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CRITERIA FOR THE RECOGNITION OF PEDOGENIC/SUPERGENE AND NONPEDOGENIC/HYPOGENE DEPOSITS AND THEIR RELATIONSHIP TO THE ORIGIN OF CALCITE/OPAL DEPOSITS AT YUCCA MOUNTAIN

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CONTENTS

Introduction

This study is part of the research program of the Yucca Mountain Project intended to provide the State of Nevada with a detailed assessment of the geology and geochemistry of Yucca Mountain and adjacent regions. The purpose of this report is to try and establish criteria for the recognition of pedogenic/supergene deposits of calcite/opal versus non-pedogenic/hypogene deposits of calcite/opal. Far from being of esoteric concern, this subject is of paramount importance to the pedogenic-hypogene debate which rages around the suitability of Yucca Mountain as a high-level radioactive waste repository site.

In this report, separate criteria for the recognition of pedogenic or hypogene calcite/opal deposits will discussed first, and then whether this criteria is met by the calcite/opal deposits at Yucca Mountain will be discussed next. The photographs of Hill and Schluter (1993) and drawings of Hill (1993a) are especially pertinent to the following discussion.

Pedogenic/Supergene Criteria

Petrocalcic Horizons

One of the primary criteria for the recognition of pedogenic deposits is that they consist of horizontal, or near-horizontal, layering sequences, which are approximately parallel to the land surface (Soil Science Society of America, 1987). Carlisle (1980, p. 7) described pedogenic calcretes (as opposed to nonpedogenic calcrete) as: "In essence pedogenic calcretes (i.e., ordinary caliches) result from predominantly vertical redistribution of Ca, Mg, CO_3^{2-} and trace elements within the soil moisture zone or from the air. They are extensive, thin horizons within the soil and mainly illuvial." Machette (1985) restricted the term "calcrete" to refer to near-surface or shallow, terrestrial deposits of calcium carbonate that have accumulated in or replaced a pre-existing soil, unconsolidated deposit, or weathered rock material, to produce an indurated mass. Such deposits are often called "soil-horizon caliche" (Carlisle et al., 1978, p. 25) and are considered to be soil horizons by several lines of evidence: "they parallel the soil surface (unless buried); their upper boundaries commonly occur within several inches to about 2 feet of soil surface; they have distinctive morphologies which show lateral continuity of overlying and underlying horizons; they occur between horizons containing relatively little carbonate; they occur in sediments of various composition and texture; and they form in a developmental sequence" (Gile et al., 1965, p. 74).

A petrocalcic horizon is cemented by fine-grained, authigenic $CaCO_3$ to the extent that it cannot be penetrated by spade or auger when dry and fragments of the petrocalcic horizon do not slake in water (Soil Survey Staff, 1990). Generally, progressively more complex carbonate horizons occur in soils of progressively older geomorphic surfaces (Gile et al., 1981). In petrocalcic horizons some layers may be massive and some less massive, but where the calcretes "are thick and lack any major horizontal development, bedding, or structure, they represent a very large quantity of calcium carbonate and because of their physical nature are unlikely to be formed by ...pedogenic processes" (Goudie, 1973, p. 142; underlining ours).

Yucca Mountain. The calcite/opal deposits at Yucca Mountain do not meet this primary criteria of being parallel to the land surface. While the Yucca Mountain deposits can parallel the land surface, they may also occur at any angle including, very often, the subvertical to vertical (e.g., Hill, 1993a, p. 4 and her figs. 2 and 3; Hill and Schluter, 1993, their fig. 5B). In addition, some of the supposedly pedogenic calcretes at Yucca Mountain are thick and massive and lack any horizontal development (e.g., Stagecoach Trenches A and B; Site 199, South Trench 14, Wahmonie travertine/gypsite mound; Hill and Schluter, 1993), a criteria which, according to Goudie (1973), makes these of unlikely pedogenic origin. In particular, the massive deposits at Site 199 were determined by Paces et al. (1993) to be of spring origin.

Extent of Petrocalcic Horizons

Petrocalcic-soil horizons are usually laterally continuous, having a very large areal spread (Goudie, 1973; Carlisle, 1980). They are also characterized by a downward decrease in cementation and induration (Gardner, 1972). Bachman and Machette (1977, p. 1) said that criteria for recognizing calcic soils are "a distinctive morphology that is zoned horizontally and can frequently be traced over tens to hundreds of square kilometers". This is because soil-forming processes take place over large regions wherever conditions are suitable for calcrete/caliche formation.

Yucca Mountain. The calcite/opal deposits at Yucca Mountain are not laterally continuous. Instead, they are localized along faults or fault zones (Hill, 1993a). In places where faults are well-exposed, the calcite/opal mineralization occurs primarily as seams or veins along or near the fault plane and dies out away (a few meters) from the fault (e.g., Wailing Wall). The calcite/opal does not usually occur in soil horizons between fault zones. For example, in an exposed soil horizon at the Highway 95 gate-gravel pit, the soil contains not even a poorly-developed calcic horizon, whereas less than a kilometer north of the gate along this same road, calcite mound deposits are locally abundant. As a rule, K-horizons (soil horizons in which at least 90% of the soil fabric is impregnated with carbonate; Gile et al., 1965) are light-colored and visibly prominent. Such horizons are not present in the soils of the Yucca Mountain area.

The calcite/opal deposits at Yucca Mountain are characterized by a downward decrease in the amount of calcite/opal material, but not in the manner described by Gardner (1972). In the case of Yucca Mountain, veins made out of calcite/opal material pinch out with depth instead of soil horizons decreasing with depth.

Soil Matrix/Clastic Content

Another primary criteria for a pedogenic ("pertaining to soil formation") deposit is that it have a soil matrix. The two major components in a calcic soil or pedogenic calcrete are: (1) the calcareous fraction, and (2) the detrital or noncalcareous fraction of the soil (Bachman and Machette, 1977). Gile et al. (1965, p. 74) described the calcareous fraction with the term K-fabric (K, after the German *Kalk* meaning carbonate) as a "fine-grained authigenic carbonate which coats or engulfs, and commonly separates and cements skeletal pebbles, sand, and silt grains". Interstices between skeletal grains are partially or completely filled with carbonate. The K-horizon concept (i.e., horizon with >90% K-fabric) includes many prominent carbonate-impregnated horizons termed variously as caliche, desert crust, or calcrete (Gile et al., 1966). Carbonate can be concentrated in, or between, soil horizons, with concentrations of total carbonate ranging from <1 to >90%, but the s-matrix of the soil ("s-matrix of Brewer, 1964, and "groundmass" of Bullock et al., 1985) always contains some clastic material. For example, Monger et al. (1991a, p. 47) reported a weighted average of 12.1% carbonate for their nodular zone-3, up 3.4% from their zone 2. These are typical values of carbonate enrichments in calcic soil horizons. The original framework grains of calcic soil may represent only 5-10% of the volume of a soil horizon, but the clastic grains are still there.

The amount of carbonate in laminar soil horizons, however (which horizons represent an advanced stage in the development of ancient calcic soils), can be >90% and can contain only minor amounts of clay, organic matter, silica as chert, and sand and silt grains (Lattman, 1973). Carbonate layers in laminar horizons are relatively pure because detrital grains are pushed ahead of a calcite crystallization front resulting from downward-percolating water which is stopped by a relatively impermeable zone such as a plugged zone of a petrocalcic horizon (a continuously cemented or indurated calcic horizon), or bedrock (Gile et al., 1966; Allen, 1985).

Pressure solution or force-of-crystallization may also contribute to the relatively pure laminar layers (Maliva and Siever, 1988; Reheis, 1988; Monger and Daugherty, 1991).

Yucca Mountain. In contrast to pedogenic calcrete deposits which have clastic grains around which carbonate has precipitated, most of the controversial calcite/opal deposits at Yucca Mountain appear (in hand lens and microscopic examination) to be completely devoid of clastic grains. Under thin-section (3 sections, two from WT-7 and one from the Wailing Wall), the calcite/opal displays a very fine-grained (millimicron or less) structure, with marble- or swirl-like flow textures. The lack of clastic grains for the calcite/opal at Yucca Mountain needs to be confirmed by SEM (scanning electron microscopy) techniques on a number of different kinds of samples.

Other of the calcite/opal deposits at Yucca Mountain are not devoid of detrital material. These are mostly massive-type mound deposits or those which are located at Busted Butte in the sand ramps (Hill and Schluter, 1993). The debris in these deposits has been interpreted as being talus or sand incorporated into the calcite/opal as it was being precipitated as a spring-travertine deposit (Hill, 1993a).

Laminated/Banded Texture

Laminated texture, where the soil is microlaminated with respect to alternating carbonate/sand/silt/clay layers is a quite-common feature of pedogenic calcretes.

The laminae can be a few millimeters to centimeters in width, unicyclic (one set of laminae) or multicyclic (several sets of laminae). In multiple sets the laminae may parallel one another, or some set may truncate the other angularly (e.g., Gile, 1961, his Figure 2A). According to Gile et al. (1966), laminar horizons in soils often overlie horizons plugged with carbonate material. The laminar horizon is created by water percolating downward through the soils and stopping at the plugged horizon. If the laminar horizon is located on bedrock, it is termed a petrocalcic horizon. Such laminar zones occur only at the near-surface, upon direct exposure, or when the caliche is near enough to the surface to receive infiltrating water. According to Reeves (1976, p. 52): "the laminae, which have a thickness range of only a few millimeters, are produced at the top of caliche profiles when the profile is effectively plugged to infiltrating water, thus forcing the water to lateral distribution. The total thickness of a group of laminae seldom exceeds one or two inches although there are often several plates of laminae." Sometimes carbonaceous layers of fossil plant debris can be interdispersed between soil horizons in pedogenic deposits. Many laminar calcretes are biogenic in origin due to cyanobacterial, lichens, or calcified root mats (Retallach and Wright, 1990).

<u>Yucca Mountain</u>. A majority of calcite/opal deposits at Yucca Mountain display a banded or laminated texture (Hill and Schluter, 1993). Layers within these banded/laminated sequences contain various amounts of mixed calcite and opal, the darker layers containing more opal and the lighter ones more calcite. Layering can vary in thickness from millimeters (laminations) to centimeters (bands) and they can

vary in orientation from the horizontal to the vertical. Vaniman et al. (1988) described banded samples of calcite/opal from Trench 14: an earlier mixed calcite and opal-CT band overlain by a later, pure opal-A band.

The presence of laminations/bands in the calcite/opal at Yucca Mountain may seem to implicate these deposits as being pedogenic, but this is not necessarily the case. Laminar structure is not restricted to pedogenic deposits but is common in many varieties of calcrete (Banchman and Machette, 1977). The following differences between known-pedogenic, laminated, calcrete/caliche deposits and the banded calcite/opal at Yucca Mountain are:

(1) The banding of the Yucca Mountain samples is calcite/opal, with mixed amounts of calcite and opal (from 0-100% for each end member) occurring. This is in contrast to reported pedogenic deposits which contain mostly (or only) calcite (calcrete) or opal (silcrete).

(2) The thickness of the band/laminations of the Yucca Mountain samples is much greater (often centimeters) than that reported for pedogenic calcrete/caliche deposits (usually millimeters).

(3) The total thickness of a group of laminations/bands at Yucca Mountain are often on a scale of meters, not centimeters.

(4) The calcite/opal laminated sequences at Yucca Mountain bear no relationship to plugged horizons, petrocalcic horizons or bedrock, conditions which are supposed to be responsible for the formation of laminar horizons in pedogenic deposits (Gile et al., 1966).

(5) In petrocalcic deposits, sets of laminae are truncated by younger, superadjacent sets, but in the case of the Yucca Mountain deposits, the calcite/opal of the different bands seems to be intermixed ("mixed-texture") or intergrown ("invasive texture") and discrete sets of laminae do not usually appear to be truncated by later sets of laminae (see photos of Hill and Schluter, 1993).

(6) The laminated/banded sequences at Yucca Mountain are not horizontally oriented along soil horizons. In fact, many of these cut across soil horizons and are oriented in the vertical to near-vertical direction.

Nodular/Glaebular/Pisolitic Texture

Another important criteria for recognizing pedogenic deposits is the presence of nodular ("glaebular") texture (Allen, 1986). This is because nodular structures are so common in pedogenic deposits (ancient or modern) that these structures are often diagnostic for these deposits (Atkinson, 1986). Nahon (1991) divided the process of "glaebulization" into four stages and described the development of these stages. Pedogenic nodules can vary from millimeters to nearly 30 cm in diameter but the most common size is about 2.5-7.5 cm in diameter (Reeves, 1976). Pisoliths are glaebles which are laminated in contrast to nodules which are not laminated.

Yucca Mountain. Not one of the ~175 samples of calcite/opal collected from Yucca Mountain and vicinity displays a nodular texture characteristic of pedogenic calcretes. Hill and Schluter (1993) did describe and show (their fig. 10) "algal/ooidal texture;" Vaniman et al. (1988) and Vaniman (1991) also reported "ooidal" layers and rims of calcite/opal/sepiolite at Trench 14. Algal/ooidal texture in samples collected near the Wailing Wall consists of rounded grains about 3 mm in diameter which were interpreted by Hill and Schluter (1993) to be algal structures related to spring activity. The appearance and size of these ooids suggests that these are of algal/spring- rather than pedogenic/caliche-origin (compare Hill and Schluter's, 1993, fig. 10 with Reeves', 1976, fig. 3-10b); however, "algal" structures can easily be mistaken for "pisolitic" structures (Goudie, 1973) and so it is suggested that these ooidal samples be viewed under SEM in order to determine the correct origin of these structures.

Vesicular Texture

Vesicles differ from vugs principally in that their walls consist of smooth, simple curves. Usually vesicles are formed by bubbles of gas or steam, but they are occasionally found in young caliches (Brewer, 1964, p. 191). Reeves (1976, p. 45) called vesicular structure in marine carbonates and young caliche deposits "birdseye." Birdseye structures found in caliches are usually 1-2 mm in diameter and often 20-30 mm long; these resemble the planer isolated type of vesicles described by Shinn (1968) which give the appearance of bedding rather than the type formed by gas bubbles.

Yucca Mountain. Vesicular texture is common in the calcite/opal deposits at Yucca Mountain (Hill and Schluter, 1993, their fig. 14). At Yucca Mountain the vesicles may be randomly spaced within the calcite/opal matrix or they may be aligned in rows along roughly-banded sequences or flow texture. The holes themselves can be ellipsoidal, the ellipsoids being elongated in the direction of the flow bands or layering; rarely, the holes are aligned in swirl-shaped rows.

At present it is unclear whether the vesicles in the Yucca Mountain calcite/opal are due to degassing of hydrothermal solutions or if they are due to pedogenic processes. They do not resemble any of the "birdseye" structures shown by Shinn (1968), but SEM work should be done to distinguish between these two completely different origins. According to one of the authors (Monger), the vesicular structures present in samples collected from Yucca Mountain are unlike any that he has seen in the pedogenic calcrete deposits of southern New Mexico.

Pebble/Clast Rinds and Coatings

Another diagnostic feature of many pedogenic deposits are clasts (e.g., pebbles) that are coated with carbonate material (Gile et al., 1966). The clasts can be completely surrounded by carbonate material, they may be coated primarily on their top sides ("cap structures"; Nahon, 1991, p. 145), they may be coated preferentially on their bottom sides, or they may have a cupped upper surface and draped laminae on their undersides (Bretz and Horberg, 1949). In pedogenic deposits, clasts can be coated with manganese and organic matter as well as calcium carbonate. In arid and semi-arid environments the presence of secondary calcium carbonate accumulations on the undersides of coarse fragments is especially typical of pedogenic calcretes that receive an influx of carbonate dust and/or have carbonate-rich parent material (Blank and Fosberg, 1990).

Yucca Mountain. No coated clasts have been observed in the controversial calcite/opal deposits at Yucca Mountain. Thin rinds do coat volcanic clasts at the summit of Lathrop Cone, a recent (119-141 ka) volcanic crater, but these coatings do not resemble the controversial deposits in any way. Calcite/opal does form the matrix material cementing alluvium/colluvium, but these clasts are never coated with layers of calcite/opal.

Rhizoliths/Root Casts

Another important criteria for recognizing pedogenic deposits are rhizoliths ("rhiza" = root) -- fossil roots or root traces. In paleosols roots may be preserved as carboniferous traces whereas in modern calcic soils they may be preserved as root casts or upright calcite-filled tubes ("calcified vertical tubes") (Retallach and Wright, 1990). Trees and branches can also be found as casts in pedogenic deposits but usually fossil roots are predominant.

Yucca Mountain. Root casts are common in some of the calcite/opal at Yucca

Mountain, especially in the sheet deposits at Busted Butte (Hill and Schluter, 1993, their fig. 20). Vaniman et al. (1988, p. 46) also reported root-cast texture at Trench 14 and thought that organic material such as root casts were perhaps responsible for the deposition of opal-A.

While root casts are common in some of the calcite/opal deposits at Yucca Mountain, this does not necessarily favor a supergene-pedogenic origin over a hypogene-spring origin. Plants/trees grow wherever water is available, and a spring location would actually enhance the growth of vegetation over a non-spring location in an arid climate so that root casts should be expected in spring-travertine deposits as well as in pedogenic deposits.

Bioturbation/Microorganisms

Pedogenic deposits are also characterized by "bioturbation" -- that is, the churning and stirring of sediment by organisms. Bioturbation features may include the remnants of organisms, fecal pellets, tubes, burrows, or swirl textures denoting digested soil material, among others. Microorganisms are also usually present in pedogenic deposits. Monger et al. (1991b, p. 999) reported calcified fungal filaments and circular fungal *Microcodium* structures in pedogenic calcretes. Opal phytoliths are formed by the precipitation of silica in and among the living cells of plants.

Yucca Mountain. None of the above features were observed (in hand specimen or under the microscope) in the calcite/opal samples at Yucca Mountain. However, this does not mean they are not there but may mean that these samples need to be viewed under higher resolution (SEM). Vaniman (1991, p. A117) reported "pelletal aggregates" of calcite/opal/sepiolite in faults at Yucca Mountain, but did not specify if these were fecal pellets. Vaniman (1991, p. A117) also reported "fungal and perhaps bacterial activity in the decay of plant roots;" but again, such features could favor a spring origin as well as pedogenic origin.

Solution Features

Pedogenic calcrete/caliches deposits often display solution features such as solution cavities (e.g., Gile, 1961, his fig. 2B) or solution pipes (Reeves, 1976). These features result during exposure of the caliche. Also, sometimes speleothemic textures result from the solution and reprecipitation of calcite into solution cavities within the calcrete deposits.

Yucca Mountain. No solution cavities or pipes were observed in the calcite/opal deposits at Yucca Mountain. However, speleothemic textures were observed by Hill and Schluter (1993, their fig. 21) at Pull Apart fault where water has dissolved the calcite/opal and redeposited it as speleothemic forms on undersides of the calcite/opal mass.

Sparry Calcite in Voids/Vugs

Sparry calcite often occurs in the voids of pedogenic calcretes (e.g., Monger et al., 1991a, p. 50).

Yucca Mountain. Sparry calcite is exceedingly uncommon in the calcite/opal deposits at Yucca Mountain. Most calcite (>95%) is micrtic (5 µm); the coarsest crystals are anhedral, void-filling calcites of 100-200 µm (Vaniman, 1991). This has been one of the major problems in distinguishing between a pedogenic or hypogene origin for the controversial deposits at Yucca Mountain: both the calcite and the opal are usually too fine-grained to be subjected to fluid-inclusion analysis. However, very rarely quartz spar can be found in vesicles within these deposits. At Pull Apart fault, quartz filling vugs in the calcite-opal was found to have fluid inclusion homogenization temperatures of $T_h = 140°C$ (avg) (Harmon, 1993).

Veins

Carbonate veins can occur as fillings along fracture planes in pedogenic calcretes and these veins can be vertically oriented. Such veins usually range in thickness from <2.5 cm to 7.5 cm and may be continuous or discontinuous.

Yucca Mountain. The calcite/opal deposits at Yucca Mountain often occur as veins cross-cutting strata or clastic debris (Hill, 1993a). However, the scale of these veins is up to a meter or more wide and up to 25 m or more in height (as viewed in surface exposures) -- completely out of the size range of veins reported for pedogenic calcretes. In addition, supposedly pedogenic calcite has been reported in veins as deep as 400+ m below the surface in the unsaturated zone (Marshall et al., 1993).

One sample collected from Pull Apart fault does display "veined-texture" on the scale reported by Gile (1961); i.e., see Hill and Schluter (1993, their fig. 15). In addition, Levy and Naeser (1991, p. 14) reported abundant fracture fillings composed mainly of silica in their samples from Trench 14.

Composition of Calcretes

Pedogenic calcretes often contain clay materials such as montmorillonite, palygorskite, and sepiolite and they also can contain water-soluble salts such as gypsum, phosphates, organic matter, and occasionally iron sulfide or glauconite (Bachman and Machette, 1977). For example, sepiolite and gypsum both exist in surficial calcic (Ka) horizons in Kyle Canyon, Nevada (Sowers et al., 1988). According to Bachman and Machette (1977), sepiolite occurs in calcic soils only where palygorskite is dominent and montmorillonite is relatively depleted. Sepiolite in calcic soils usually occurs in the medial protion of the soil suggesting that the occurrence of this mineral may be a function of depth of soil-water infiltration. Also, unless inherited, sepiolite generally is found in older Pleistocene soils.

Yucca Mountain. None of the calcite/opal deposits at Yucca Mountain contain the above water-soluble minerals with the exception of the Wahmonie travertine/gypsite mound which contains 20-30% gypsum (Hill and Schluter, 1993). The Wahmonie mound is located along a fault zone where a sulfide mass resides at depth (Hill, 1993a).

Sepiolite does occur in the calcite/opal deposits at Yucca Mountain but there is no correlation with respect to depth or soil horizons or palygorskite as described by Bachman and Machette (1977) for pedogenic calcrete deposits. Instead, the sepiolite occurs as pore fillings in the calcite/opal matrix and also as discrete pods of material in silica fracture fillings (Hill, 1993b). Sepiolite has also been reported in the subsurface at Yucca Mountain, with opal in fractures within the unsaturated zone (Vaniman, 1993).

Nonpedogenic/Hypogene Criteria

Problems exist with establishing criteria for nonpedogenic/hypogene calcrete deposits. One problem is that, while the literature on pedogenic calcrete deposits is abundant, the literature on nonpedogenic or hypogene deposits is sparse to almost non-existent. It seems that this study may actually be one of the first to address the issue of supergene versus hypogene calcretes.

Another problem is that just because a deposit is nonpedogenic does not necessarily mean it is hypogene. For example, Carlisle et al. (1978) and Carlisle (1980) described nonpedogenic, uraniferous deposits from western Australia and South Africa which came from the lateral flow of water (what they called "valley calcretes," Figure 1). These deposits are nonpedogenic (unrelated to soil processes) but not hypogene (deep-seated) since they did not originate from the vertical rise of fluid from a deep source. Despite this fact, Carlisle's genetic classification of calcretes is appropriate to our discussion of the calcite/opal deposits at Yucca Mountain. Note in

Figure 1 that nonpedogenic calcretes can form as superficial deposits, in the gravitational and capillary water zones, and more important to this study, as "alluvial fan, cienga, fault trace, or other groundwater calcretes." Some of these nonpedogenic calcretes can be ascribed to a hypogene origin and it is this criteria that is discussed in the following section.

Fault Zones

Fault zones may be one of the best indicatiors of a hypogene origin for calcrete deposits. This was recognized even early-on by investigators such as Cuyler (1930, p. 109): "It has been found in many faulted areas that calcium-laden waters rise along the fault plane due to hydrostatic pressure and on reaching the surface evaporate, leaving secondarily deposited lime. These deposits may frequently be traced for miles across open lands, over hills, and through valleys."

Alluvial fan calcretes are known from many parts of southern Nevada and these have usually been interpreted as pedogenic caliche deposits (e.g., Kyle Canyon; Sowers et al., 1988). However, it is possible that even some of southern Nevada's alluvial fan deposits may be nonpedogenic and related to faults; for example, the McCollough fan deposits (formerly interpreted to be pedogenic calcretes; Cooley et al., 1975) may actually be fault-related travertine (J. Hawley, personal communication, 1993).

Yucca Mountain. Almost all of the controversial calcite/opal deposits at Yucca

Mountain are found along fault zones (Hill, 1993a). For example, Trench 14 is along the Bow Ridge fault, Busted Butte is raised up along two segments of the Paintbrush fault, the Wailing Wall is along the Solitario fault, etc. This field observation is extremely important to the proper interpretation of the calcite/opal deposits at Yucca Mountain.

Vein Geometry

Epithermal mineral deposits are those which display a vein morphology and which form at or near the Earth's surface (within 1 km) from hydrothermal solutions. Characteristically, the geometry of epithermal mineral deposits consists of a feeder vein which bifurcates or splays out near the surface and which can crosscut soil layers and also earlier mineral deposits (Berger and Eimon, 1982; fig. 2). Epithermal veins are typically formed by solutions which rise from depth to the surface where they bifurcate due to a decrease in overburden and compressibility in the rock strata.

Yucca Mountain. At Yucca Mountain the calcite/opal deposits are often associated with "feeder veins" where they have been vertically exposed by trenching or by valley downcutting. This association can be seen at Trench 14 and at the fault scarp exposed at Site 106 and is most dramatic on the west and east sides of Busted Butte where valley erosion has dissected sand ramps. As exposed fully in the sand ramps, the veins narrow towards the base but thicken and splay out into multiple veins near (within a few meters of) the sand-ramp ground surface. At Trench 14 calcite/opal veins crosscut soil horizons and also earlier veins. Hill (1993a) recognized at least five crosscutting vein episodes of epithermal mineralization exposed in Trench 14.

The vein geometry shown by the calcite/opal deposits at Yucca Mountain is an extremely important criteria for placing them in the hypogene category. Why would pedogenic deposits form as feeder and splayed veins instead of as layered soil horizons? And even if it is hypothesized that the vein morphology was caused by faults having filled with pedogenic calcite/opal, this origin seems impossible at Busted Butte where the calcite/opal veins are located in sand ramps. How could slowly-accumulating, pedogenic, calcite/opal fill faults in sand? Why wouldn't the faults have filled with sand long before the calcite/opal could accumulate pedogenically?

Groundwater Springs

Under Carlisle's (1980) category of "cienaga and other groundwater calcretes" (Figure 1) are spring travertine deposits. Bachman and Machette (1977) described spring and travertine deposits as usually being characterized by megascopic, irregularly-shaped pores, where porous zones may grade laterally into more densely-cemented alluvial deposits near their margins. In pure travertines detrital grains are generally rare, although the basal part of a travertine deposit may cement coarse alluvium. Cienaga deposits are those which form in marshy areas where the ground is wet due to the presence of seeps or springs, often with standing water and abundant vegetation (from the Spanish ciénaga meaning "marsh, bog, miry place").

Yucca Mountain. A number of the calcite/opal deposits at Yucca Mountain resemble travertine, especially those in the sand ramps at Busted Butte. At Busted Butte feeder veins of dense calcite/opal connect with porous, travertine-like, surface deposits which continue downgradient, sometimes to the toe-of-slope of a ramp and beyond. The sides of the veins and basal parts of these deposits have cemented the sands of the sand ramps at Busted Butte. The location of these travertine-like deposits along the Paintbrush fault and the lack of similar carbonate material in non-faulted sections of the butte suggests that the travertine precipitated from fault-controlled springs.

Some of the massive-textured deposits in the Yucca Mountain area may fit into the category of cienaga or spring deposits. Paces et al. (1993) determined that the calcite/opal at Site 199 and the diatomaceous earth site along Highway 95 (Horsetooth site) were of spring origin. Also, a modern spring, Cane Springs, exists northwest of Mercury. The source of this spring water has not been determined.

Trace Element Enrichment

One of the main conclusions of Carlisle et al. (1978) was that ore-bearing calcretes are nonpedogenic. This is because metals are unlikely to be enriched by a pedogenic process but must be carried in hydrothermal solutions ascending from deep-seated, metal-rich bodies in the subsurface.

Yucca Mountain. The calcite/opal deposits at Yucca Mountain are not nearly as enriched in metal as are the petrogrphically-similar calcite/opal deposits in the Bare Mountain Mining District to the west of Yucca Mountain. However, they do display some metal enrichment. For example, Hill and Livingston (1993) reported relatively-high concentrations of zinc in the calcite/opal of Trench 8 (166 ppm), New Trench (90 ppm) and Wailing Wall (90 ppm), and Weiss et al. (1990) reported similar values for zinc (75-90 ppm) at Trench 14. It is doubtful whether this amount of zinc enrichment could have been caused by a supergene/pedogenic process -- according to this process, where would this zinc have come from? Considering the low concentration of metal in fresh tuff (e.g., Castor et al., 1989; Weiss et al., 1990) such metal enrichment would seem to support a hypogene-hydrothermal origin over a supergene-pedogenic origin for the deposits.

Episodes of Deposition

Another criteria which may characterize hypogene calcretes is episodic deposition. Pedogenic calcretes should be expected to deposit in a fairly continuous manner corresponding mainly to climatic conditions; they should not be punctuated by episodes of non-deposition such as may characterize spring deposits controlled by pumping from an underground source.

Yucca Mountain. The calcite/opal deposits at Yucca Mountain seem to have formed in discrete episodes. Szabo and Kyser (1990) and Vaniman (1993) both mentioned that the ages of the calcite in the calcite/opal deposits at Yucca Mountain cluster in groups of approximately 28 ka, 170 ka, and 280 ka. Paces et al. (1993) reported four separate episodes of mineralization at Site 199 and at the diatomaceous earth (Horsetooth) site near Highway 95; these episodes were one of the main reasons why these authors classified the mineralization as spring deposits. The episodes of spring activity at these two sites occurred at approximately 18 ka, 30 ka, 45 ka, and >70 ka. It is interesting that the ~28 ka episode of calcite/opal in the vein deposits at Yucca Mountain so nearly matches the ~30 ka age of the spring carbonates.

Discussion

One of the main reasons why the pedogenic-hypogene debate rages on is that the data that does exist is often ambiguous: e.g., the $^{87}Sr/^{86}Sr$, carbon-oxygen, and lead isotope data can be taken to support either model (e.g., Quade and Cerling, 1990; Szymanski et al., 1993). This ambiguity applies to petrographic textures of the calcite/opal deposits as well. For example, vesicles are usually indicative of degassing, but they can also occasionally occur in pedogenic caliches (Reeves, 1976). Laminations are common in pedogenic deposits, but they can also occur in hypogene deposits; sepiolite can be pedogenic or it can be hydrothermal and related to faults (Hill, 1993b); etc. Calcrete deposits can also be of mixed pedogenic-nonpedogenic origin in which both the vertical and lateral transport of material is important (Carlisle, 1980). Hence, the origin of some calcrete deposits may be indeterminable, especially when these are polygenetic (Bachman and Machette, 1977).

The real question is: Can a hypogene-nonpedogenic model explain all of the data (isotopic, petrographic, etc.) better than a supergene-pedogenic model? We believe that it can. A wind-dust carbonate pedogenic process does not make sense for calcite veins >400 m deep in the subsurface. It doesn't even make sense for surficial veins 25+ m deep (e.g., at Busted Butte). So called "pedogenic deposits" have been shown to have fluid-inclusion temperatures of 140°C (mean) (Harmon, 1993). They also sometimes can have high trace-element metal concentrations (Hill and Livingston, 1993). In addition to these objections, the criteria discussed in this report do not favor a pedogenic origin for the calcite/opal deposits at Yucca Mountain. These deposits do not form in petrocalcic horizons nor do they have extensive areal distribution. Rather they form as veins along fault zones. These deposits do not exhibit clastic grains, nodular texture, or pebble/clast rinds and coatings as is typical of most pedogenic calcrete deposits. Additionally, pedogenic calcretes generally do not contain continuous veins of opal; instead, opal has been reported mainly as localized coatings and void fillings (e.g., McGrath, 1984; Sowers, 1985; Chitale, 1986).

Origin of calcium for the deposits. A problem of major importance with respect to the pedogenic-hypogene debate and this discussion is: What is the source of calcium for the calcite constituent of the calcite/opal deposits at Yucca Mountain? Five possible sources exist for the deposits at Yucca Mountain:

(1) tuffaceous bedrock

(2) rainwater

(3) capillary rise from groundwater

(4) eolian limestone dust

(5) seismic pumping of groundwater

The source of calcium for most calcretes is limestone or dolomite. However, there are no surface exposures of limestone or dolomite in the Yucca Mountain area, only Paleozoic carbonate rocks in the subsurface below Tertiary tuffaceous rock. The tuffaceous bedrock at Yucca Mountain is very low in calcium (usually only a few percent) and also in carbonate (<2%; Hill and Livingston, 1993). For this and other reasons (mostly isotopic) it is agreed on by most researchers that the tuffs at Yucca Mountain cannot be the source of calcium to the calcite/opal deposits.

Rainwater is an alternative source of carbonate as rain contains dissolved salts (6-7 ppm Ca; Goudie, 1973; Birkeland, 1984). However, according to most authors, this is a relatively low figure. Goudie (1973, p. 139) reported that with an annual rainfall of 325 mm (much higher than at Yucca Mountain) it would take as much as five million years to build up 60 cm of calcrete by this mechanism. However, Gile et al. (1981, p. 63) estimated that rainwater could form about 1.5 g of pedogenic carbonate/square meter/year whereas dry dust could suppy only 0.35-0.55 g/square meter/year of carbonate.

Early workers thought that calcium for caliche deposits was brought from depth to the surface by capillary rise of groundwater. However, the major soil process for calcrete deposits is actually the leaching of carbonates from upper soil horizons by downward percolating water (Bachman and Machette, 1977). The model of rising capillary water, if it were a major mechanism (which it is not), is also not appropriate for Yucca Mountain since the water table is presently ~600 m below the ground surface.

The argument involving Yucca Mountain revolves around the last two sources of calcium (4) (5). The pedogenic proponents (e.g., Stuckless et al., 1991) insist that eolian limestone dust is brought into the region in sufficient quantities to provide enough calcium for the calcite of the calcite/opal deposits. Opponents of the pedogenic model insist that this source is insufficient, and because it is insufficient, a seismic-pumping of groundwater from the Paleozoic limestone aquifer (5) must have occurred (e.g., Szymanski et al., 1993).

Wind-blown carbonate dust (loess) is known to be a major source of calcium to a number of southwestern calcrete/caliche deposits (Reeves, 1976; Bachman and Machette, 1977; Gile et al., 1981; Machette, 1985; etc.). But the question is: Is there volumetrically enough wind-blown dust at Yucca Mountain to have supplied all of the calcite for the extensive calcite/opal deposits there? A study especially pertinent to this question is that of Lattman (1973) who found that alluvial fans flanking the Las Vegas Basin of southern Nevada are composed of detritus which may be dominantly carbonate, andesite-basalt, rhyolite and rhyolitic tuff, or siliceous sedimentary rock -- yet all fans have been cemented by calcium carbonate to some degree. The carbonate and andesite fans show the best-developed cementation and the rhyolitic fans and those composed dominantly of siliceous sediments have markedly less well-developed cementation. Calcic horizons ranging from pebble coatings to plugged and laminar horizons (sequential steps in the formation of mature calcic horizons according to Gile et al., 1986) were found on alluvial-fan deposits of carbonate and andesite lithologies, but on rhyolite, rhyolitic tuffs (like at Yucca Mountain) and noncalcareous sediments, only thin pebble coatings, discontinuous strings of calcareous cement, or weak calcic horizons were found, even where large quantities of calcareous dust were available (Lattman, 1973).

Lattman's study is pertinent to our findings at Yucca Mountain. In the summit crater of Lathrop Wells Cone, volcanic clasts are covered with a thin (few mm) carbonate coating that must have had a wind-blown dust, pedogenic origin. These pedogenic coatings have a measured carbon-oxygen isotope value of $\delta^{13}C = 0.47$, $\delta^{18}O = -5.82$ (PDB) (Harmon, 1993) compared to the controversial, so-called "pedogenic" calcite/opal deposits which usually fall into the range of $\delta^{13}C = -6$ to -8, $\delta^{18}O = -9$ to -12 (Quade and Cerling, 1990). This occurrence is important because it show that pedogenic carbonate build-up in the rhyolitic-tuff setting of Yucca Mountain is minimal (like in Lattman's, 1973, study). There should be thin pebble coatings or weak calcic horizons at Yucca Mountain from a wind-blown limestone dust, pedogenic source, but <u>not</u> extensive calcite/opal deposits that extend 400 m deep into the subsurface.

Another study relevant to the question of a wind-blown dust origin for the calcite/opal deposits at Yucca Mountain is that of Bachman and Machette (1977) who compared calcic soil profiles to overlying wind-blown sand at Llano de Albuquerque, New Mexico. These authors concluded that it was volumetrically impossible to derive all the calcium carbonate in the relict calcic soil profile (1.5-2.5 m in thickness) from the overlying cover of eolian sand (5-10 m thick; 2-3% Ca) by normal weathering processes. At Yucca Mountain the deficiency is even greater: there is <u>no</u> covering of eolian sand and the Ca from rhyolitic tuff is <2-3% (Hill and Livingston, 1993).

<u>Stages of pedogenic calcrete development</u>. Calcic soils and pedogenic calcretes follow a six-stage sequence of morphologic development based on the classification of Gile et al. (1966) and Bachman and Machette (1977):

Stage I: The first or younger stage includes filamentous or faint coatings of carbonate on detrital grains.

Stage II: The second stage includes pebble coatings which are continuous; firm carbonate nodules are few to common.

Stage III: The third stage includes coalesced nodules which occur in a friable or disseminated carbonate matrix.

Stage IV: The fourth stage includes a platy, firmly cemented matrix which engulfs nodules; the soil horizon then becomes plugged to downward-moving solutions.

Stage V: The fifth stage includes soils which are platy to tubular, dense, and strongly cemented. A well-developed laminar layer occurs on the upper surface of the plugged horizon. Stage V morphology includes thick laminae and incipient pisolites (Machette, 1985).

Stage VI: The sixth and most advanced stage is massive, multilaminar, and strongly cemented calcrete with abundant pisoliths, the upper surface of which may be brecciated. Stage VI morphology includes the products of multiple cycles of brecciation, pisolite formation, and wholesale relamination of breccia fragments (Machette, 1985). Older, more advanced calcretes commonly contain sepiolite and palygorskite and a higher proportion of micrite to microsparite or sparite (Bachman and Machette, 1977).

One problem with the calcretes at Yucca Mountain is this: the soils at Yucca Mountain display Stage I and possibly some Stage II development (e.g., the coatings over clasts at Lathrop Wells Cone and Taylor's, 1986, soil horizons in Fortymile Wash), but the controversial calcite/opal deposits display Stage V-VI development, *if* indeed they can by put into *any* morphologic soil category. The calcite/opal vein deposits at Yucca Mountain do not display pisolitic texture as typical of advanced calcrete development and sepiolite is not accompanied by palygorskite; in addition, these deposits display textures (e.g., flow textures, etc; Hill and Schluter, 1993) that have never been reported for pedogenic deposits in any stage of development. So the pertinent questions are: (1) How can a Stage V-VI morphology develop in a primarily Stage I-II terrain, without the intermediate stages of soil development being involved? and (2) Why doesn't the calcite/opal at Yucca Mountain display textures characteristic of developmental soil stages in pedogenic deposits?

Rate of calcrete accumulation. Another problem is that advanced (Stage V-VI) soils require a long time to develop whereas some of the calcite/opal deposits at Yucca Mountain are very young. Advanced stages of soil development can take millions of years to form: e.g., the Miocene constructional surface of the Ogallala Formation of eastern New Mexico and western Texas and the Pliocene Mormon Mesa surface of the Muddy Creek Formation east of Las Vegas, Nevada. Gardner (1972) estimated that at least 25% of the calcium carbonate in caliche at Mormon Mesa was derived from dissolved Ca^{++} and HCO_3^- in rainwater with the remainder probably furnished by eolian carbonate dust; Gardner (p.143) also estimated the time for development of this caliche to be "at least 400,000 years and possibly as long as 2,500,000 years." The so-called "pedogenic" calcrete and vein deposits at Yucca Mountain, however, are known to be as young as 26,000 years (USWG-3/GU-3, 131 m), 27,000 years (Trench CF1), approximately 30,000 years (Wailing Wall), 38,000 years (Trench 14), etc.

Bachman and Machette (1977) and Machette (1985) discussed the rate of calcite soil formation in the southwestern United States and reported it was somewhere between 0.09-0.5g/cm^2/kyr. Taylor (1986) used a rate of 0.1 g/cm^2/10^3 yrs for Fortymile Wash, Yucca Mountain. Using the maximum (0.5) rate of accumulation for pedogenic calcretes in the Southwest, the amount of time for the so-called "pedogenic" deposits at Yucca Mountain can be roughly calculated. For example, thickness of the calcite/opal deposits at the Wailing Wall is ~3-4 m along the fault zone. At a rate of 0.5 g/cm^2/1000 years, this would place the Wailing Wall calcite/opal at a minimum age of 10^5-10^6 years; yet, the calcite/opal at this site has been dated at approximately 30 ka (R. Harmon, pers. comm., 1992).

Recommendations

It is recommended that calcite/opal samples be analysed by a qualified soil scientist using SEM techniques in order to determine the following:

(1) Are the calcite/opal deposits devoid of a soil matrix as it appears from thin-section microscopic examination? If they are devoid of clastic grains, does this mean they are nonpedogenic?

(2) Observe the "algal-ooidal" - textured specimens to see if this is typical of nodular texture in pedogenic calcretes or if it is of algal-spring origin.

(3) Determine if there are bioturbation/microorganismal features associated with the calcite/opal. If the calcite/opal is hypogene in origin it should be expected that the mass of calcite/opal cooled and precipitated quickly with the liberation of gas and thus microorganisms should not have been involved with this precipitation (although roots could have grown into hypogene spring deposits later in time).

(4) Examine the vesicles to determine if they could have a pedogenic/caliche origin, as is the case for birdseye texture. If not, this factor in itself would strongly

favor a hypogene-hydrothermal origin for the controversial deposits.

(5) Examine the samples with cathodoluminescence. One of the authors (Monger) has already taken a quick look at one thin section under cathodoluminescence and it luminesced beautifully. Cathodoluminescence may be an important tool for comparing pedogenic and hypogene deposits.

(6) A long-term recommendation is to study a number of so-called "pedogenic" deposits in southern Nevada and compare these with the calcite/opal deposits at Yucca Mountain.

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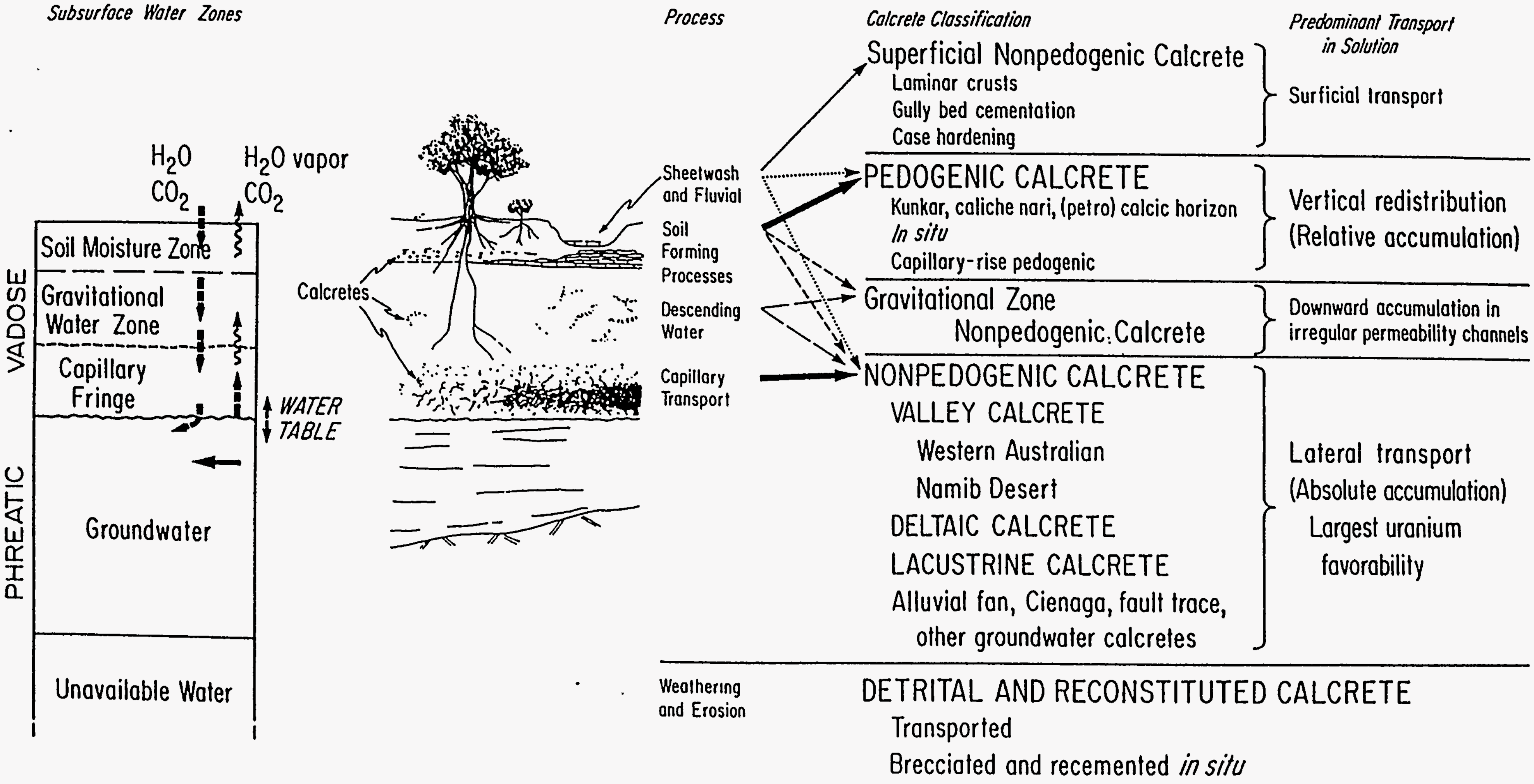

Figure 1. A genetic classification of calcretes. After Carlisle (1980).

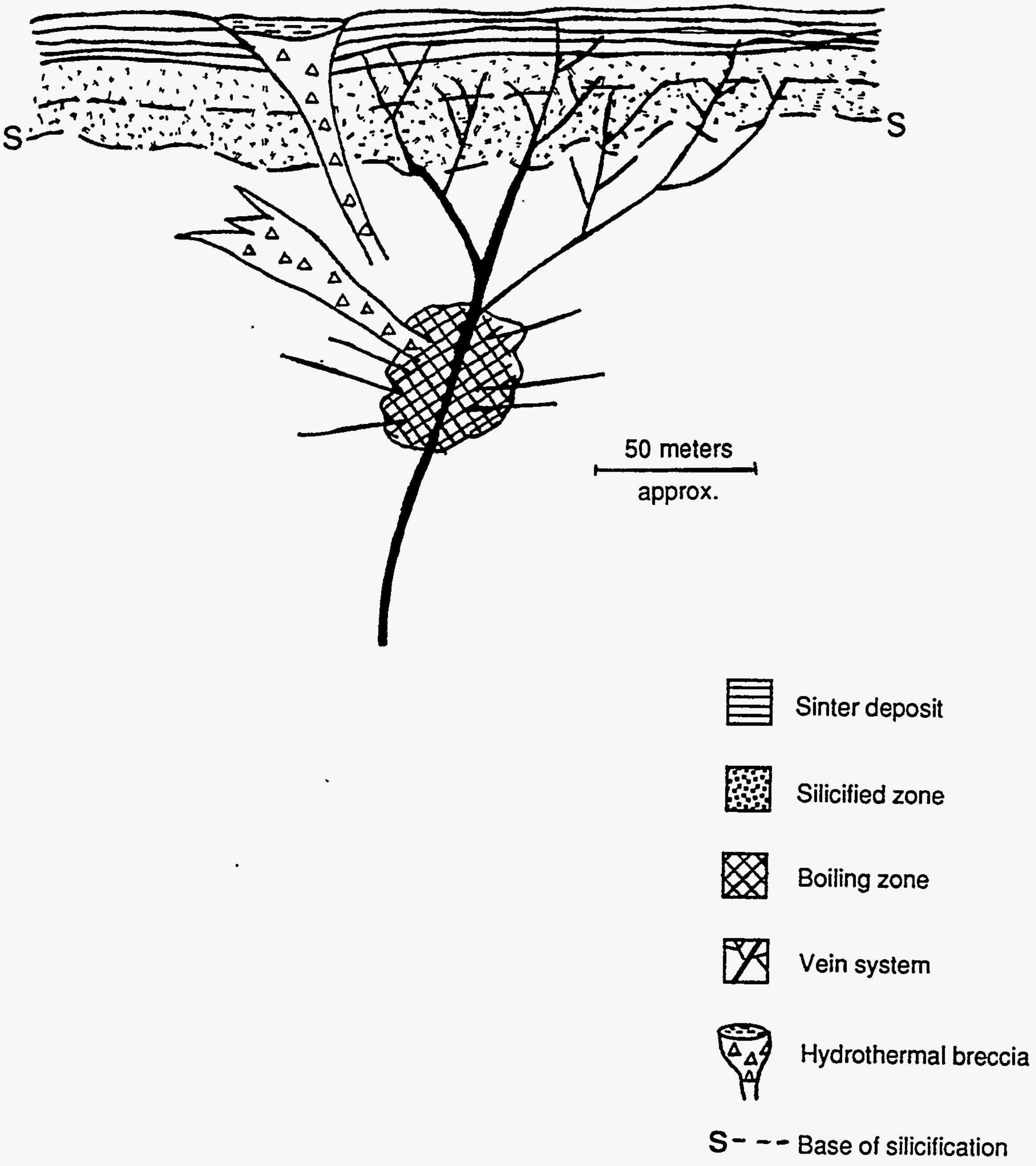

Figure 2. Schematic cross-section of epithermal vein deposits, after Berger and Eimon (1982). Calcite/opal deposits at Yucca Mountain have a similar morphology of a feeder vein bifurcating near the surface into multiple smaller veins and they also consist of surface sinter (calcite and opal travertine) and disseminated metal enrichment.