Facies Analysis of Tertiary Basin-Filling Rocks of the Death Valley Regional Ground-Water System and Surrounding Areas, Nevada and California

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Abstract

Existing hydrologic models of the Death Valley region typically have defined the Cenozoic basins as those areas that are covered by recent surficial deposits, and have treated the basin-fill deposits that are concealed under alluvium as a single unit with uniform hydrologic properties throughout the region, and with depth. Although this latter generalization was known to be flawed, it evidently was made because available geologic syntheses did not provide the basis for a more detailed characterization. As an initial attempt to address this problem, this report presents a compilation and synthesis of existing and new surface and subsurface data on the lithologic variations between and within the Cenozoic basin fills of this region. The most permeable lithologies in the Cenozoic basin fills are freshwater limestones, unaltered densely welded tuffs, and little-consolidated coarse alluvium. The least permeable lithologies are playa claystones, altered nonwelded tuffs, and tuffaceous and clay-matrix sediments of several types. In all but the youngest of the basin fills, permeability probably decreases strongly with depth owing to a typically increasing abundance of volcanic ash or clay in the matrices of the clastic sediments with increasing age (and therefore with increasing depth in general), and to increasing consolidation and alteration (both hydrothermal and diagenetic) with increasing depth and age. This report concludes with a categorization of the Cenozoic basins of the Death Valley region according to the predominant lithologies in the different basin fills and presents qualitative constraints on the hydrologic properties of these major lithologic categories.

Introduction

Cenozoic basin-fills of the Death Valley region (fig. 1) range from late Eocene to Quaternary in age, from coarse to fine in grain size, from fresh to strongly altered, and from unconsolidated to well consolidated. They include a broad range of both volcanic and sedimentary lithologies including lavas, welded and nonwelded tuffs, and alluvial, fluvial, colluvial, eolian, paludal, and lacustrine sediments. The presence of excellent aquifers within parts of these basin fills has been demonstrated by long-term well-water production (Dudley and Larson, 1976; Harrill, 1986), whereas the presence of spring discharge sites in other areas has been related to structural juxtaposition of confining units within some basin fills against more permeable rocks (Winograd and Thordarson, 1975; Hunt and others, 1966; Dudley and Larson, 1976). Despite their great lithologic diversity and proven large variation in hydrologic behavior, those parts of the Cenozoic basin-filling sequences of the Death Valley region that are covered by recent surficial deposits have commonly been modeled as a unit with uniform hydrologic properties, both throughout the region and with depth (IT Corp., 1996; D'Agnese and others, 1997).

Much of the mystery surrounding the Cenozoic basin fills of the Death Valley region reflects the fact that the basins typically have been defined in hydrologic models as the areas of present-day cover by unconsolidated surficial deposits. These recent surficial deposits are also part of the Cenozoic basin fills, but in most of the region are too thin to extend below the water table. Lateral lithologic variations in these largely post-tectonic surficial deposits typically bear little or no relationship to those in the older, dominantly synextensional and early extensional basin-fill deposits at the depth of the water table and below. Exposures of consolidated Cenozoic strata are treated in most hydrologic models as a separate hydrologic unit (or units) from adjacent, concealed basin-fill strata. However, most outcrops of consolidated Tertiary strata that are exposed adjacent to alluvial cover are within the original area of the basins, most of which formed in the Miocene. In most cases, these strata project down under the adjacent alluvium and are the lateral equivalents to strata concealed under the recent alluvium. These exposures of basin fill show that strong lateral changes in lithology, thickness, and structure exist

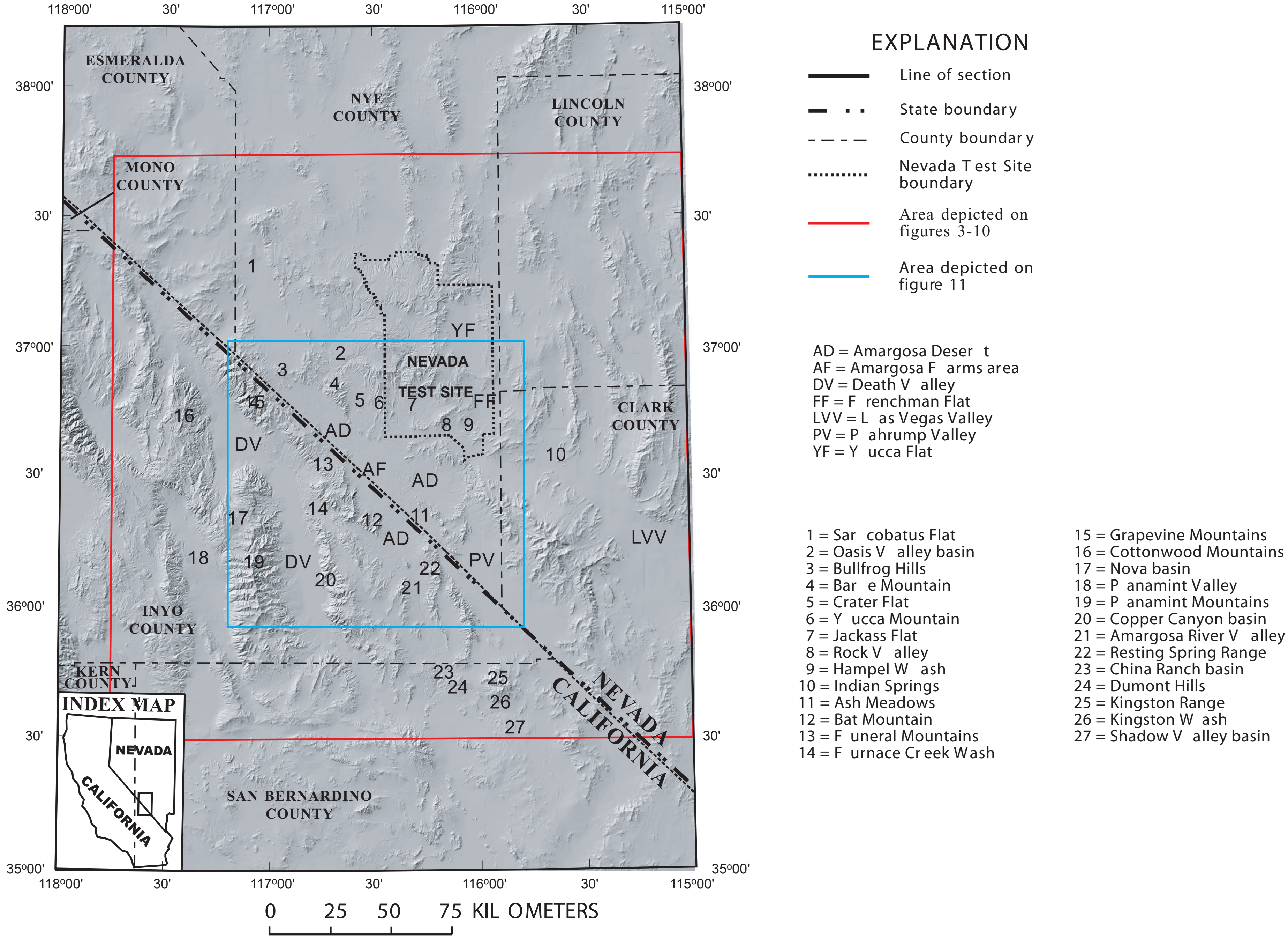


Figure 1. Location map and place names, Death Valley region, Nevada and California

within these deposits. Under the areas of alluvial cover, these changes are concealed, but much can be surmised by interpolating and extrapolating from adjacent exposures, in combination with borehole and geophysical data.

This report presents a facies analysis of Tertiary basin-filling deposits for the Death Valley region, exclusive of the named volcanic units in the vicinity of the southwestern Nevada volcanic field. The purpose of this report is to assemble the available information on lithologic variations within the Cenozoic basin-filling sequences throughout the Death Valley region, based on surface mapping data, drill-hole data, and geophysical constraints. These data are then applied to development of a generalized characterization of the lithologic variability of the basin fills, along with available qualitative information about the relative hydrologic properties of the different lithologies.

Cenozoic Stratigraphy of the Death Valley Region

This lithologic study addresses primarily the southern part of the Death Valley groundwater flow system of the southwest Great Basin, Nevada and California (Bedinger and others, 1989). In the Cenozoic, this region has undergone a complex history of transtensional deformation, which has ultimately created a tectonic landscape that is a mosaic of alternating, narrow basins and ranges (basin-range topography). As the tectonic basins of this region formed and evolved, they were filled by a locally thick sequence of terrestrial sediments and volcanic rocks, which provide a record of the Cenozoic environmental history of this region. This history shows three major types of changes in this region over the last 40 m.y., each of which has had a major impact on the lithologies in the basin-fill sequences (Fridrich and others, 2000):

- A progressive change from the initially humid conditions of the Late Eocene, to the very arid conditions of today. This climatic change is reflected in a change from a dominance of fluvial cobble conglomerates and freshwater limestones in the oldest basin-fill sequences to a dominance of alluvial fan breccias and playa claystones in the youngest deposits. In addition, the early humid conditions fostered the production of clay as a product of weathering, a process that has diminished strongly with time.

- Progressive tectonic fragmentation of the region. The earliest Cenozoic tectonism apparently created very broad and shallow basins. Basin-range topography, as we know it today, first developed in the Death Valley region from ~14-to-~12 Ma, it evolved through three successive tectonic episodes, and it is still actively evolving in the southwesternmost part of the Death Valley region, and to the west. The tectonic evolution of this region is reflected in changes in sedimentation patterns, from an earlier pattern dominated by regional-scale fluvial transport to a later pattern dominated by sedimentary transport and deposition largely confined within relatively small intermontane basins with local sediment sources.

- Volcanic input to the basins as a result of the strong pulse of volcanism in mid and late Miocene time, primarily from the southwestern Nevada volcanic field and to a lesser extent from the central Death Valley volcanic field. From ~40 to 15 Ma, the Death Valley region had no local volcanism. A variety of volcanic fields were the source for distal tuffs that reached the region in this initial prevolcanic interval. Most of these volcanic source areas were in central and southern Nevada and together they defined a slowly southward-migrating pattern of volcanism. The migrating pattern of volcanism eventually moved into the Death Valley region at ~15 Ma, peaked with very high eruption rates between 13.5 and 11 Ma, and then declined with time as the focus of volcanism migrated generally westward, largely moving out of the region at ~6 Ma. This volcanic history is reflected in changing input of both primary volcanic units and of volcaniclastic detritus into basin fills throughout this history. Moreover, the volcanism and related tectonism provided the heat for local hydrothermal activity, which has greatly reduced the permeability of some basin-fill deposits, especially of nonwelded tuffs and ashy sediments.

Tertiary strata of the Death Valley region have been subdivided into seven unconformity-bounded sequences (see fig. 8; Snow and Lux, 1999; Fridrich and others, 2000). These seven sequences can, in turn, be generalized into three sequences according to their relation to the tectonic evolution of the region: (1) an early extensional sequence that predates the formation of basin-range topography, (2) a synextensional sequence that corresponds to the major period of formation of basin-range topography in this region, and (3) a 6-Ma-to-present late extensional to post-extensional sequence.

The base of the early extensional sequence, which is the basal Tertiary contact, varies in age from ~40 to ~25 Ma over different parts of the region. This variation appears largely to reflect progressive burial of topography, as discussed below. In general the basal Tertiary contact youngs to the west and south within the Death Valley region. The contact between the early extensional and synextensional sequences varies from ~14 to ~12 Ma in different locales, reflecting local variations in the onset of basin-range tectonism, or the change in sedimentary depositional environments that occurred as a consequence of basin-range tectonism. The basal synextensional contact generally youngs to the northwest. The contact between the synextensional and the late extensional sequences varies from ~10 Ma in the northeasternmost part of the Death Valley region to ~6 Ma in Death Valley and west of it. Above this contact the strata are late extensional from eastern margin of Death Valley westward, and they are post-tectonic to the east of Death Valley. The early extensional sequence was prevolcanic up to ~15 Ma, when andesite-rhyolite volcanism gradually migrated into the region from the north and east. The synextensional sequence coincided with the dominant period of volcanism in the region, which was bimodal in character. The late- to post-extensional sequence corresponds to a period of waning, largely basaltic volcanism in the Death Valley region.

Early Extensional Sequence

Sedimentary strata deposited before the creation of basin-range topography are widely distributed throughout the Death Valley region. The major unifying characteristics of these early extensional deposits are that: (1) lateral changes in lithology in these strata are mostly very gradual throughout the region, (2) abrupt lateral thickness changes in the lowermost (~40 to 27 Ma) part of this sequence apparently reflect burial of moderately high-relief topography at the basal Tertiary surface, some of which evidently was tectonic in origin, and (3) in the few cases where abrupt lateral facies and thickness changes are found in the middle and upper (27 to ~14 Ma) part of this sequence, they correspond spatially to a small number of long-abandoned structures that are locally exposed within the modern-day ranges, rather than to topographically expressed (modern-day) basin-range boundaries.

Lithologically, the early extensional sequence can be divided into three major packages, as a generalization. The oldest of these packages largely ranges in age from ~40 to ~25 Ma and consists dominantly of conglomerates and lesser basal breccias, both of cobble-to-boulder-size, mostly in clay-rich matrices. The next package covers the age range from ~25 to ~19 Ma and consists mostly of interbedded fluvial sandstones, freshwater limestones and marls, and lesser playa claystones and pebble conglomerates. Together, these two oldest lithologic packages have been named the Titus Canyon Formation in the Grapevine Mountains (Reynolds, 1974), in the northern Funeral Mountains (Wright and Troxel, 1993), and in an area immediately west of the Nevada Test Site (Fridrich, Minor, Ryder, and others, 1999). They have also been called the Ubehebe Formation in the Cottonwood Mountains (Snow and Lux, 1999), the conglomerate and limestone members of the Amargosa Valley Formation in the southeast Funeral Mountains (Cemen and others, 1999), and the brown gravel unit of the rocks of Joshua Hollow on the northeast side of Bare Mountain (Monsen and others, 1992). In the Rock Valley area, the equivalent rocks have been called the rocks of Winapi Wash (J. Yount, USGS, oral comm., 1992). Earlier, they were mapped as the Horse Springs Formation (Hinrichs, 1968), a lithologically similar, but younger (20-12 Ma) unit exposed in the area east of Las Vegas (Bohannon, 1984). On most other maps of the region, the strata of these oldest two lithologic packages have been lumped with other strata as older Tertiary sediments.

Strata that range in age from ~19 to ~17 Ma are apparently absent throughout the Death Valley region, owing to nondeposition or erosion (Fridrich and others, 2000). The uppermost of the three sections of the early extensional sequence, above this missing section, exhibits greater lithologic variability than all of the older Cenozoic strata. This uppermost sequence is ~16 Ma at the base and, as discussed above, has a top that ranges in age from ~14 to ~12 Ma. Volcanic rocks within this uppermost early extensional sequence consist of andesitic agglomerates and lavas of the central Death Valley volcanic field in the southern part of the region and rhyolitic tuffs of the southwestern Nevada volcanic field in the northern part of the region. Both of these volcanic sections were deposited on a basal (~16 to ~14 Ma) section of sediments, mostly arkosic fluvial sandstones (mostly redbeds) in the south and fine-grained tuffaceous sediments with locally thick interbedded conglomerates in the north. Moreover, both volcanic sections interfinger laterally with arkosic red sandstones that constitute the majority of this section in the central part of the region. Volcanic units of the southwestern Nevada volcanic field are in general not considered in this report. Only in those areas where tuffs of probable affinity to the southwestern Nevada volcanic field are intercalated with coeval Tertiary sediments and have not been explicitly identified are they included as part of the undifferentiated Tertiary basin-filling rocks.

This uppermost of the three early extensional sections includes the unnamed redbed sections intermittently exposed on either side of the Beatty Junction cutoff road from ~2 to ~9 km south-southeast of Hell's Gate, at the northwest limit of the Funeral Mountains (Wright and Troxel, 1993). It also includes the Panuga Formation of the Cottonwood Mountains (Snow and Lux, 1999). In the southeastern Funeral Mountains, it is the upper part of the Amargosa Valley Formation. In the Kingston Range, the equivalent section is the lower part of the Resting Spring Formation, which is composed predominantly of sandstone, limestone, and andesite (Fowler and Calzia, 1999; Friedmann, 1999). In the southwestern Nevada volcanic field, this section includes a basal part, which has variably been called the Tunnel Formation (in the northern part of the volcanic field, where it consists dominantly of bedded tuffs) or the rocks of Pavits Spring (in the southern part of the volcanic field, where it consists dominantly of tuffaceous sandstones), among other names, and an upper (~14-to-~12-Ma) part, which consists of volcanic formations including the Lithic Ridge Tuff and associated units, the tuffs and lavas of the Crater Flat Group, and the Wahmonie Formation (Sawyer and others, 1994).

Hydrologically, the early extensional sequence of the Death Valley region shows a range of behaviors. The coarse clastic sediments with clay-rich matrices that constitute the majority of the lowermost part of this sequence are predominantly confining units. The best evidence for this is the common localization of springs at contacts between Late Proterozoic quartzites and these clay-matrix sediments, especially where the quartzites are exposed uphill from the Tertiary sequence. These quartzites are generally impermeable except where they are locally fractured; they have been classified as part of the lower clastic aquitard of the Death Valley region (Winograd and Thordarson, 1972). The setting of these hillside springs suggests that the clay-matrix sediments of the lower part of the early extensional sequence are even less permeable. Parts of the volcanic sections of the uppermost (16-to-~12-Ma) part of the early extensional sequence are known to be aquifers, especially the densely welded tuffs. For example, the tuffs of the Crater Flat Group, which have been penetrated by numerous drill holes into Yucca Mountain and Crater Flat, have been shown to be good water producers in many of these wells (Waddell and others, 1984; Luckey and others, 1996). The other strata of the early extensional group largely have unproven hydrologic characteristics, but probably cover a broad range of properties. Where these sediments are strongly tuffaceous, they typically also are quite altered and probably are impermeable. The arkosic sandstones in this sequence probably are only marginal aquifers, because they typically contain abundant tuffaceous material that is strongly diagenetically altered. Limestones, as a rock type, should be a good aquifer, but existing data suggest that the limestones in this sequence are very discontinuous, which would strongly limit their importance as aquifers, even if they are very permeable.

The hydrologic behavior of the early extensional sequence also depends upon the structural setting in addition to the lithologic factors discussed above. Deposition of this sequence predated most of the strong transtensional deformation that has occurred in the Death Valley region in the Cenozoic, so these rocks are tectonically disrupted in much of the region. This probably has resulted in structural dismemberment of the aquifers in this sequence in many areas. However, the confining units in this sequence are also dismembered in many areas and are strongly faulted in most of the region; hence these confining units, at a minimum, are probably rather leaky in most areas. At Yucca Mountain, it is clear from the difference in head between the deep Paleozoic carbonate aquifer and the welded tuff aquifer, in well USW p#1, that the impermeable strata in the lower part of the early extensional sequence, which intervene between these two aquifers, act as an effective confining unit. Thermal and carbon-isotopic data on groundwater under Yucca Mountain also show, however, that this confining unit leaks along the major faults cutting the mountain (Fridrich and others, 1994).

In summary, the lower and middle part of the early extensional sequence is typically a leaky confining unit, and the upper part is mixed in properties as a function of locale. In some areas it is a leaky confining unit like the underlying rocks and elsewhere it is a moderately permeable aquifer like most of the overlying units.

Synextensional Sequence

In the early extensional sequence, lateral changes in stratigraphic thicknesses and lithologic characteristics are very gradual in all directions, in general. In particular, there are no appreciable changes across the crests or range-fronts of present-day mountain ranges. Locally, the uppermost (~14-to-~12-Ma) part of the ~40-to~12-Ma strata of the region includes some tectonic sediments that are related to the initial development of a small number of the most major basin-range faults that were active primarily after 12 Ma. These earliest group of sediments that are synextensional (relative to the major basin-range-forming tectonic episode) consist primarily of coarse alluvium. At ~12 Ma, the shift to predominantly local provenance of the clastic sediments, which had from ~14 to ~12 Ma been confined to a very localized range, was abruptly extended over the whole central and eastern part of the region, reflecting the initial uplift of the modern-day mountain ranges, excepting those west of the Death Valley physiographic feature. This major basin-range-forming tectonic episode, which began locally at ~14 and became regionally extensive at ~12 Ma, continued until about 10 Ma in the northeasternmost part of the Death Valley region and to ~6 Ma in the vicinity of the Northern Death Valley/Furnace Creek fault.

The synextensional part of the fill of each of the region's basins is essentially a separate formation in each basin. Each of these synextensional basin fills has considerable individuality in its thicknesses, lithologies, provenance of clasts, and many other features. Moreover, lateral variations in these features are found within each of these basin fills that (1) commonly bear a relationship to the northwestward migration of the focus of tectonism during the synextensional episode, and (2) commonly exceed the variability of the early extensional sequence across the entire region. Moreover, the diversity of lithologies in the synextensional strata exceeds that of any of the younger or older basin-fill deposits because: (1) the climate during the synextensional episode was transitional between the relatively humid before and the relatively arid conditions after this time period, resulting in the interlayering of sedimentary rocks deposited in varying climatic conditions, and (2) volcanic activity peaked in the synextensional episode, resulting in a greater abundance and diversity of volcanic rocks than that found in both the younger and older deposits. Because of the very high rate of felsic pyroclastic volcanic activity, early (~14-to-~10-Ma) synextensional alluvial deposits of this age range typically have matrices that contain significantly more tuffaceous material than do any younger or older alluvium of the region.

As variable as the lithologies are in the synextensional sequence, and as much as they vary in character between the different basins of the region, there are certain generalizations that can be made about the characteristics of these deposits, as a function of geographic position:

(1) In the vicinity of the southwestern Nevada volcanic field, the major lithologies in the synextensional sequence consist of moderately to densely welded tuffs, alluvial and landslide breccias, as well as some nonwelded tuffs and lavas (Byers and others, 1976; Sawyer and others, 1994). The majority of these deposits are at least moderately permeable, except in the area immediately in and around the central caldera complex of the volcanic field, where hydrothermal alteration has destroyed much of the original permeability (Winograd and Thordarson, 1975; Blankennagel and Weir, 1973; Laczniak and others, 1996). Moreover, the horizons within these strata that are relatively impermeable are sufficiently faulted in most cases that they probably are not effective confining units. The approximate areal extent of volcanic rocks derived from the southwestern Nevada volcanic field is defined to the west by outcrops in the Funeral and Grapevine Mountains, to the south and southeast by borehole intercepts along U.S. Highway 95 south of Yucca Mountain and in northwestern Frenchman Flat, and to the east by depositional pinchouts near the Nye County-Lincoln County line. The area in which this characterization applies includes the synextensional sections found in the following alluvial basins: Yucca Flat, Frenchman Flat, Jackass Flats, Crater

Flat, Oasis Valley basin, and Sarcobatus Flat (fig.1). In all of these basins, these synextensional deposits overlie early extensional strata that are leaky confining units. The deep carbonate aquifer is known or presumed to underlie Yucca Flat, Frenchman Flat, and at least parts of the Crater Flat and Jackass Flats basins, but is probably absent under the majority of the Sarcobatus Flat basin. In the vicinity of the southwestern Nevada volcanic field, the synextensional section consists of the tuffs and lesser lavas of the Paintbrush, Timber Mountain and Thirsty Canyon Groups, along with many lesser volcanic units and interbedded, largely unnamed sediments.

(2) In the area of the central Death Valley rhombochasm (Wright and others, 1991), which extends from the east flank of the Panamint Mountains eastward to the Resting Spring Range and from the southwest flank of the Funeral Mountains southward to southern Death Valley fault zone, synextensional basin fills are largely sedimentary at the base - including conglomeratic sandstones and breccias - but otherwise consist primarily of bimodal (dacite-basalt) volcanic rocks and tuffaceous sediments (McAllister, 1970; 1973; 1974; Cemen and others, 1985; Wright and others, 1991; Greene, 1997). Throughout the majority of this area, these rocks are hydrothermally altered to the point where the original permeability has been largely destroyed, except perhaps in some of the coarsest sediments, locally found near the base of synextensional sections and near the margins of the basin. Significant permeability probably has survived in these deposits only in very limited locales. The only deposits recognized as significant aquifers within this synextensional basin-fill sequence are breccias found along the western flank of the Resting Spring Range (Cemen, 1983) that are presumed to project westward under the adjacent part of the Amargosa River Valley. Some permeable breccias may also be present immediately adjacent to the southwestern flank of the Funeral Mountains. Otherwise, the synextensional basin fill deposits of the central Death Valley rhombochasm probably are fairly impermeable. The early extensional sequence is structurally omitted within most of the Death Valley rhombochasm (Wright and others, 1999); synextensional deposits are structurally complex and have been included as part of the Amargosa Chaos in the

southwestern part of the basin (Wright and Troxel, 1984; Topping, 1993). In the rest of the basin, the major named parts of the synextensional basin fill include the Artist Drive Formation and the coeval Shoshone volcanics as the major units (Wright and others, 1991). Paleozoic carbonates probably are present beneath the easternmost part of this basin, but are likely to be tectonically thinned and discontinuous throughout most of the central Death Valley rhombochasm.

(3) In the area of the China Ranch basin, Dumont Hills, and around the perimeter of the Kingston Range, synextensional Cenozoic deposits consist largely of very coarse alluvium and rock-avalanche breccias, which are probably quite permeable, and lesser amounts of impermeable playa claystones (Fowler and Calzia, 1999; Prave and McMackin, 1999; Friedmann, 1999). The playa claystones are present in restricted areas where they typically are completely surrounded by alluvium and breccias; hence, it is improbable that they form effective confining units because groundwater may flow around these areas of impermeable sediments. The limited exposures of synextensional sediments in the Pahrump Valley are of sediments similar to those in the China Ranch-Kingston Range area. The synextensional deposits in this area are largely unnamed but include the China Ranch beds and the fill of the Shadow Valley basin on the south side of the Kingston Range (Prave and McMackin, 1999; Friedmann, 1999).

(4) The Amargosa Desert is the most difficult basin to characterize hydrogeologically within the southern Death Valley ground-water system, partly because this huge area of alluvial cover is a composite of several structural basins. Additionally, Cenozoic strata exposed on different sides of this basin differ strongly in their lithologies, suggesting the presence of pronounced lateral facies changes. Sediments having the characteristics described in all of the above three areas are found in different parts of the Amargosa Desert basin. The synextensional sequence (along with the uppermost part of the underlying early extensional sequence) includes a large thickness of permeable densely welded tuffs in the three areas that border the western arm of the Amargosa Desert, namely, the Crater Flat basin (Fridrich, 1999; Fridrich, Whitney, and others, 1999), the

Bullfrog Hills (Maldonado, 1990; Fridrich, Minor, and Mankinen, 1999), and the hills along the northern flank of the Funeral Mountains, just south of the Bullfrog Hills (Wright and Troxel, 1993). Aeromagnetic data indicate, however, that equivalent volcanic rocks are present only in a spotty fashion under the alluvium that intervenes between the exposures in these three areas (Grauch and others, 1999; Blakely and others, 2000). The drilling evidence that exists in this intervening area (the western arm of the Amargosa Desert) indicates that the basin fill is mostly sedimentary, consisting of an upper permeable part, mostly alluvium, and a lower part, consisting mostly of tuffaceous sediments that probably are not very permeable owing to diagenetic alteration. In the eastern arm of the Amargosa desert, the few synextensional deposits that are exposed closely resemble those of basins to the south and east (category 3, above) and are likely to be permeable. These sediments overlie an impermeable early extensional sequence; hence the synextensional aquifer in this area may be separated from the underlying deep carbonate aquifer in at least part of the area by a leaky, heavily faulted and probably discontinuous confining unit. The central part of the Amargosa Desert is a north-trending trough, which is much deeper than the east and west arms of the Amargosa Desert basin-complex (Blakely and others, 1999). The basin fill in the northern part of this trough resembles that of the western arm of the Amargosa Desert (Oatfield and Czarnecki, 1989; Carr and others, 1995), whereas that of the southern part of the trough is more similar to the central Death Valley rhombochasm, but with a larger proportion of interbedded sandstones, which probably have moderate to low permeability (Naff, 1973). In summary, the basin fill includes a widespread high quality alluvial aquifer in the east and west arms of the Amargosa Desert and in the northern part of the central trough. Permeability of the basin-fill decreases southward within the southern part of the Amargosa trough (Oatfield and Czarnecki, 1989; Naff, 1973), based on the southward increasing abundance of altered nonwelded tuffs. Southward along the course of the Amargosa River, transmissive rocks likely are present again in a narrow corridor under this valley from just south of Eagle Mountain to the town of Shoshone, where exposed basin fill deposits consist of less permeable lithologies (Morrison, 1999). Further south, the Amargosa River flows through basin fill of the China Ranch area, which is permeable except in a few areas dominated by playa sediments (Prave and McMackin, 1999; Morrison, 1999). The locations of active springs and Pleistocene spring deposits along the course of the Amargosa River, as well as the stretches where this river flows most of the year, tend to mirror the changes in lithology of basin-filling deposits exposed along the course of this river.

Late extensional/post-extensional sequence

As discussed above, the synextensional sequence ends upsection at a contact that varies in age from ~10 Ma in the northeastern part of the Death Valley region to ~6 Ma in the vicinity of Death Valley, and to the west. East and north of the Death Valley rhombochasm, this overlying section is post-tectonic and consists largely of alluvium and lesser sediments of other types, mainly playa sediments. Within the Death Valley rhombochasm and to the west, these deposits are late extensional because extensional tectonism has continued in most of this area to the present, but the lithologies are basically the same as where this section is post-tectonic. Because the volumetrically dominant alluvial deposits of this youngest section largely postdate felsic pyroclastic volcanism in the region, the alluvium is not particularly tuffaceous. In most of the region, this alluvium has never been deeply buried and generally it is poorly consolidated. The majority of the late extensional/post-extensional sequence is therefore permeable. The major places where it is not permeable is in those areas where it consists mostly of playa sediments, such as much of the Furnace Creek basin (in the northernmost part of the Death Valley rhombochasm), and on the floor of Death Valley physiographic feature.

Stratigraphic Setting of Tertiary Basin-Filling Deposits

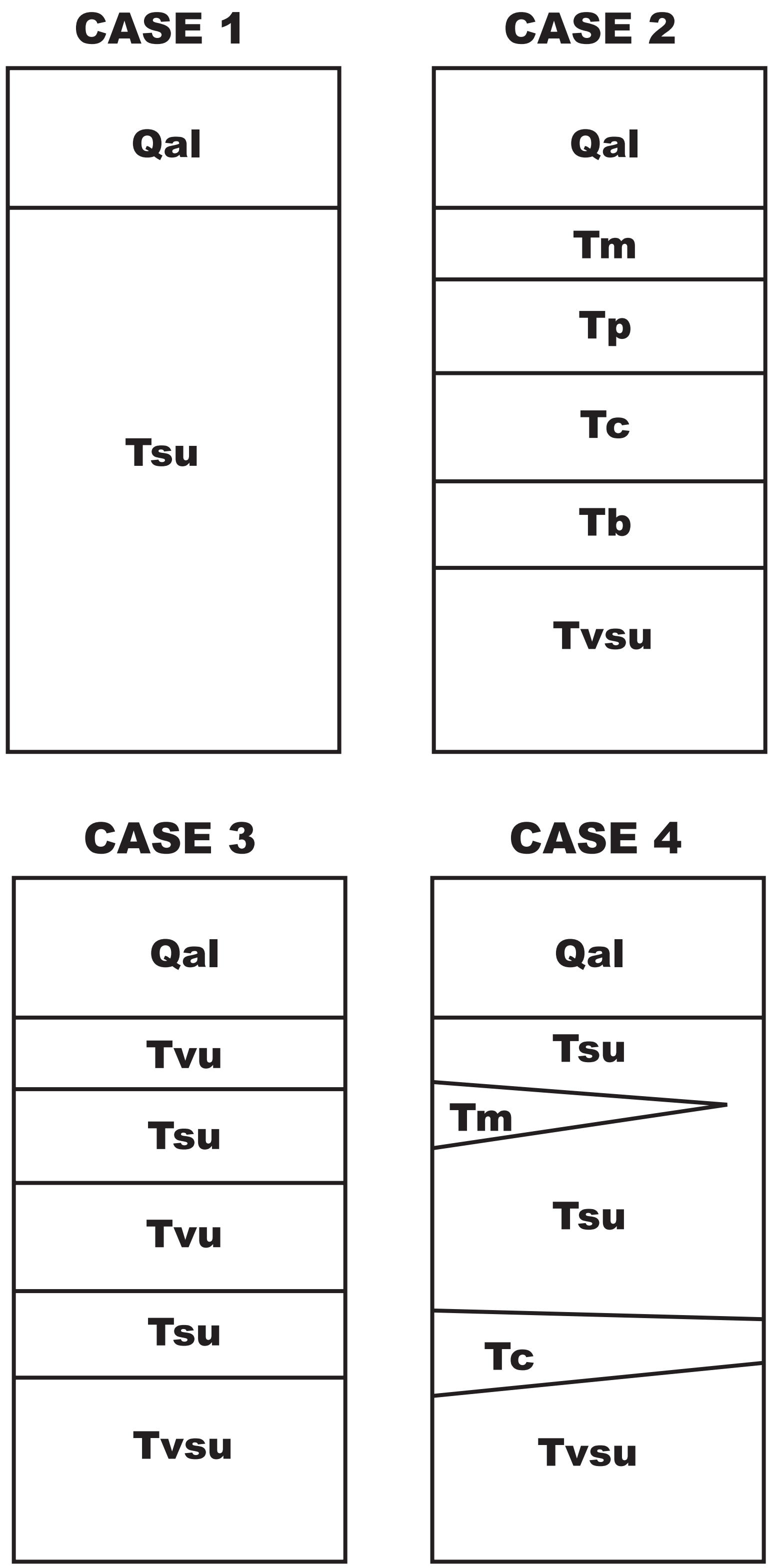
Regional ground-water flow models of the Death Valley region (IT Corp., 1996; D’Agnese and others, 1997) have described the Tertiary basin-filling rocks using a hydrogeologic unit that encompasses the entire undifferentiated sequence of Tertiary basin fill. When modeled as a single hydrogeologic unit, these rocks appear in various stratigraphic scenarios, described below in order of their increasing complexity.

In case 1 (fig. 2), Tertiary sedimentary rocks directly underlie Quaternary alluvium. Sedimentary sections are free of thick intervals of volcanic rocks, although the sedimentary units may have a volcaniclastic component. This is the case in Las Vegas Valley and the Indian Springs area where the Middle Miocene Horse Springs Formation is overlain by the Las Vegas Formation and Quaternary valley fill (Bohannon, 1984; Plume, 1989); in Hampel Wash and Rock Valley on the Nevada Test Site where the “rocks of Winapi Wash” and the “rocks of Pavits Spring” are overlain by Quaternary alluvium (Hinrichs, 1968); and in Kingston Wash and the northern part of the Shadow Valley basin where Tertiary conglomerates and megabreccias are overlain by Quaternary sediments (Friedmann, 1999; Prave and McMackin, 1999).

In case 2 (fig. 2) Tertiary sedimentary rocks underlie a thick sequence of regionally extensive ash-flow tuffs derived from the southwestern Nevada volcanic field. The volcanic units are thick enough and well enough known to be modeled as their own hydrogeologic units (rather than being lumped with the Tertiary sediments as in case 3). Situations like case 2 occur in northwestern Frenchman Flat, Yucca Flat and beneath portions of southern Yucca Mountain (fig. 1). As the volcanic pile thickens proximal to the volcanic sources, boreholes do not penetrate the entire thickness of the volcanic rocks. Thus, the extent of the Tertiary sediments beneath the volcanic rocks is unknown close to the volcanic source.

In case 3 (fig. 2), Tertiary sediments are interbedded with Tertiary volcanic rocks such that neither can be modeled as a separate hydrogeologic unit at the scale of a regional model. This situation occurs in much of the central Death Valley volcanic field, Furnace Creek Wash and the Amargosa Desert. This is the approach used in analyzing the outcrop and borehole data presented in this report.

In case 4 (fig. 2), named volcanic units of the southwestern Nevada volcanic field interfinger at their distal edges with coeval Tertiary sediments. This is the most complex situation to model because of the potential for repetition of hydrogeologic units – something to be avoided. Situations like this occur in narrow bands near the margins of



Explanation

Qal Quaternary alluvium

Miocene volcanic rocks of the southwestern Nevada volcanic

Tm Timber Mountain Group
Tp Paintbrush Group
Tc Crater Flat Group
Tb Belted Range Group

Types of Tertiary basin-filling

Tvsu Tertiary sedimentary and volcanic rocks, undivided

Tsu Tertiary sedimentary rocks, undivided

Tvu Tertiary volcanic rocks, undivided

Figure 2. Diagrammatic examples of possible stratigraphic position of undifferentiated Tertiary volcanic and sedimentary rocks.

the volcanic field; for example, in central Frenchman Flat and in some of the Nye County Early Warning Drilling Program (EWDP) boreholes to the south of Yucca Mountain.

Methods of Study

Outcrop Data

Various workers have collected outcrop data from Tertiary strata during the course of studies attempting to reconstruct the Tertiary extensional history of the region. Outcrops of Tertiary strata are present mostly as stranded, rotated successions along range fronts. In a number of cases, the base of the Tertiary section is exposed, but not the top; this represents a possible source of bias in the data. Uncertainty also exists in how far to project the geology preserved in these outcrops into the subsurface. Tables 1 and 2 present a compilation of outcrop data from throughout the region; a total of 33 localities are presented. Locations of the outcrop data are shown in figure 3. The data compilation includes total thickness, aggregate thickness of the volcanic component (including rhyolite and basalt flows, tuff, and air-fall deposits), aggregate thickness of the sedimentary component (including conglomerate, megabreccia, sandstone, siltstone, and limestone), and the thickness of the limestone portion of the sedimentary sequence.

Subsurface Data

Boreholes have been drilled in the Tertiary basin fill for various reasons including mineral exploration, water wells, test holes on the Nevada Test Site and as part of the site characterization at Yucca Mountain. Most of the boreholes do not penetrate the entire Tertiary section, leading to an underestimation in the total thickness of the section, and a bias towards data from the upper part of the section. Data quality is variable -- some of the data from the Amargosa Desert are from driller’s logs where the Tertiary sedimentary section may be reported as “gravel”, “colluvium” or “paleocolluvium”. Tables 3 and 4 present a compilation of borehole data from throughout the region, a total of 64 localities. Borehole locations are shown in figure 3. Many more boreholes are available, but these holes were chosen to mimic the density of the outcrop data, provide a broad spatial distribution, include the deepest boreholes, and include those holes that were representative of a closely-spaced group of boreholes.

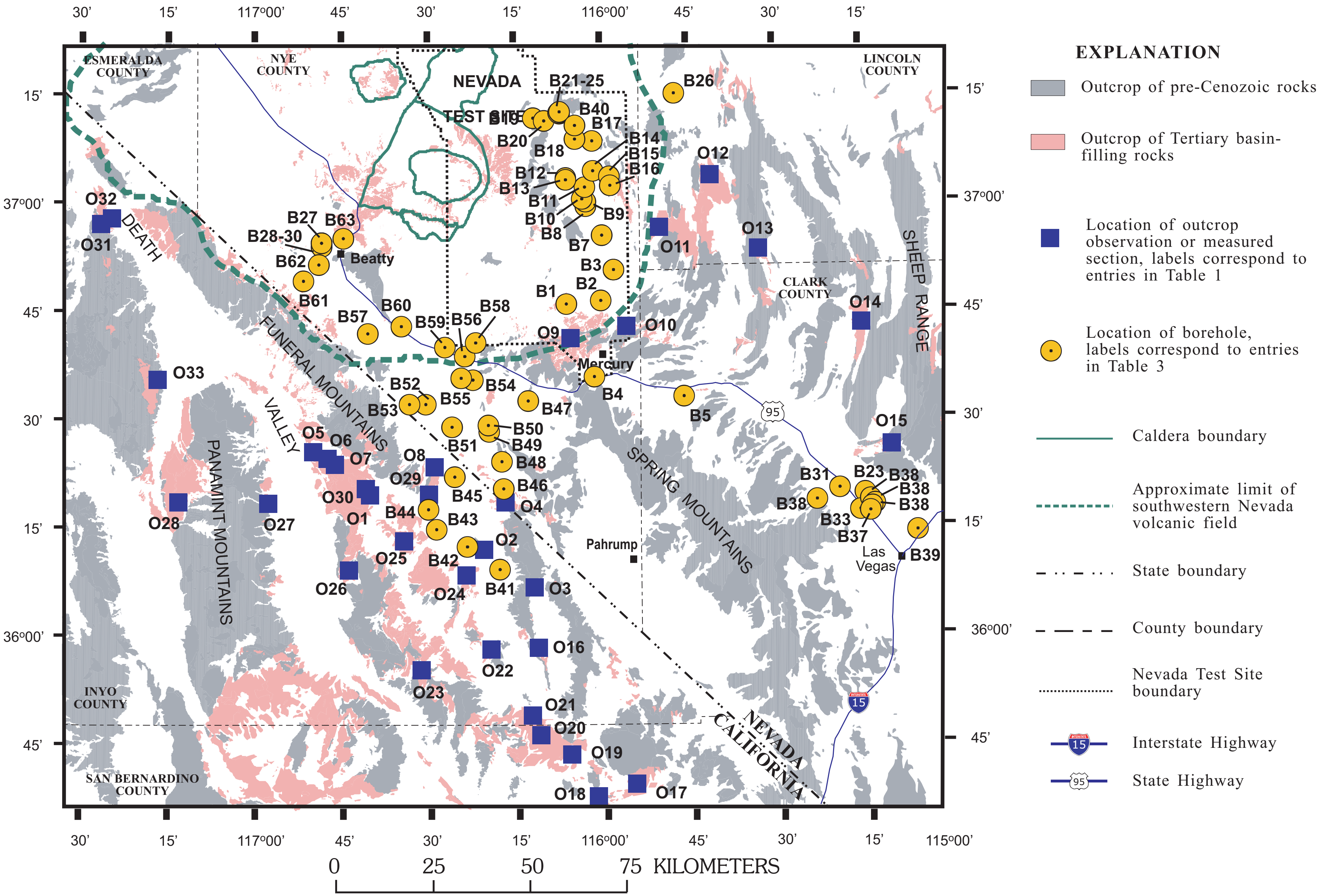


Figure 3. Location map of outcrops and boreholes used in this study.

Table 1. Location of outcrop data used for facies analysis

Location Number	Location Name	Latitude	Longitude	Reference
O1	Ryan Mine	36° 18’ 38”	116° 40’ 16”	Niemi and others (2001), fig. 2; Cemen and others (1985).
O2	Eagle Mountain	36° 11’ 40”	116° 20’ 46”	Niemi and others (2001), fig. 2 and Appendix 1.
O3	East of Resting Spring Range	36° 06’ 27”	116° 12’ 03”	Niemi and others (2001), fig. 2 and Appendix 1.
O4	North of Resting Spring Range	36° 18’ 18”	116° 16’ 53”	Cemen (1983); Denny and Drewes (1965)
O5	Black Mountains, section B-B'	36° 25’ 22”	116° 49’ 59”	Niemi and others (2001), fig. 14; Greene (1997).
O6	Black Mountains, section E-E'	36° 24’ 26”	116° 47’ 36”	Niemi and others (2001), fig. 14; Greene (1997).
O7	Black Mountains, section G-G'	36° 23’ 40”	116° 46’ 21”	Niemi and others (2001), fig. 14; Greene (1997).
O8	Bat Mountain north	36° 21’ 04”	116° 28’ 59”	Cemen and others (1985), fig. 4; Cemen and others (1999), fig. 7.
O9	Hampel Wash	36° 41’ 04”	116° 05’ 28”	Hinrichs (1968).
O10	Mercury quadrangle	36° 42’ 43”	116° 55’ 53”	Barnes and others (1982).
O11	Nye Canyon	36° 56’ 28”	116° 49’ 59”	Hinrichs and McKay (1965).
O12	Buried Hills	37° 03’ 42”	116° 41’ 01”	Tschanz and Pampeyan (1970); Guth and others (1988).
O13	Gravel Canyon, Pintwater Range	36° 53’ 25”	116° 32’ 55”	Longwell and others (1965); Guth and others (1988).
O14	Black Hills basin	36° 42’ 59”	116° 15’ 11”	Guth and others (1988).
O15	Gass Peak basin	36° 25’ 55”	116° 10’ 14”	Guth and others (1988).
O16	Southern Resting Spring Range	35° 57’ 57”	116° 11’ 23”	Wright (1999).
O17	Kingston Wash	35° 38’ 54”	116° 54’ 49”	Prave and McMackin (1999), fig. 9.
O18	Western Kingston Wash	35° 37’ 15”	116° 01’ 28”	Prave and McMackin (1999), fig. 9.
O19	Dumont Hills, section E	35° 43’ 05”	116° 05’ 51”	Prave and McMackin (1999), fig. 6.
O20	Dumont Hills, section C	35° 45’ 49”	116° 11’ 07”	Prave and McMackin (1999), fig. 6.
O21	Amargosa Canyon, China Ranch	35° 48’ 32”	116° 12’ 31”	Holm and others (1994), fig. 11.
O22	Dublin Hills	35° 57’ 51”	116° 19’ 35”	Chesterman (1973).
O23	Salsberry Pass	35° 55’ 00”	116° 31’ 36”	Wright and Troxel (1984).
O24	Greenwater Range, Brown Peak	36° 08’ 06”	116° 23’ 49”	Wright and others (1981).
O25	Greenwater Range, Funeral Peak area	36° 13’ 00”	116° 34’ 27”	Drewes (1963).
O26	Copper Canyon basin	36° 08’ 55”	116° 43’ 57”	Drewes (1963).
O27	Trail Canyon	36° 18’ 13”	116° 57’ 44”	McKenna and Hodges (1990).
O28	Nova basin	36° 18’ 27”	116° 13’ 18”	Hodges and others (1989).
O29	Bat Mountain south	36° 19’ 24”	116° 30’ 05”	Snow and Lux (1999), fig. 6; Cemen and others (1999), fig. 9.
O30	Billie Mine	36° 20’ 17”	116° 40’ 59”	Wright and others (1999).
O31	Cottonwood Mountains, Section UH1	36° 57’ 10”	116° 26’ 48”	Snow and Lux (1999), plate 2.
O32	Cottonwood Mountains, Section UH2	36° 57’ 56”	116° 24’ 59”	Snow and Lux (1999), plate 2.
O33	Cottonwood Mountains, Section CC1	36° 35’ 29”	116° 16’ 59”	Snow and Lux (1999), plate 2.

Table 2. Thickness data for lithologic types from measured sections and outcrop descriptions

Location Number	Total exposed thickness, in m	Thickness of sedimentary rocks, in m				Thickness of volcanic rocks, in m		
		All sedimentary rocks	Coarse-grained clastic rocks	Fine-grained clastic rocks	Limestone	All volcanic rocks	Flows and welded tuff	Falls and nonwelded tuff
O1	925	625	590	23	12	330	0	330
O2	295	295	268	27	0	0	0	0
O3	295	280	0	0	0	15	0	15
O4	750	550	400	150	0	200	0	200
O5	950	555	220	335	0	395	395	0
O6	1790	665	380	285	0	1105	1105	0
O7	1700	0	0	0	0	1700	1700	0
O8	1282	1279	777	282	220	3	0	3
O9	1780	1494	386	950	158	286	201	85
O10	785	625	395	0	230	160	160	0
O11	225	40	40	0	0	185	0	185
O12	1800	1800	1800	0	0	0	0	0
O13	1600	1300	300	0	0	300	0	300
O14	1800	1300	1300	300	0	200	0	200
O15	293	285	49	44	192	8	0	8
O16	1500	50	30	0	20	1450	1450	0
O17	270	270	150	120	0	0	0	0

Table 2. Thickness data for lithologic types from measured sections and outcrop descriptions -- Continued

Location Number	Total exposed thickness, in m	Thickness of sedimentary rocks, in m				Thickness of volcanic rocks, in m		
		All sedimentary rocks	Coarse-grained clastic rocks	Fine-grained clastic rocks	Limestone	All volcanic rocks	Flows and welded tuff	Falls and nonwelded tuff
O18	450	450	450	0	0	0	0	0
O19	2200	2200	2000	200	0	0	0	0
O20	1000	1000	900	100	0	0	0	0
O21	660	660	460	200	0	0	0	0
O22	335	23	0	0	0	312	312	0
O23	740	55	0	55	0	685	665	20
O24	2200	0	0	0	0	2200	2000	200
O25	1125	60	0	60	0	1065	1065	0
O26	3000	2900	2000	900	0	100	100	0
O27	635	0	0	0	0	635	635	0
O28	2300	2200	2200	0	0	100	100	0
O29	595	585	490	0	95	10	0	10
O30	1300	960	910	0	50	340	220	120
O31	635	560	560	0	0	75	75	0
O32	1010	995	995	0	0	15	15	0
O33	392	375	350	15	10	7	7	0

Table 3. Location of borehole data used for facies analysis

[Data are compiled from the following sources: USGS – NWIS: U.S. Geological Survey National Water Information System; State of Nevada: State of Nevada, Division of Water Resources, Well Driller's Report; for cited publications, see "References" section of this report]

Location Number	Location Name	Latitude	Longitude	Data Source
B1	TW- F (1871 ft)	36° 45' 34"	116° 6' 59"	USGS - NWIS
B2	TH- 5	36° 46' 1"	116° 1' 3"	USGS - NWIS
B3	UE- 5c WW	36° 50' 11"	115° 58' 47"	USGS - NWIS
B4	Army 1 WW	36° 35' 30"	116° 2' 14"	USGS - NWIS
B5	Army 3	36° 32' 38"	115° 46' 46"	USGS - NWIS
B7	WW- C-1	36° 55' 0"	116° 0' 39"	USGS - NWIS
B8	UE- 6d	36° 59' 5"	116° 3' 32"	USGS - NWIS
B9	WW- 3	36° 59' 43"	116° 3' 29"	USGS - NWIS
B10	UE- 1h	37° 0' 5"	116° 4' 3"	USGS - NWIS
B11	UE- 1r WW	37° 1' 42"	116° 3' 33"	USGS - NWIS
B12	UE- 1d	37° 3' 1"	116° 6' 53"	USGS - NWIS
B13	UE- 1f	37° 2' 46"	116° 6' 49"	USGS - NWIS
B14	U - 3an 3	37° 3' 54"	116° 2' 14"	USGS - NWIS
B15	TH- 9	37° 3' 11"	115° 59' 18"	USGS - NWIS
B16	U - 3mh (NT 1008)	37° 1' 57"	115° 59' 14"	USGS - NWIS
B17	UE- 9 ITS US-U-22	37° 8' 7"	116° 2' 17"	USGS - NWIS
B18	U - 2df (NT 604)	37° 8' 22"	116° 5' 15"	USGS - NWIS
B19	U -12e.03-1	37° 11' 22"	116° 12' 22"	USGS - NWIS
B20	Effinger 4	37° 10' 59"	116° 10' 30"	USGS - NWIS
B21	Whiterock Springs 3	37° 11' 58"	116° 7' 55"	USGS - NWIS
B22	Whiterock Springs 3A	37° 11' 59"	116° 7' 52"	USGS - NWIS
B23	Whiterock Springs 1	37° 12' 4"	116° 7' 55"	USGS - NWIS
B24	USGS Shot Hole	37° 12' 5"	116° 8' 2"	USGS - NWIS
B25	Whiterock Springs 2	37° 12' 10"	116° 7' 50"	USGS - NWIS
B26	Watertown 2 WW	37° 14' 39"	115° 48' 00"	USGS - NWIS
B27	Amargosa Farms 45672	36° 54' 8"	116° 49' 1"	State of Nevada
B28	Amargosa Farms 40410	36° 54' 7"	116° 49' 1"	State of Nevada
B29	Amargosa Farms 51620	36° 54' 7"	116° 48' 60"	State of Nevada

Table 3. Location of borehole data used for facies analysis - continued

[Data are compiled from the following sources: USGS – NWIS: U.S. Geological Survey National Water Information System; State of Nevada: State of Nevada, Division of Water Resources, Well Driller's Report; for cited publications, see "References" section of this report]

Location Number	Location Name	Latitude	Longitude	Data Source
B30	Amargosa Farms 66226	36° 53' 42"	116° 49' 00"	State of Nevada
B31	Janet Aubrey	36° 19' 49"	115° 20' 18"	USGS - NWIS
B32	C.R. Coke	36° 19' 8"	115° 16' 1"	USGS - NWIS
B33	Laurence Barringer	36° 16' 45"	115° 16' 49"	USGS - NWIS
B34	Unknown	36° 18' 15"	115° 15' 9"	USGS - NWIS
B35	Don W. Charleboix	36° 17' 32"	115° 14' 21"	USGS - NWIS
B36	J.J. Fairchild	36° 17' 9"	115° 14' 53"	USGS - NWIS
B37	Leon Bright	36° 16' 36"	115° 15' 12"	USGS - NWIS
B38	H. & Edna Bierbach	36° 18' 16"	115° 24' 13"	USGS - NWIS
B39	CNLV Leavitt	36° 13' 49"	115° 7' 5"	USGS - NWIS
B40	UE- 8e (2470 ft)	37° 10' 14"	116° 5' 16"	USGS - NWIS
B41	US Borax Exploration SEM-5	36° 8' 53"	116° 18' 41"	State of Nevada
B42	US Borax Exploration AM-2	36° 12' 1"	116° 24' 14"	State of Nevada
B43	US Borax Exploration L-3	36° 14' 27"	116° 29' 27"	State of Nevada
B44	US Borax Exploration S-2	36° 17' 13"	116° 30' 48"	State of Nevada
B45	US Borax Exploration NA-8	36° 21' 43"	116° 26' 19"	State of Nevada
B46	US Borax Exploration GS-3	36° 19' 58"	116° 17' 54"	State of Nevada
B47	USGS Tracer Study Exploratory Hole 3	36° 32' 12"	116° 13' 36"	Johnston (1968)
B48	Nye County Land Co. Amargosa Farms 9343	36° 23' 48"	116° 18' 12"	State of Nevada
B49	Spring Meadows, Inc. Amargosa Farms 12942	36° 27' 52"	116° 20' 22"	State of Nevada
B50	Nye County Land Co. Amargosa Farms 9028	36° 28' 50"	116° 20' 28"	State of Nevada
B51	Michael Gilgan Amargosa Farms 6943	36° 28' 33"	116° 26' 43"	State of Nevada
B52	James E. Owens Amargosa Farms 20042	36° 31' 44"	116° 31' 9"	State of Nevada
B53	US Borax Exploration NT-1	36° 31' 47"	116° 34' 0"	State of Nevada
B54	Felderhoff Federal 25-1	36° 35' 6"	116° 23' 1"	Carr and others (1995)

Table 3. Location of borehole data used for facies analysis – continued

[Data are compiled from the following sources: USGS – NWIS: U.S. Geological Survey National Water Information System; State of Nevada: State of Nevada, Division of Water Resources, Well Driller's Report; for cited publications, see "References" section of this report]

Location Number	Location Name	Latitude	Longitude	Data Source
B55	Lawrence Funder Amargosa Farms 5926	36° 35' 19"	116° 25' 8"	State of Nevada
B56	Desert Farms Amargosa Farms 7702	36° 38' 22"	116° 24' 30"	State of Nevada
B57	US Borax Exploration NA-6	36° 41' 31"	116° 41' 5"	State of Nevada
B58	NC-EWDP-5S	36° 40' 12"	116° 22' 37"	State of Nevada
B59	NC-EWDP-2D	36° 39' 39"	116° 27' 57"	State of Nevada
B60	NC-EWDP-1S	36° 42' 33"	116° 35' 18"	State of Nevada
B61	Bond Gold Bullfrog Inc. BGMW- 3	36° 48' 53"	116° 52' 8"	State of Nevada
B62	Bond Gold Bullfrog Inc. ETW II- (PW-2)	36° 51' 10"	116° 49' 30"	State of Nevada
B63	Beatty Water District Amargosa Farms 52728	36° 54' 49"	116° 45' 13"	State of Nevada

Table 4. Thickness data for lithologic types from boreholes.

Location Number	Total exposed thickness, in m	Thickness of sedimentary rocks, in m				Thickness of volcanic rocks, in m		
		All sedimentary rocks	Coarse-grained clastic rocks	Fine-grained clastic rocks	Limestone	All volcanic rocks	Flows and welded tuff	Falls and nonwelded tuff
B1	436	436	0	436	0	0	0	0
B2	113	0	0	0	0	113	113	0
B3	421	0	0	0	0	421	421	0
B4	76	0	0	0	0	76	76	0
B5	136	0	0	0	0	136	136	0
B6	421	0	0	0	0	421	421	0
B7	332	0	0	0	0	332	0	332
B8	898	872	872	0	0	26	0	26
B9	244	244	244	0	0	0	0	0
B10	204	204	204	0	0	0	0	0
B11	3	3	3	0	0	0	0	0
B12	67	0	0	0	0	67	0	67
B13	73	52	52	0	0	21	21	0
B14	509	0	0	0	0	509	509	0
B15	311	0	0	0	0	311	0	311
B16	20	20	20	0	0	0	0	0
B17	358	0	0	0	0	358	358	0
B18	2	0	0	0	0	2	2	0
B19	220	0	0	0	0	220	220	0
B20	3	0	0	0	0	3	3	0
B21	13	0	0	0	0	13	13	0
B22	3	0	0	0	0	3	3	0
B23	22	0	0	0	0	22	22	0
B24	32	0	0	0	0	32	32	0
B25	26	0	0	0	0	26	26	0
B26	187	0	0	0	0	187	187	0
B27	393	0	0	0	0	393	393	0

Table 4. Thickness data for lithologic types from boreholes -- Continued.

Location Number	Total exposed thickness, in m	Thickness of sedimentary rocks, in m				Thickness of volcanic rocks, in m		
		All sedimentary rocks	Coarse-grained clastic rocks	Fine-grained clastic rocks	Limestone	All volcanic rocks	Flows and welded tuff	Falls and nonwelded tuff
B28	183	0	0	0	0	183	183	0
B29	95	0	0	0	0	95	94	1
B30	346	6	0	6	0	340	340	0
B31	166	166	166	0	0	0	0	0
B32	104	104	0	104	0	0	0	0
B33	47	47	7	40	0	0	0	0
B34	51	51	0	51	0	0	0	0
B35	69	69	18	51	0	0	0	0
B36	145	145	120	25	0	0	0	0
B37	30	30	8	22	0	0	0	0
B38	52	52	52	0	0	0	0	0
B39	304	304	6	298	0	0	0	0
B40	37	16	0	16	0	21	0	21
B41	263	252	252	0	0	11	5	6
B42	390	255	29	226	0	135	135	0
B43	563	450	224	192	34	113	42	71
B44	534	515	169	346	0	19	19	0
B45	583	583	375	208	0	0	0	0
B46	604	604	0	604	0	0	0	0
B47	92	90	90	0	0	2	2	0
B48	179	179	52	84	43	0	0	0
B49	248	248	0	154	94	0	0	0
B50	179	179	9	114	56	0	0	0
B51	90	90	0	90	0	0	0	0
B52	124	124	100	24	0	0	0	0
B53	468	300	234	0	66	168	168	0
B54	529	370	361	0	9	159	159	0

Table 4. Thickness data for lithologic types from boreholes – Continued.

Location Number	Total exposed thickness, in m	Thickness of sedimentary rocks, in m				Thickness of volcanic rocks, in m		
		All sedimentary rocks	Coarse-grained clastic rocks	Fine-grained clastic rocks	Limestone	All volcanic rocks	Flows and welded tuff	Falls and nonwelded tuff
B55	175	175	23	140	12	0	0	0
B56	187	187	107	80	0	0	0	0
B57	170	54	54	0	0	116	116	0
B58	278	251	101	50	0	27	0	27
B59	142	112	112	0	0	30	0	30
B60	715	590	337	253	0	125	78	47
B61	103	103	103	0	0	0	0	0
B62	172	172	172	0	0	0	0	0
B63	151	123	95	0	28	28	28	0
B64	427	0	0	0	0	427	427	0

Tertiary Thickness Modeled from Gravity Data

Inverse modeling of gravity data from the region (fig. 4) has greatly contributed to the knowledge of the Tertiary tectonic style and the subsurface configuration of the Tertiary basins (Blakely and others, 1999). Such models can be used to estimate the thickness of Tertiary basin fill, but with some caveats. The model estimates the thickness of Cenozoic deposits based on a computational inversion (Jachens and Moring, 1990) of gravity data (Saltus and Jachens, 1995; Blakely and others, 1998; Blakely and others, 1999) combined with density-depth assumptions. The models separate the pre-Cenozoic "basement" from the entire Cenozoic basin fill, including Tertiary and Quaternary sedimentary and volcanic rocks. In areas that are far from volcanic sources, such as the Pahrump Valley, portions of the Amargosa Valley and the Las Vegas Valley, the modeled thickness may approximate the thickness of the Tertiary basin-filling rocks. However, the gravity models do not separate out volcanic rocks where they are thick enough to be assigned their own hydrogeologic unit. Thus, the thickness of the Tertiary section as described by the gravity model is not indicative of the thickness of the undifferentiated Tertiary basin-filling rocks when close to volcanic fields.

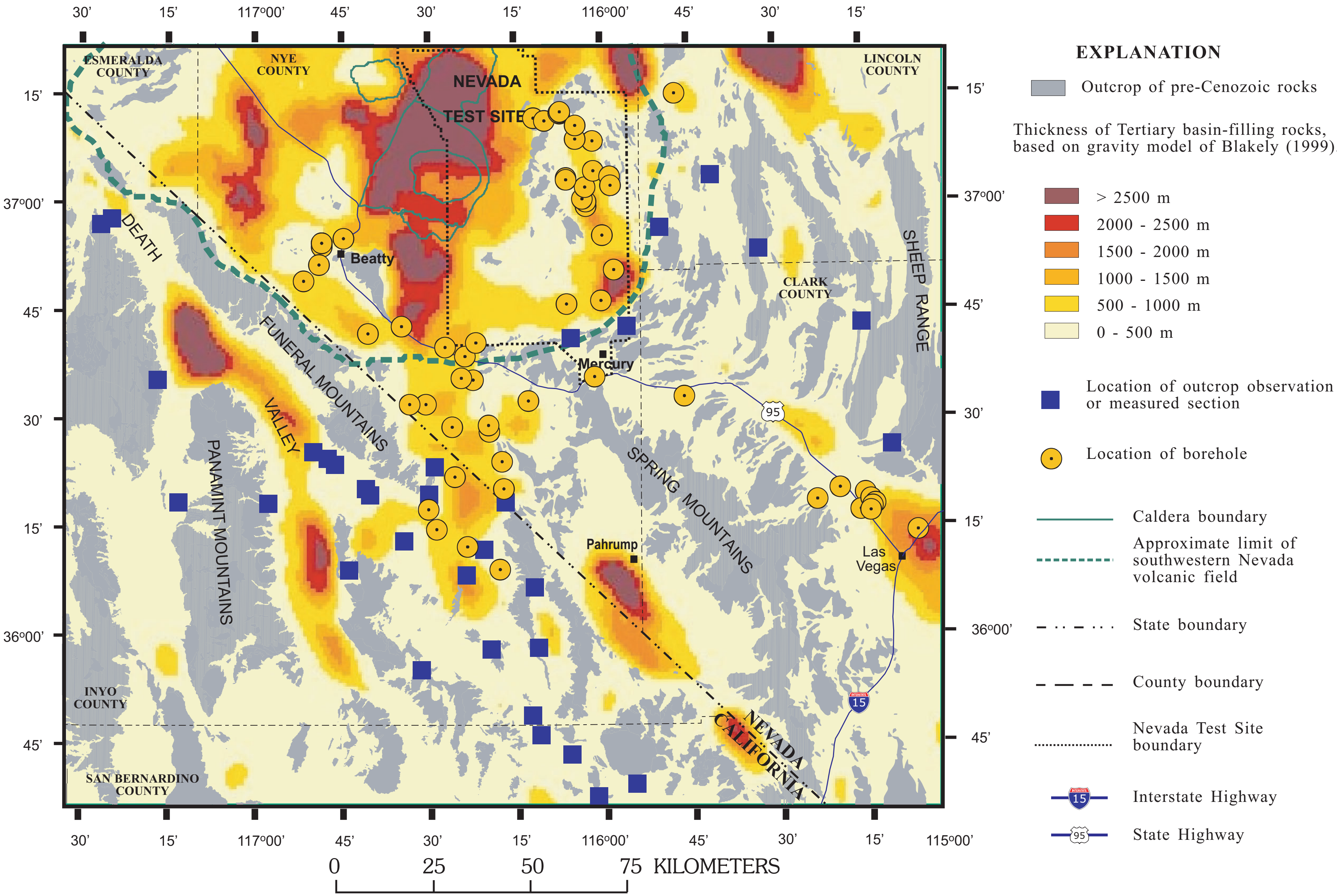


Figure 4. Thickness of Cenozoic basin fill based on gravity model.

Regional Facies Trends

Thickness

Thickness of undifferentiated Tertiary basin fill as measured from boreholes and outcrop is skewed toward outcrop data (fig. 5); most of the boreholes are shallow and underestimate the total thickness of the unit. The contoured data show bull's eye type trends due to sparse data coverage.

Thickness estimated from an inversion of the gravity data (Blakely and others, 1998; 1999) (fig. 4) better delineates the Tertiary basins, but includes all Cenozoic rocks. In areas that are far from volcanic sources, the modeled thickness may approximate the thickness of the Tertiary basin-filling rocks. Modeling of regional gravity data has revealed the presence of a number of deep troughs that are likely to be filled with Tertiary sedimentary rock (Blakely and others, 1999). Gravity modeling of the Stewart Valley-Pahrump strike-slip fault zone (roughly parallel to the California-Nevada boundary on figure 5) shows that the fault is associated with complex variations in the elevation of the Tertiary-Paleozoic contact (Blakely and others, 1998). In the Pahrump Valley, the Stewart Valley-Pahrump fault zone forms a buried transpressional bedrock ridge separating two steep-sided, probably fault-bounded Tertiary basins (Blakely and others, 1998). The basins are interpreted to be transtensional basins associated with right steps in this fault system (Wright, 1989; Blakely and others, 1998). To the northwest in the Amargosa Valley, this fault zone forms another northwest trending bedrock ridge that separates two northwest trending basins (Blakely and others, 1999). Modeling of regional gravity data from Death Valley reveals a number of narrow, step-sided, sediment-filled troughs (Blakely and others, 1999).

Compositional Trends

Figures 6 and 7 show the distribution of sedimentary and volcanic portions of the Tertiary basin fill, respectively. Depocenters for Tertiary sedimentary rocks include coarse conglomerates in the Kingston Wash area (southern edge of fig. 6) and the Nova basin to the west of the Panamint Mountains, as well as more localized sedimentary successions in Furnace Creek Wash, in the southern part of the Nevada Test Site, and in

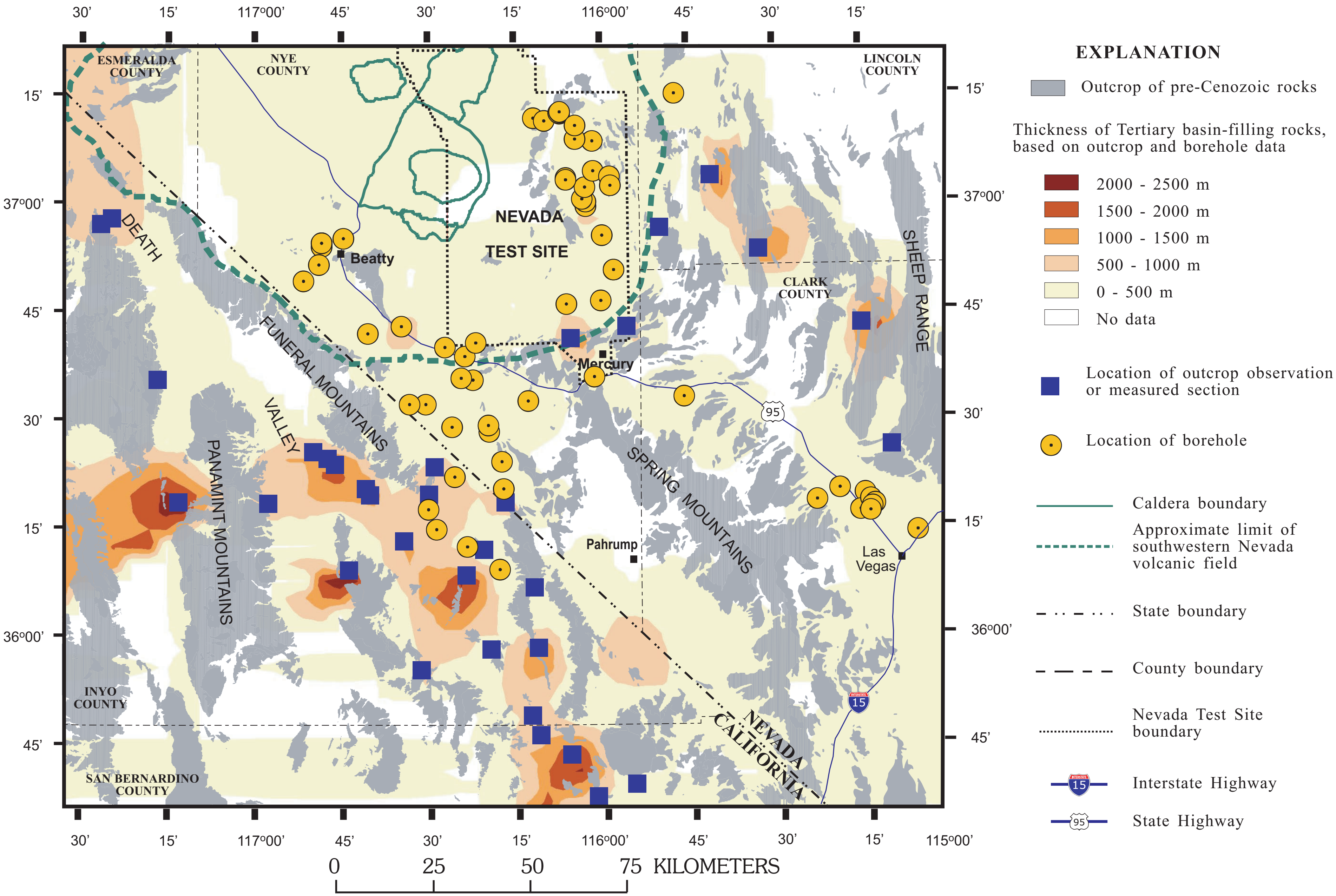


Figure 5. Thickness of undifferentiated Tertiary basin fill based on measurements in outcrop and in boreholes.

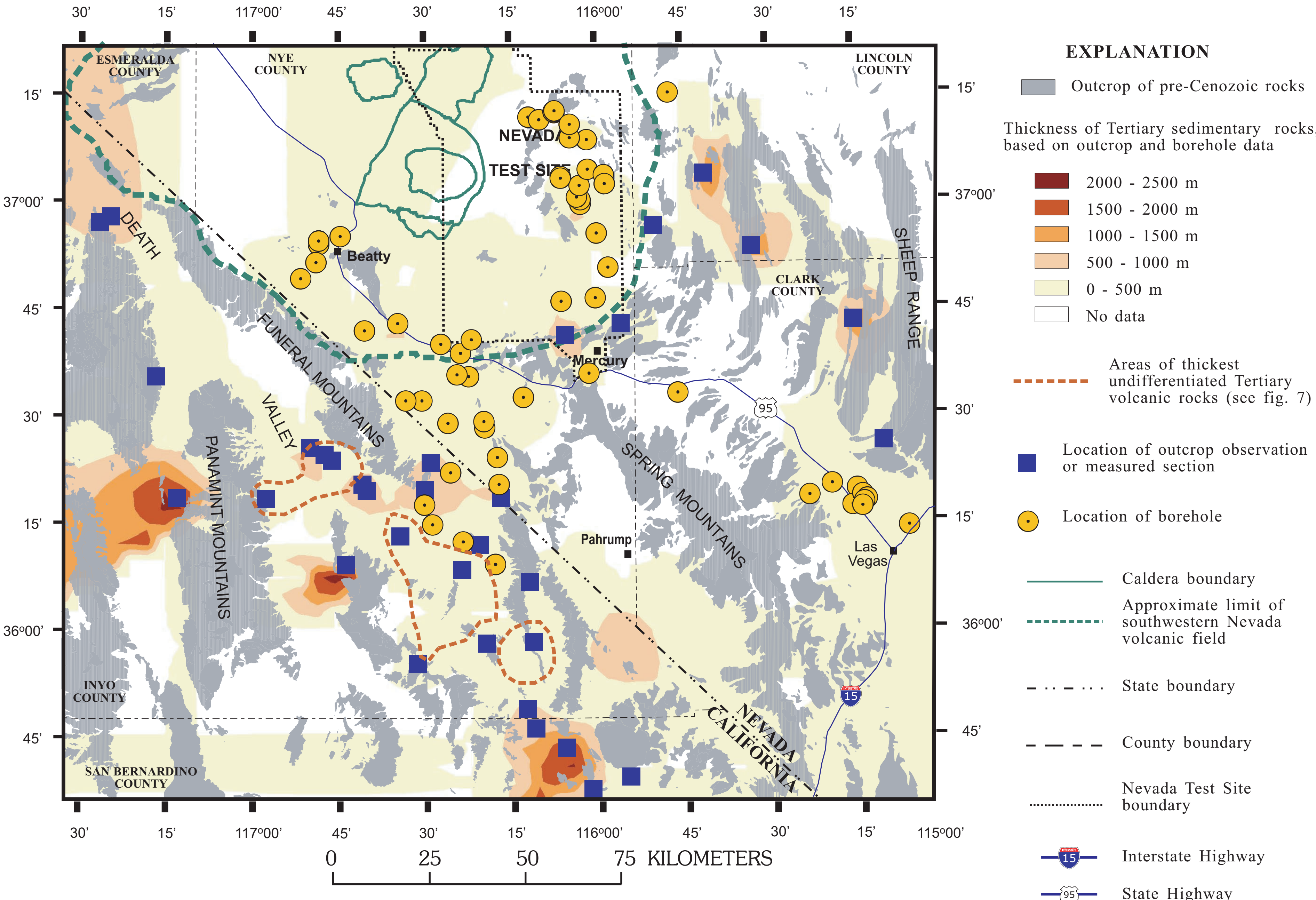


Figure 6. Thickness of Tertiary sedimentary rocks based on measurements at outcrops and in boreholes.

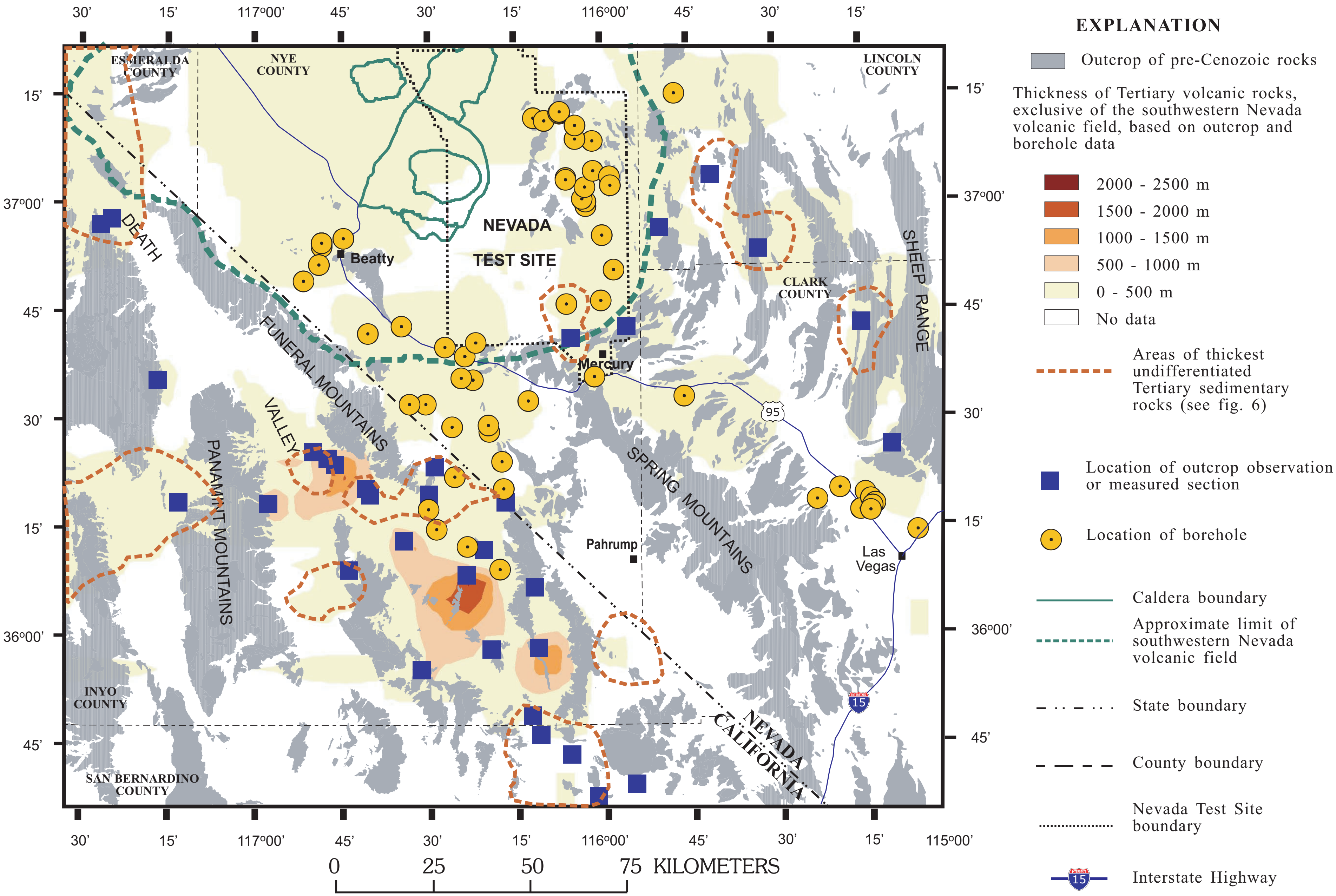


Figure 7. Thickness of Tertiary volcanic rocks outside the southwestern Nevada volcanic field.

Lincoln County. The extent of sediments under the volcanic pile of the southwestern Nevada volcanic field is largely unknown. Shallow boreholes in the northwest part of the Las Vegas Valley do not penetrate the thick Tertiary section in the center of the valley (Longwell and others, 1965; Plume, 1989). The extensive Tertiary sedimentary rocks that underlie Death Valley are here represented by a single outcrop data point – the uplifted Copper Canyon basin.

Tertiary volcanic rocks exclusive of the named volcanic rocks from the southwestern Nevada volcanic field are primarily aligned along a northwest-southeast trend (fig. 7) that is associated with the Furnace Creek fault and the central Death Valley volcanic-plutonic province. Tertiary sedimentary and volcanic rocks occupy different depocenters; primarily the result of the sweep of tectonism and volcanism across this region that results in spatially variable and shifting locus of deposition through time.

The distribution of Tertiary limestone (fig. 8) varies both spatially and stratigraphically throughout the region. North of Las Vegas and to the north and west of Mercury, the thickest Tertiary limestones are present in the lower to middle Miocene rocks that are equivalent to the "rocks of Pavits Spring" on the Nevada Test Site. Late Oligocene to Early Miocene limestones are exposed at Bat Mountain (Cemen and others, 1999). In the central Amargosa Valley, a shallow Tertiary limestone of unknown but probably younger age is present in many of the boreholes in the Amargosa Farms area.

Tertiary basins dominated by sedimentary rocks (fig. 9) include the Amargosa Desert, the Las Vegas Valley, the Pahrump Valley and the Shadow Valley basin/Kingston Wash/China Ranch area. Death Valley and the northern half of the Pahrump Valley are not well represented due to lack of data. A breakdown of coarse-grained (sand-sized and larger) versus fine-grained (smaller than sand) sedimentary rocks is also shown on figure 9. Grain size information is variable in quality and depends on the detail present in published descriptions. There are some bull's-eyes based on limited, isolated data, but some trends are recognizable as well. The transition from coarse-grained to fine-grained sedimentary rocks in the northwest edge of the Las Vegas Valley, previously documented by Plume (1989) is evident here. The coarse synextensional gravels and megabreccias in the Kingston Wash area are also evident. The Amargosa Desert shows a complex pattern

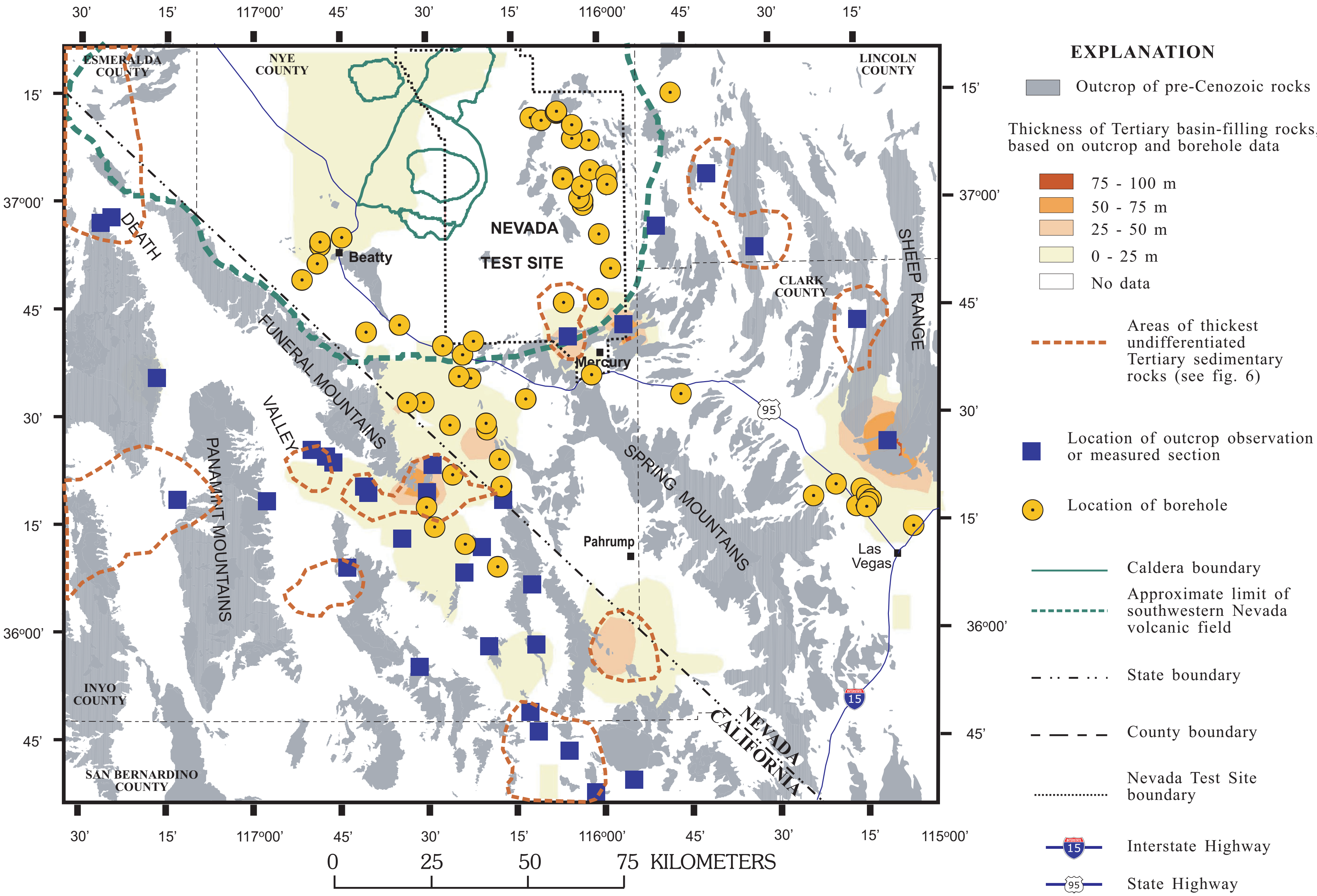


Figure 8. Thickness of Tertiary limestones based on measurements at outcrops and in boreholes.

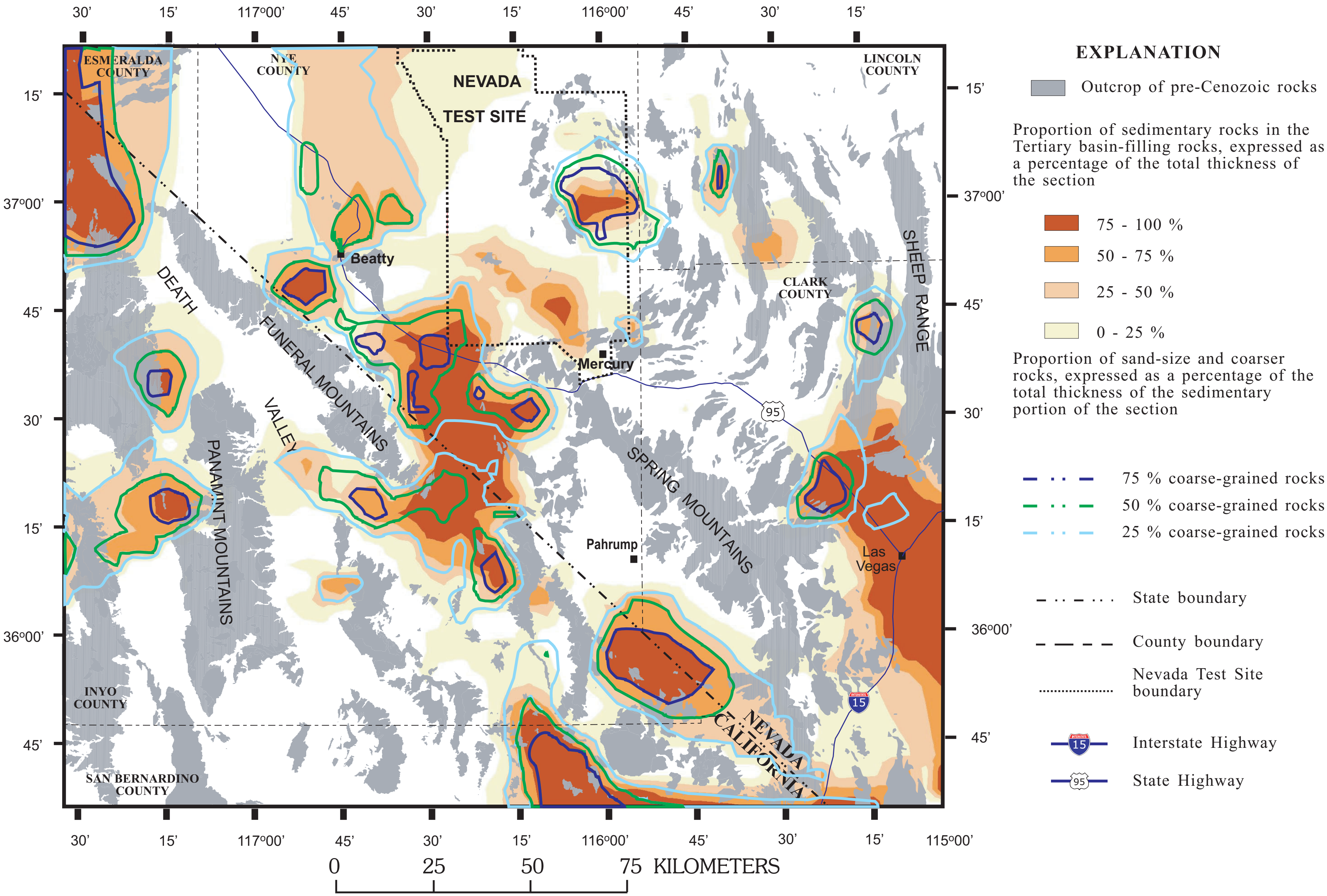


Figure 9. Relative proportion of sedimentary rocks in the Tertiary section and grain size characteristics.

of grain size distribution, in part reflecting the presence of fine-grained sediments in the basin center.

Tertiary basins dominated by volcanic rocks (fig. 10) include the margins of the southwestern Nevada volcanic field and the central Death Valley volcanic-plutonic province. Thick sequences of regionally extensive ash-flow tuffs derived from the southwestern Nevada volcanic field known to be present beneath Yucca Flat, Crater Flat and at Yucca Mountain are not shown on figure 10. These volcanic units are thick enough and well enough known to be modeled as their own hydrogeologic units, rather than being lumped with coeval Tertiary sediments. When rhyolite and basalt lava flows and ash-flow tuffs are separated from airfall tuff and ash deposits (contours on figure 10), the thick accumulations of volcanic rocks are seen to be dominated by the tuffs and lava flows, as expected proximal to volcanic source areas. Thinner, distal sections are dominated by airfall material, such as in the Ash Meadows area of the Amargosa Desert.

Amargosa Desert Borehole Data

A preliminary compilation of data from 188 boreholes in the Amargosa Desert compliments surface and subsurface geologic investigations conducted in the area at the regional scale (1:250,000). Borehole data are being used to identify Quaternary and Tertiary volcanic and sedimentary rocks within the basin, classify them into hydrogeologic units, and map the subsurface distribution of these units. The principal hydrogeologic units that can be recognized and correlated in the Amargosa Desert are:

- Fine-grained alluvium including playa deposits and basin-axis mudstone;
- Quaternary and Tertiary coarse-grained alluvium (sand and gravel) including near surface unconsolidated gravels and sands and late-stage basin fill;
- Quaternary-Tertiary spring/lacustrine deposits including an upper limestone aquifer;

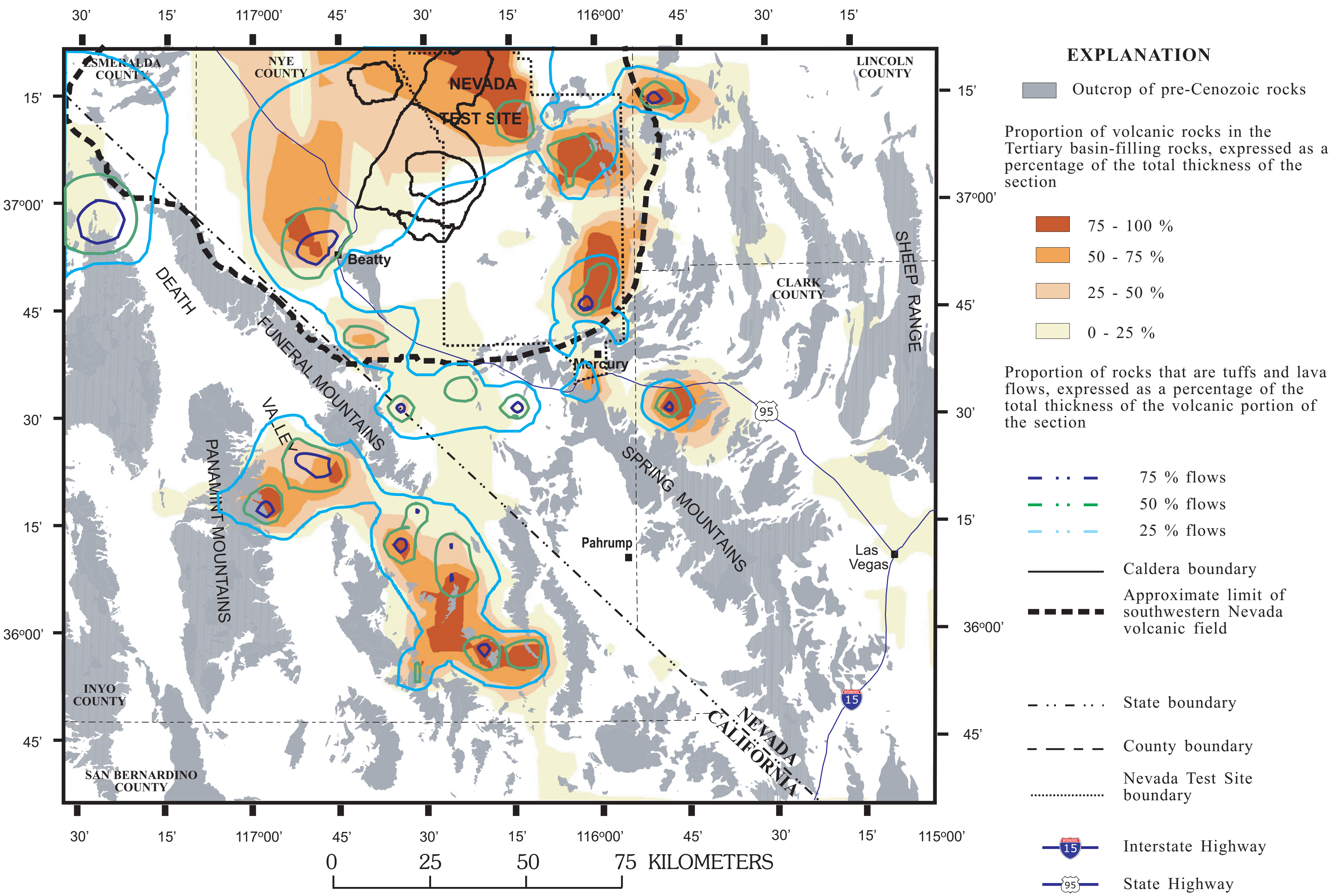


Figure 10. Relative proportion of volcanic rocks in the Tertiary section and rock type.

- Basalt;
- Silicic volcanic welded tuffs, subdivided when adequate data are available;
- A consolidated (mostly Tertiary) mixed unit of clastic and volcaniclastic rocks.

A principal difficulty in the initial compilation and stratigraphic analyses of borehole data from the Amargosa Desert involved integrating subsurface lithologic data known to be of high quality, such as those data from the Nye County Early Warning Drilling Program (EWDP) boreholes to the south of Yucca Mountain and the Felderhoff boreholes (Carr and others, 1995) with information contained in driller's logs that are source of data for many of the holes in the Amargosa Farms area (Oatfield and Czarnecki, 1989). Many of the boreholes in the area (fig. 11) are shallow; deeper boreholes provide important control points. Subsurface geologic units are defined in generalized lithologic terms, based on characteristics of hydrogeologic importance such as permeability and are compared where possible to existing surficial maps to define the spatial extents of the major lithologic units, including alluvial channels, spring deposits, outcrops of freshwater limestones, basin center and playa deposits, and transitions from coarse-grained to fine-grained clastic sedimentary deposits.

Two preliminary stratigraphic sections across the Amargosa Desert (figs. 12 and 13) display some of the stratigraphic complexity and facies trends within the basin. The east-west section (fig. 12) highlights the segmented nature of the basin: a relatively thick section of Tertiary volcanic rocks along the northeastern flank of the Funeral Mountains gives way to sections that are dominated by shallow Tertiary limestones in the Amargosa Farms area. Boreholes on the eastern end of the section penetrate local basalt flows. Many of the boreholes at the northern end of the north-south cross section (fig. 13) penetrate volcanic rocks associated with the southwestern Nevada volcanic field. These volcanic rocks are absent beyond the central part of the section, giving way again to the shallow Tertiary limestones in the Amargosa Farms area, thicker limestone-poor sections to the south, and at the southern end, a section that contains volcanic rocks associated with the central Death Valley volcanic field.

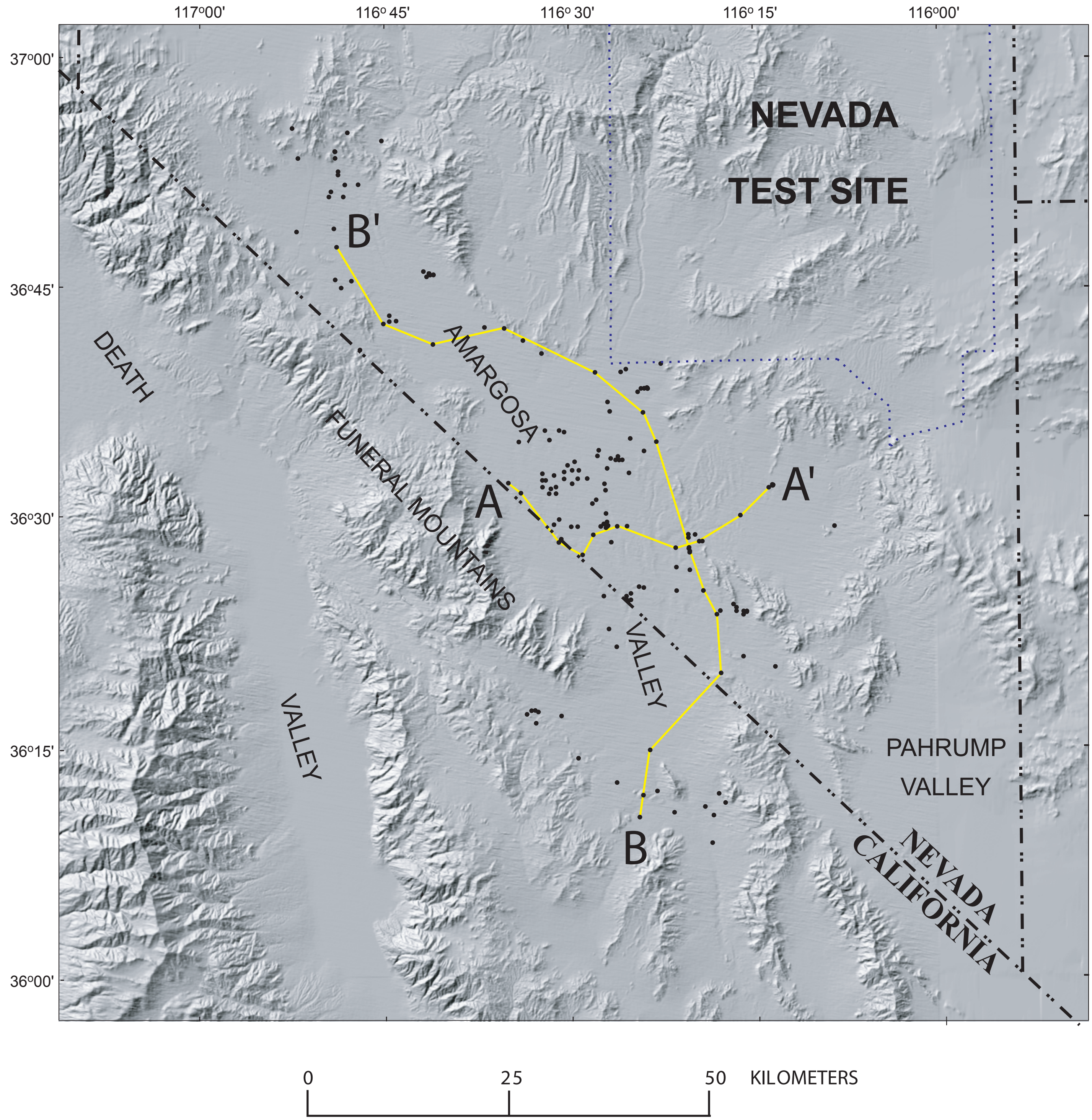


Figure 11. Location map of boreholes and stratigraphic cross sections in the vicinity of the Amargosa Desert.

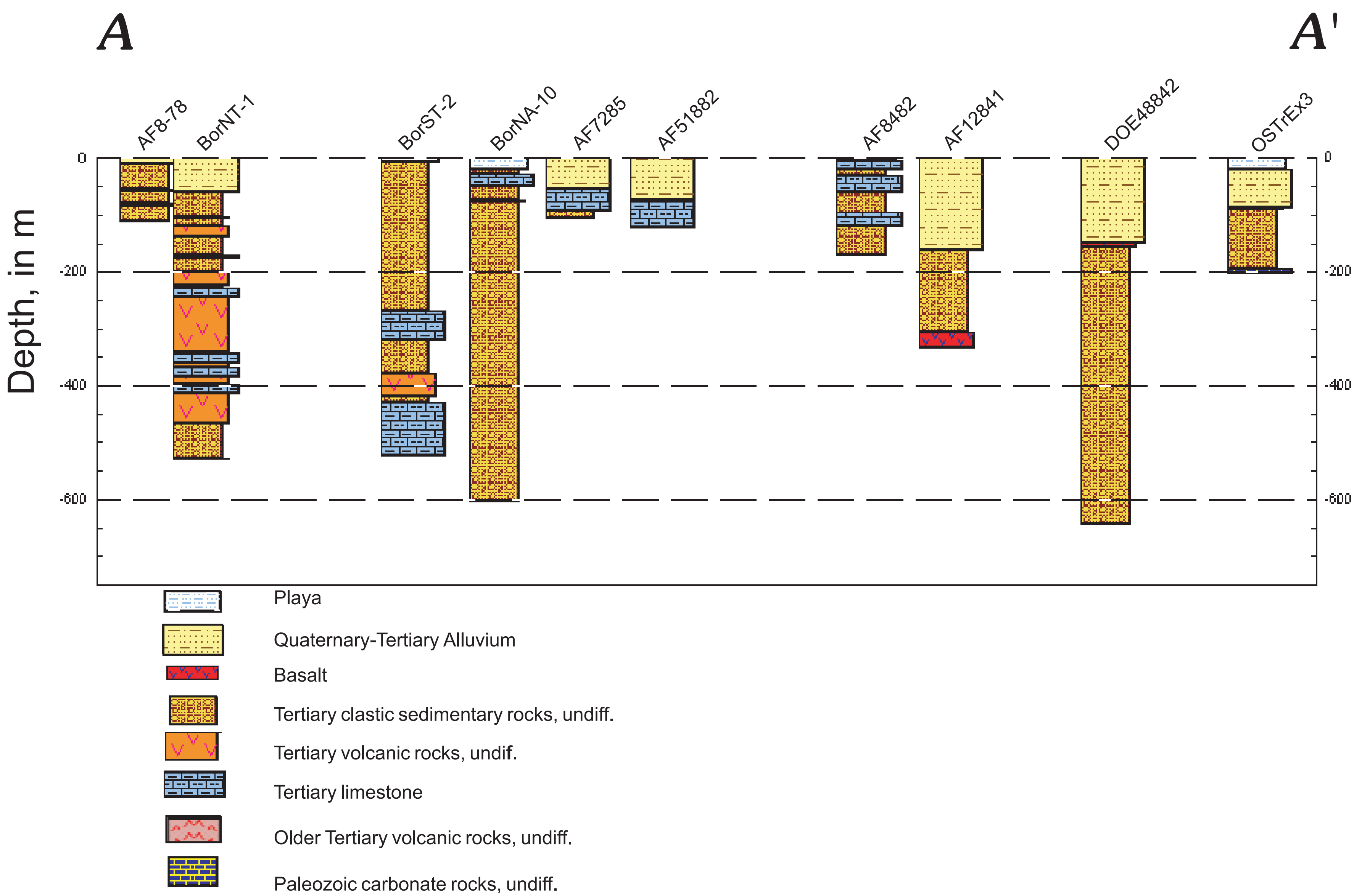


Figure 12. Stratigraphic cross section A-A'. Section is oriented approximately east-west through the central portion of the Amargosa Desert. See fig. 11 for section line.

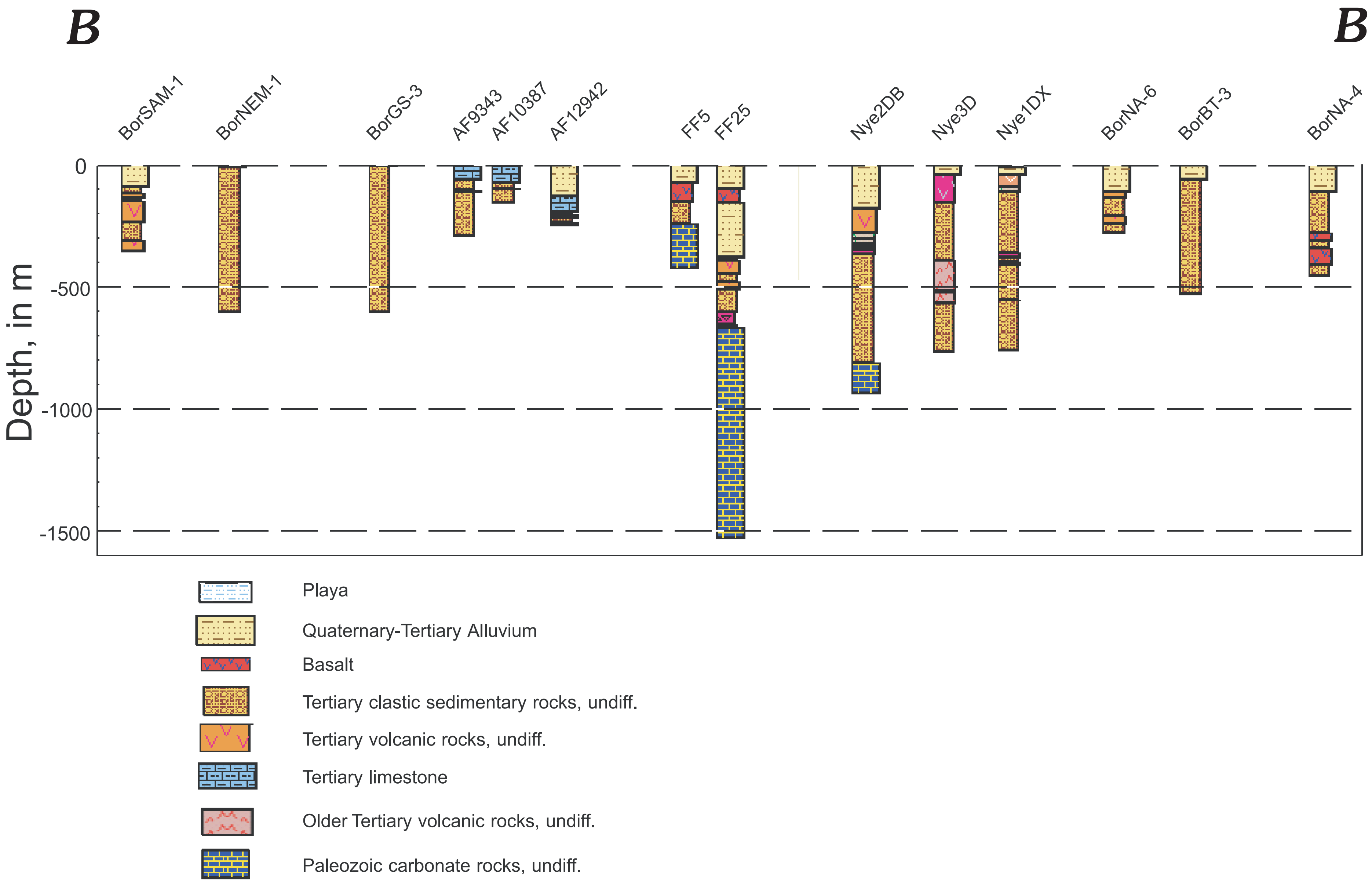


Figure 13. Stratigraphic cross section B-B'. Section is oriented approximately north-south along the axis of the Amargosa Desert. See fig. 11 for section line.

Summary of Material Properties

On the basis of the distribution of sedimentary and volcanic components and structural setting of the Tertiary basin-filling rocks of the Death Valley ground-water basin, five broad zones have been delineated (fig. 14) that represent areas with potentially distinct material properties and potentially different hydraulic properties. Each of these zones is discussed below.

Zone 1: This zone includes the eastern part of region. Stratigraphic successions consist of early extensional to synextensional sediments that are largely free of volcanic rocks and occupy regions that have been moderately extended. This region includes the Las Vegas Valley, the Indian Springs area and valleys to the north of Indian Springs and the southeastern portion of the Nevada Test Site. The Pahrump Valley is shown as a sub region. Tertiary strata in this basin are not as well characterized, but the basin is far enough away from volcanic fields that the sedimentary successions are likely to be similar to those elsewhere in this zone.

Zone 2: This zone corresponds to marginal parts of the southwestern Nevada volcanic field, where Tertiary sedimentary rocks underlie a thick sequence of regionally extensive ash-flow tuffs. Volcanic rocks penetrated by boreholes may not have been explicitly identified, but are probably derived from the southwestern Nevada volcanic field.

Zone 3: This zone includes synextensional sediments related to extreme extension. Coarse synextensional gravels and megabreccias characterize these sections. Included in this region are the Shadow Valley supradetachment basin, Death Valley, and the Nova basin to the west of Death Valley.

Zone 4: This zone includes the synextensional volcano-sedimentary trough that incorporates the central Death Valley volcanic-plutonic field and the Furnace Creek basin. Stratigraphic successions are a mixed assemblage of sedimentary and volcanic rocks whose deposition was closely associated with movement along the Furnace Creek fault zone.

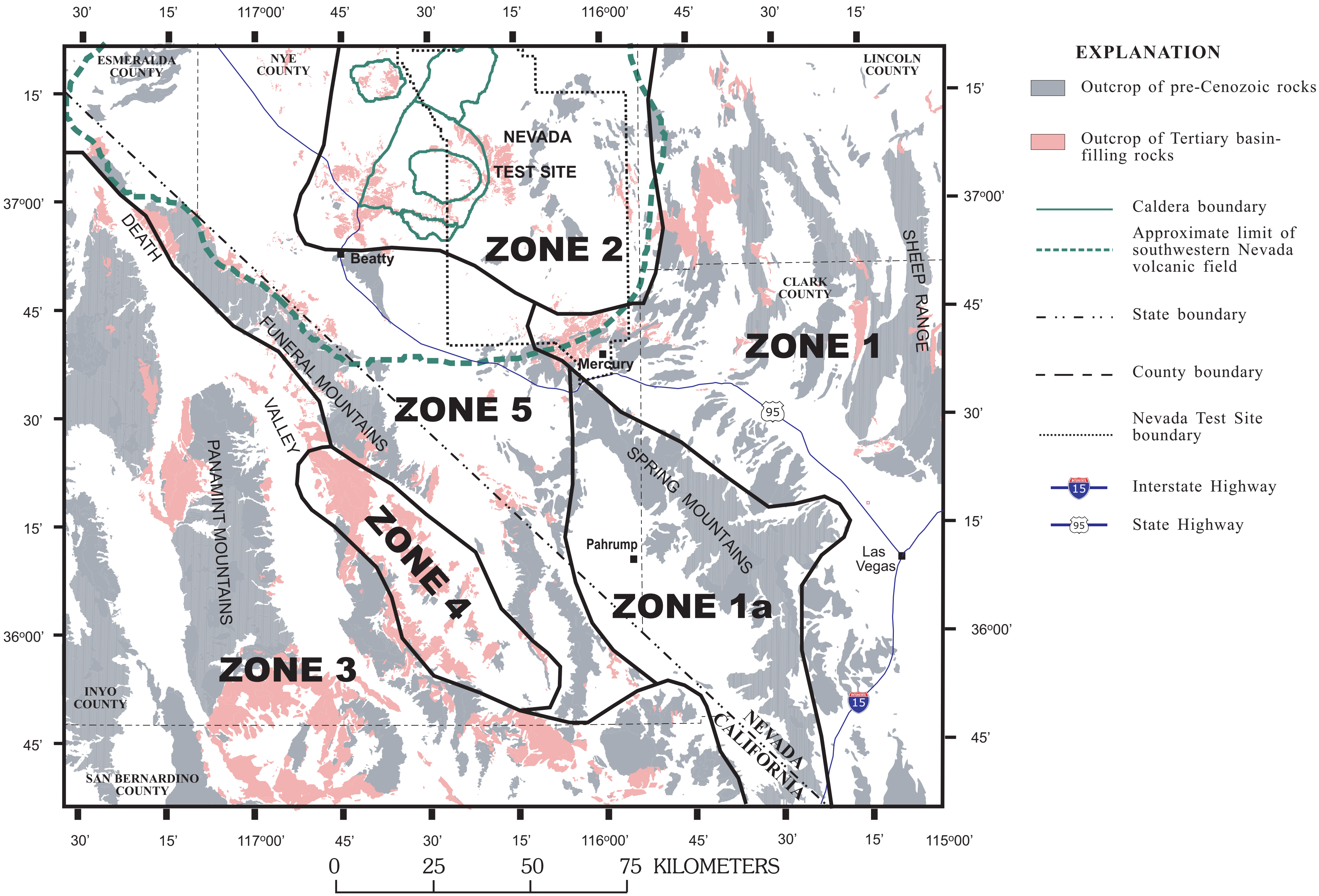


Figure 14. Map showing location of zones that may define major regional differences in material properties.

Zone 5: Stratigraphic successions within this zone are similar only in their generally high stratigraphic and structural complexity. The region is characterized by its wide variety of sedimentary rocks, including coarse-and fine-grained alluvial fill, lacustrine deposits and playa deposits, fluvially reworked tuffs and tuffaceous sedimentary rocks that span an age range from Oligocene to the Pliocene. Volcanic rocks are present in varying proportions. These rocks have been affected both by extension and by strike-slip deformation associated with the Stewart Valley-Pahrump fault zone.

The sum effect of all of the above is that a few of the basin fills are fairly permeable top to bottom and a few are impermeable top to bottom. But most of the basin fills could either be represented by an aquifer overlying a leaky confining unit, or alternatively, by a single unit that decreases in permeability with depth.

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