that the experimenter does not know the active state variables (i.e., phase-space variables) — let alone measure them.

Frequently, the experimenter can record only one variable as a function of time, creating a single-time series.

The analysis, interpretation, and utilization of single variable time series from multi-variable chaotic systems was a major and innovative step in the study of chaos. It is still the cornerstone of most analysis of non-numerical and nonlaboratory studies of chaos.

### A.8.4 Time Series Analysis

The time series analysis of data from a suspected chaotic system is called the time delay embedding method. It is based on creating a pseudo phase or an embedding space plot in place of the usual but now inaccessible phase-space plot (i.e., the actual attractor trajectory). An embedding space plot is derived directly from the time series. The method for calculating an embedding space is demonstrated in the following example.

Consider a simple phase space consisting of $x$ and $\dot{x}$, where $\dot{x}$ is the time derivative of $x$. To follow the evolution of a system, we follow $x$ and $\dot{x}$ as function of time $t$ by plotting $\dot{x}$ versus $x$. Recalling that $\dot{x} \approx [x(t+\Delta t) - x(t)]/\Delta t$, then knowledge of $x(t+\Delta t)$ is essentially equivalent to a knowledge of $\dot{x}$. Put slightly differently, a knowledge of a trajectory of points $[x(t), x(t+\Delta t)]$ is essentially equivalent to a knowledge of the trajectory of points $[x(t), \dot{x}(t)]$. This method can be generalized to create an embedding space plot from which attractor fractal dimension can be inferred.

A typical $n$-dimensional phase-space plot consists of a trajectory of points with each point of the form $x(t) = [x_1(t), x_2(t), ... x_n(t)]$ an $n$-tuple. In time delay embedding method, the phase-space trajectory $x(t)$ is replaced by an artificial trajectory or sequence of points $y(t) = \{y(t), y(t+\Delta t), ... y(t+m\Delta t)\}$ where $y(t)$ is the measured data. From a set of measurements of a single quantity $y(t)$, a sequence of points of an artificial phase space is constructed. Mathematically, this sequence of points makes up the points of trajectory of the embedding space and is of the form

$$x(t) = [y(t), y(t+\Delta t), ..., y(t+m\Delta t)]$$

$$x(t+\Delta) = [y(t+\Delta t), ..., y(t+m\Delta t)]$$

$$x(t+2\Delta) = [y(t+2\Delta t), ..., y(t+(m+2)\Delta t)]$$

.

.

.... etc. ....

Then, from this series of points in the embedding space, a correlation dimension is calculated and the chaos analysis continues.

The choice of $\Delta t$, which is some number of discretized data sampling intervals, is usually made after some trial and error. Typically, it is equal to the data sampling or digitizing interval. If the data sampling interval was not fortuitously chosen to fit the dynamics, then other criteria must be used. For example, if $\Delta t$ is too long (i.e., greater than information decay time), the data points do not correlate and the data are essentially random. If $\Delta t$ is too short, evolution of the system is not strongly reflected in neighboring data points and extremely large data sets are required.

Of particular importance is the determination of $m$. Usually, the correlation dimension is computed for a series of values $m = 1,2,\ldots$. The correlation increases with increasing $m$. However, once $m$, the dimension of the embedding space, is large enough the correlation dimension saturates and becomes constant. If $m_o$ is the minimum value of $m$ for which the correlation dimension approximately equals the saturated value, then $d = m_o + 1$ is called the embedding dimension, which is the minimum dimensionality of the pseudo phase space necessary to include the attractor. It has been shown (Moon, 1987) that embedding dimension is related to attractor dimension $D$ by the expression $d = 2D + 1$. Or, put in a different way, in order to use an embedding space approach to analyze an attractor from a time series, a $2D + 1$ dimension space must be used. It is easy to see that large time series and extensive computing are required for an embedding analysis.

In addition to the time delayed embedding method, Wolf et al. (1985) have shown that a time series can be used to directly determine the Lyapunov exponent and quantify chaos. It is only mentioned here and not described because it is quite complex.

## A.8.5 Noise, Error, Inaccuracy, and Predictability

In all data acquisition, a number of factors may be present that obfuscate analysis and interpretation. These include but are not limited to noise, instrument insensitivity and inaccuracy, inaccessibility of the system, rate at which system produces measurable data, and data digitizing length. When a system is suspected of being chaotic, these factors are particularly frustrating since the usual methods for suppression used in traditional dynamics cannot be used. These methods typically exploit the regularity, predictability, or coherence in data which are not present in chaotic data. Simply put, noise and chaos look too much alike for these methods.

Moller et al. (1989) quantified the study of errors in large data sets (i.e., 20,000 data points). They examined two types of error: random noise and digitize (i.e., resolution or bit-length error). Although these results have limited applications to small data set field studies, Moller et al. (1989) found that random noise tended to give overestimates of the calculation of attractor dimension and digitizing error caused underestimates. Interestingly, these are opposite-signed affects, but as pointed out by Moller et al. (1989), they do not simply cancel.

When noise, errors, inaccuracies, etc. are strong components of a data set, it is equivalent to having a random or stochastic component in the data. If the random component is dominant, the data may simply be unusable. However, if noise etc. does not totally overwhelm the data and if chaotic dynamics of the system are low dimensional, noise can sometimes be minimized by the use of the time delay embedding method which was described (Guckenheimer, 1982; Kostelich and Yorke, 1990).

Using the embedding method, inaccuracies in the embedded trajectories can be identified and corrected. In addition, numerical evidence suggests that this noise reduction method improves the accuracy of other analyses, including the Lyapunov exponent and dimension calculations (Kostelich and Yorke, 1990).

Sugihara and May (1990) present a method in which nonlinear forecasting is used as a way of distinguishing chaos from measurement error in time series. They distinguish between chaos and error by asserting that: "for a chaotic time series the accuracy of forecasting falls off with increasing the prediction-time (at a rate which gives an estimate of the Lyapunov exponent), whereas for uncorrelated noise, the accuracy is roughly independent of prediction interval." Their basic premise is that if deterministic laws govern the system, then even if dynamical behavior is chaotic, the future may to some extent be predicted from the behavior of past values that are similar to those of the present. They applied their method to a number of highly sampled, natural systems and showed surprisingly good results.

### A.8.5.1 Fractal Basin Boundaries

If a classical (i.e., nonchaotic) system has more than one attractor and, hence, more than one basin of attraction, an additional source of error can occur. If the initial conditions of the system are uncertain by an amount $\epsilon$, then for those initial conditions within $\epsilon$ of the boundary between the basins, an *a priori* prediction cannot be made as to which attractor the orbit will tend.

This situation is worse in chaotic systems. Here the basin boundaries between strange attractors are fractal. Grebogi et al. (1987) examined the problem of fractal basin boundaries and found that for one example, the equations for a forced damped pendulum, to gain a factor of 2 in ability to predict the asymptotic final state of the system, it was necessary to increase the accuracy of the measurement of conditions by a factor substantially greater than 2, here about 10. They concluded that fractal basin boundaries represent an obstruction to the predictability in nonlinear dynamics.

## A.9 CHAOS OR STOCHASTICS

A key issue in the study of dynamics is distinguishing between a chaotic and stochastic system and the implications of one to the other when neither can be uniquely precluded. The crucial issues in this exercise are data volume, degrees of freedom, and noise. The identification and suppression of noise in a chaotic analysis has been presented. In a stochastic approach, removal of random noise is a contradiction, since the full data set is assumed random. However, if additional information like a model or an analogue is available, then noise suppression may be possible based on presumed probability distribution.

### A.9.1 Data Volume

If the volume of data is small, choosing a stochastic or chaotic approach and accepting the resulting interpretation may be unwarranted and an undefendable position. Interpreting data from an insufficiently sampled system can give incomplete and misleading results. Similarly, interpreting data about a sparsely occurring event can also give misleading results. The decision as to the utility and quality of the interpretation of an analysis is that of the experimenter and analyst. The sampling interval and the implication of sparse occurrences are two characteristics which frequently can be examined from a theoretical modeling approach.

## A.9.2 Degrees of Freedom

Given a sufficient data volume, if a system—whether classical or chaotic—has many degrees of freedom that are active (e.g., multiple attractors or high-dimension single attractor), it is most likely the best and only analysis of data from this system is stochastic. Although the system is not random, its complexity is such that it precludes a deterministic approach and a yield of traditional or chaotic parameters.

In some cases, a stochastic analysis of data created by a low-dimension chaotic system is an acceptable and possibly only means of useful analysis and interpretation. This is true for short recording windows where transients have not damped out, and where noise or inaccuracy are strong factors in the data.

If an adequate data volume is recorded and the degrees of freedom of a system are low or have compressed down to be equivalently low, then a chaotic analysis is warranted. If the system is found to be chaotic, then more specific information can be determined about the system and its development from a chaos analysis than from a stochastic analysis. A chaotic state imposes limitations on its analysis, but it is still a deterministic system in which closer and more careful scrutiny can yield an increase in understanding. Closer scrutiny does not necessarily increase reliability of a stochastic description.

If an investigation of a complex and possibly chaotic system shows a unique attractor trajectory, the fractal dimension of such an attractor constitutes strong evidence for a significant reduction in complexity. For example, attractors with dimensions of less then 5 represent systems having great reduction in complexity and are potentially understandable beyond a statistical description. Procaccia (1988) discusses the point that chaotic attractors with low dimension of less than 3 indicate a system near the transition between nonchaotic (i.e., predictable) and chaotic. Higher dimensional states, although well within the chaotic regimes, may be far from being considered highly complex or randomly disordered.

## A.9.3 Length of Reliable Prediction

An interesting contrast between chaos and stochastics is prediction or forecasting the future state of the system and expected data.

In stochastics, prediction is not a realistic characteristic. A stochastic description is a probabilistic forecast, not a predictive description of potential future states of the system. A more pertinent issue for a stochastic description is reliability of the underlying assumptions of analysis.

The underlying assumption of a stochastic analysis is stationarity; the system will continue to generate the same characteristic random data indefinitely. This implies to the investigator that once the probability distribution of the random variable is identified, it is assumed that distribution will continue to describe random behavior of the system indefinitely. If the physical or dynamic state of the system changes in a manner not included in the distribution of the random variable, then the stochastic characteristics of the system must be re-evaluated for applicability. Such a change is not included in any part of the stochastic description. A stochastic description is based on the concept that a large enough data set has been recorded that intrinsic random or probabilistic behavior of the system is quantified and such behavior continues indefinitely.

If the data window used to formulate probability distribution is too small, then the stochastic description must be questioned. If there is reason to believe, based on information other than that in the recorded data set, that the state of the system may change from that indicated by the data, length of the reliable probabilistic description can be questioned. For example, long-term trends in short-windowed data can be obscured by noise, error, and inaccuracies. In an under-sampled system, additional data must be recorded, if possible, to demonstrate continued reliability of the stochastic description.

In contrast to stochastics, chaos allows a predictive description. That is, the sensitive dependence on initial condition character of a chaotic state allows prediction. However, quality of the prediction necessarily degrades and is very dependent on the quality and precision of data used to formulate description of the system. The central issue of chaotic prediction is length of reliability time window of prediction. The time window is an innate characteristic of the system being investigated and the data used to formulate the prediction.

When determining length of the reliable prediction of a chaotic system, the attractor trajectory, or more specifically Lyapunov exponent $\lambda$, is critical. A positive Lyapunov exponent determines the rate of stretching or separation of attractor trajectories. This means that $\lambda$, which is calibrated in bits and time, measures loss of predictive power (i.e., information) of the initial condition as the system evolves. As described, the time window limit of predictability is given by the accuracy length of the recorded data in bits divided by the Lyapunov exponent. Obviously, determination of the Lyapunov exponent is a very important part of a study. There are a number of theoretical and data inversion methods which have been used to calculate the Lyapunov exponent (De Souza-Machado et al., 1990).

## A.10 CONCLUSION

Dynamics, chaos, fractals, stochastics, and information theory are individually complex and intricate topics. This appendix has been written to assist in explaining some aspects of these topics and their interrelationships. More detailed discussions can be found in the publications cited in section A.1.

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# APPENDIX B

# BIBLIOGRAPHY OF INFORMATION SOURCES ON NONLINEAR DYNAMICS (NOT CITED IN TEXT)

# APPENDIX B

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# APPENDIX C

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