INfiltration uranium deposits in ash flow tuffs

A THESIS
submitted in partial fulfillment of the requirements for the
Degree of Master of Science in Geology

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by

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April, 1972
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April, 1972
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>1</td>
</tr>
<tr>
<td>Introduction</td>
<td>2</td>
</tr>
<tr>
<td>General Statement</td>
<td>4</td>
</tr>
<tr>
<td>Description of the Uranium Prospects</td>
<td>6</td>
</tr>
<tr>
<td>Independence Prospect</td>
<td>7</td>
</tr>
<tr>
<td>Divide Prospect</td>
<td>13</td>
</tr>
<tr>
<td>Spanish Springs Valley Prospect</td>
<td>16</td>
</tr>
<tr>
<td>Delongchamps Prospect</td>
<td>19</td>
</tr>
<tr>
<td>Analytical Results</td>
<td>22</td>
</tr>
<tr>
<td>Summary of Important Characteristics</td>
<td>21</td>
</tr>
<tr>
<td>Discussion</td>
<td>32</td>
</tr>
<tr>
<td>The Unconformity</td>
<td>32</td>
</tr>
<tr>
<td>The Presence of Organic Terrains</td>
<td>35</td>
</tr>
<tr>
<td>Welding</td>
<td>38</td>
</tr>
<tr>
<td>Crystallization of the Glass</td>
<td>41</td>
</tr>
<tr>
<td>Migration and Concentration of Uranium</td>
<td>45</td>
</tr>
<tr>
<td>The Conceptual Model</td>
<td>50</td>
</tr>
<tr>
<td>Variations in the Basic Conceptual Model</td>
<td>53</td>
</tr>
<tr>
<td>Ore Deposit Potential</td>
<td>55</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>58</td>
</tr>
<tr>
<td>Appendix I. Terminology</td>
<td>59</td>
</tr>
<tr>
<td>Appendix II. Sample Descriptions</td>
<td>61</td>
</tr>
<tr>
<td>References Cited</td>
<td>62</td>
</tr>
</tbody>
</table>
ILLUSTRATIONS

Figure 1. Index map showing the name and location of the prospects discussed in the report 5

2. Photograph of part of the carbonaceous zone at the Independence Prospect 10

3. Photograph of iron oxide halo around the mineralized zone, Independence Prospect 12

4. Photograph of part of the carbonaceous zone at the Divide Prospect 14

5. Geologic cross-section of the Spanish Springs Valley Prospect 17

6. Photograph of the volcanic cobbles below the Garrett Ridge Sillar 22

7. Photograph of a hand specimen from the carbonaceous zone at the Delongchamps Prospect 24

8. Photograph of a hand specimen from the carbonaceous zone at the Delongchamps Prospect 25

9. Photograph of a large, silicified log from the carbonized zone at the Delongchamps Prospect 26

TABLES

Table 1. Uranium content and amount of organic material present in the samples from various portions of the carbonaceous zones 29
ABSTRACT

A study of four uranium deposits in the basal, carbonaceous zones of certain ash-flow tuffs of the Hartford Hill Rhyolite shows that uranium may be leached, transported by groundwater, and concentrated in areas of organic debris within an ash flow unit. Zones of carbonized organic material are present only in ash flows deposited on a terrain upon which plant life was established.

The uranium occurrences lack structural control or evidence of sulfide mineralization and hydrothermal alteration. Mineralization occurs in ash-flow tuffs with varying degrees of welding, but all have been thoroughly devitrified.

Visible uranium minerals are rare. Uranium mineralization is always associated with organic debris, but there is no correlation between the amount of organic material present and the amount of uranium present.

Factors governing the presence and location of infiltration uranium occurrences, such as the availability of organic debris, welding, and devitrification are discussed.

A conceptual model of the typical infiltration uranium deposit is presented and variations in the basic model are discussed. Ash-flow tuffs are common in many different geologic regimes, and similar concentrations of uranium may be of importance elsewhere.
INTRODUCTION

Following the Second World War, exploration for uranium in the United States led to an intensive research campaign concerning its genesis and distribution in space and time. As with many other metals, it was found that uranium occurred in both hypogene and supergene environments. Hypogene deposits are veins, occasionally replacement bodies, and are usually classified according to mineralogy. They occur in rocks of many ages and differing lithologies and tend to be located along regional structures. Supergene occurrences may also be referred to as epigenetic or infiltration deposits. There are many different classification schemes for these deposits, including lithology and age of the enclosing rock.

Both infiltrational and vein-replacement types of ore deposits are present in the Great Basin. Here, as elsewhere, it is generally accepted that infiltration uranium occurrences are restricted to sedimentary rocks, especially continental and fluvial sediments. In the Great Basin, such rocks are generally Tertiary in age, and some are similar to Tertiary sediments in the intermountain basins of Wyoming which contain infiltration uranium deposits.

Early in the spring of 1971, a study of infiltration uranium deposits in Nevada was initiated. A reconnaissance of all types of uranium occurrences on a regional basis was conducted, based primarily on information from Garside (1970, unpublished data). Over 300 different radio-
active occurrences were plotted on 1:250,000 scale AMS
topographic maps of Nevada. Initially, uranium occurrences
were classified in a manner modified from Garside (1970,
unpublished data); uranium in

1. Volcanic flows and plugs
2. Ash-flow tuffs
3. Tertiary terrestrial sediments
4. Tertiary lacustrine and fluvial sediments
5. Pre-Tertiary rocks
6. Pre-Tertiary plutonic rocks
7. Pegmatites and quartz veins

It was assumed that all of these occurrences could have
minor amounts of supergene uranium related to present-day
leaching associated with them, but it was thought that only
the Tertiary sediments were potential sites of important
infiltration mineralization.

The second phase of study consisted of visiting repre­
sentative occurrences of each type (excluding pegmatites and
quartz veins) in northwestern Nevada. This portion of the
state was chosen because of accessibility and because all
of the types of deposits were present. Zones of minerali­
ation and anomalous radioactivity were delineated with a
Model PR-111 Scintillator. Particular attention was paid
to possible lithologic or structural control, alteration,
mineralogy, intensity of mineralization, and extent of
anomalous radioactivity and/or visible mineralization.
Many kinds of uranium occurrences were visited, including a number in ash-flow tuffs, where uranium was found to occur in carbonaceous zones at the base of the ash flow. While attempting to determine the exact nature of mineralization and its relationship to other occurrences in volcanic rocks, the possibility that these deposits are infiltration uranium deposits was realized. Because deposits of this kind have not been mentioned in the literature, and because there are thousands of cubic miles of ash-flow tuffs in Nevada, it was decided that these deposits were worth detailed investigations.

For this purpose, three examples of this kind of uranium occurrence were chosen for detailed study. A fourth ash-flow tuff was investigated to more closely determine some of the characteristics of the carbonaceous basal ash. The prospects are shown in fig. 1, p. 5.

GENERAL STATEMENT

The terminology and classifications for pyroclastic rock units and rock types is chaotic and confused. Ignimbrite, welded-tuff, and incandescent tuff-flow have all been used simultaneously as rock unit terms and rock types. The original term, ignimbrite, was first defined by Marshall (1932, p. 200) as a rock formed by a particular eruptive process, that is, a rock unit term. However, in a later paper, Marshall (1935, p. 323, 360) refined his definition to mean rocks deposited from a unique eruptive process but which were not hot enough that the fragments were viscous and
adhered together after they reached the ground. He noted that "ignimbrite is used as a name for a 'musa ardente Katmaienne' in the nomenclature suggested by A. Lacroix". In his second definition Marshall introduced two new restrictions; some degree of welding and an acid composition. The latter effectively made ignimbrite a rock type term. In the ensuing confusion, workers used ignimbrite and its synonyms in a dual sense, or worse, applied their own terminology. Because of this confusion, the reader is referred to Appendix I, where necessary terminology has been defined for the sake of clarity.

The ash-flow tuffs are classified in the manner of Cook (1965, p. 4, 5) as vitric, crystal or lithic, according to what percentage of the particles occur as glass, crystals, or rock fragments. The adjectives vitric and lithic are applied when those components exceed 10% of the tuff by volume. Cook’s method of displaying phenocryst composition and percentage of crystals in ash-flow tuffs is also adopted. These are shown graphically as (quartz/sanidine/plagioclase/ mafics/% crystals). For example, an ash-flow which contains 15 percent crystals (by volume), that consist of 60 percent quartz, 10 percent sanidine, 20 percent plagioclase, and 10 percent biotite, is portrayed (60/10/20/10/15).

DESCRIPTION OF THE URANIUM PROSPECTS

The uranium prospects described in this report all occur in the Hartford Hill Rhyolite. Despite its name, the
Hartford Hill Rhyolite is predominantly composed of rhyolitic ash-flow tuffs, although thin lenses of sandstone, conglomerate, volcanic breccia and ash-fall tuff are present. Based on three K-Ar dates from 22.7 to 22.8 million years (Evanenden and James, 1964, p. 966), the Hartford Hill is early Miocene in age. In southern Washoe County, it is the oldest widespread Tertiary unit, and usually is found unconformably resting on Mesozoic metamorphic and granitic rocks.

The prospects were discovered in the uranium boom of the early 1950's because radioactivity could be detected by geiger counter. They were developed by bulldozer cuts and short adits. No production was recorded during development and they have not been explored beyond the initial bulldozer trenching.

**INDEPENDENCE PROSPECT**

The Independence Prospect is located on the north flank of Seven Lakes Mountain, adjacent to Dry Valley. It explores a poorly exposed ash-flow tuff designated the Dry Valley Tuff. The Dry Valley Ash-flow Tuff is pale green, partially welded, and is crystal-rich (5/10/80/5/15). A complete section is not exposed, but it is approximately 150 feet thick.

The mineralogy is simple; phenocrysts are fresh biotite, cloudy sanidine, or clear quartz. Lithic fragments are a common and distinctive feature of the tuff (5% by volume). The pumice fragments are unusually small and not
easily distinguished from the matrix. The uncommon larger fragments clearly show the beginning of a eutaxitic texture. The coarse, grainy texture of the pumice fragments is due to thorough secondary crystallization; even the shards are completely devitrified.

Vertical variations in the ash-flow tuff are gradual and subtle. The only significant megascopic change is in the degree of fracturing, which decreases markedly in the upper half of the section.

The ash-flow below the Dry Valley Tuff is a crystal-rich, very slightly welded ash-flow tuff (0/5/90/5/35). As in the case of the Dry Valley Tuff, the unit is well crystallized, and these well-indurated rocks are a distinctive reddish color. The upper ten feet of this unit, unlike the lower portions, contains a high percentage of lithic fragments, dominantly andesite, basalt, and older welded tuff fragments.

The ash-flow tuff which overlies the Dry Valley Tuff does not crop out near the prospect. Examination of float reveals it to be a brick-red, slightly welded to nonwelded ash-flow unit containing large tan pumice fragments.

The Dry Valley Tuff was deposited on an eroded terrain. Its lower surface is undulating and it must have been deposited on a topography with gentle relief. The duration of the hiatus cannot be determined accurately, but it was probably quite brief.

At the base of the Dry Valley Tuff lies a zone of
carbonized organic debris, in which the anomalous radioactivity and uranium mineralization occurs. Although it does not crop out continuously, the carbonaceous zone can be traced for at least 1000 feet along the strike of the ash-flow in discontinuous, lens-shaped, carbon-rich bodies. The poor outcrops are probably a result of the softer character of the carbonaceous material, so that the devitrified ash-flow tuff stands out in differential erosion.

In detail, the basal zone consists of carbonized wood fragments oriented parallel to the base of the ash-flow (fig. 2). The size range of the organic debris is distinctly bimodal. Small rectangular fragments (averaging 1x1x2mm) are scattered between much larger fragments (3x5x30cm). The small fragments probably represent pieces of larger carbonized limbs which were broken apart during transportation in the turbulent ash-flow. The larger pieces are elliptical in cross section and growth rings are clearly visible. These represent portions of limbs and trunks of trees which have been aligned in the direction of flowage and then compressed.

In places, the carbonaceous zone is a single thin layer, not a zone of scattered debris. The organic zone varies from a few inches to a maximum of about 6 feet (base unexposed). While it can be traced laterally for some distance, its vertical dimensions are irregular, even over short distances.

Megascopically, a simple alteration halo of iron oxides
Figure 2. Photograph of part of the carbonaceous zone in the Dry Valley Tuff, Independence Prospect, Washoe County, Nevada. The ash-flow is inclined away from the observer about 20°.
is developed around the carbonaceous zone (fig. 3). This discoloration is developed only in zones of organic debris, and not in the remainder of the ash-flow tuff. The iron oxide staining is probably due to the oxidation of iron compounds, perhaps simple iron sulfide, introduced into the ash-flows with the mineralizing solutions. The exact form of the original iron minerals is unclear because neither pseudomorphs nor unoxidized remnants of primary minerals have been found. The intensity of the discoloration is variable, but in carbonaceous zones with a high percentage of organic debris it appears to be the most well-developed.

Microscopically, alteration associated with uranium mineralization is very subtle. In general, it consists of faint, but pervasive iron oxide staining of the crystallized glassy material. Much of the organic debris has a rather strong iron oxide halo, and some of the shards have a thin rim also; but strong or intensive alteration is essentially lacking. This suggests that the mineralizing solutions were of relatively low temperature and pressure, and of a moderate pH.

The Independence Prospect was explored by several pits, a large bulldozer cut, and two short adits. The bulldozer cut is in the thickest portion of the carbonaceous zone and provides the best exposure of the organic debris. It appears that there has been no exploratory work done in the last several years.
Figure 3. Photograph of the iron oxide halo surrounding the carbonaceous zone. The carbonaceous zone is very thin here, but has an unusually well developed iron oxide halo. Independence Prospect, Washoe County, Nevada.
THE DIVIDE PROSPECT

Near the crest of Dogskin Mountain lies an erosional remnant of the Hartford Hill Rhyolite which was deposited upon granodiorite. The pyroclastic unit, named Dogskin Mountain Ash-flow Tuff, is a rudely elliptical body about 700 feet long, 300 feet wide, and about 40 feet thick. Along one edge of the erosional remnant is a zone of carbonaceous debris which contains uranium mineralization.

The Divide Prospect consists of a series of bulldozer trenches and a large open cut. The smaller trenches explore unmineralized ash-flow tuff but the large cut exposes the carbonaceous zone. Surplus bomb canisters have been filled with carbonaceous material and stockpiled near the cut, suggesting that the prospect may have had some production.

The Dogskin Mountain Tuff is a slightly welded, vitric ash-flow tuff (10/10/80/0/0/3). Pumice fragments are not abundant, but where present they are slightly collapsed. Megascopically, the ash-flow material associated with organic debris is gray, otherwise, the ashy material is light tan. The entire ash-flow tuff is devitrified, but in most cases, the shard outlines have been retained; in cases of extreme crystallization the texture of the shards and pumice fragments has been destroyed.

At one spot above the carbonaceous zone, two large weathered granodiorite boulders nearly 15 feet in diameter (fig. 4) overlie the basal ash. These were caught up by
Figure 4. View of part of the carbonaceous zone at the Divide Prospect, Dogskin Mountain, Nevada. Black lenses of carbonized wood lie below a large weathered granodiorite boulder. Rock pick at left gives scale.
the moving ash-flow during dispersal and their presence testifies to the tremendous energy of moving ash-flows. During compaction of the ash-flow, the material below the boulders was compressed to a greater degree than the rest of the tuff. Below the boulders the carbonized limbs have been flattened (fig. 4); elsewhere, the limbs have, essentially, retained their original shape. Individual carbonized limbs are up to 10 cm thick and up to 90 cm long. In thin section, small lenses of organic debris in the matrix of the tuff are common. They are black, opaque, and frequently show cellular structures. Below the boulders the carbonaceous zone is about 6 feet thick, but laterally it increases to nearly 20 feet thick. The carbonaceous zone can be traced about 100 feet laterally before being covered by talus, so its horizontal dimensions cannot be determined. As currently exposed, the carbonized zone is nearly 100 feet long, averages 8 feet thick, and contains about 10 percent organic debris by volume.

Visible uranium minerals are rare; only one small film of yellow, secondary uranium minerals was found. The exact form of the uranium mineralization is not clear. If the uranium is in the reduced state, it would probably consist of uraninite or coffinite as disseminated, powdery masses replacing the carbonized wood. These minerals are very difficult to identify because they are so fine-grained and are usually closely intergrown with the organic material. The minor amount of yellow uranium minerals may be related
to present-day weathering and oxidation of the outcrop.

Alteration, both megascopic and microscopic, is generally absent. In the carbonaceous zone iron oxide staining is common along fracture planes, but it is not present in the remainder of the ash-flow tuff. The only other feature which may be related to alteration is unusually thorough devitrification. The shards, pumice fragments, and groundmass material have crystallized to an unusually coarse aggregate of cristobalite and alkali feldspar. Both iron staining and coarse devitrification are very weak forms of alteration, and may be attributed to the influence of moving groundwater and normal weathering processes.

SPANISH SPRINGS VALLEY PROSPECT

The Spanish Springs Valley Prospect is also located in the basal ash-flow of the Hartford Hill Rhyolite. This prospect, like the Divide Prospect, is an erosional remnant which caps a hill of Mesozoic granitic rock. A geologic cross-section of the Spanish Springs Valley Prospect is shown in fig. 5.

This prospect is the only one examined which has a well-developed basal vitrophyre. Poorly formed perlitic cracks suggest that it has been hydrated, but the vitrophyre is not devitrified. Its dark gray to black color is probably related to lack of devitrification. The tuff above the basal vitrophyre is a tan colored, slightly welded
GEOLOGIC CROSS SECTION OF THE SPANISH SPRINGS VALLEY PROSPECT

FIGURE 5.
ash-flow tuff (0/0/90/10/5). Both shards and punice fragments are devitrified. The tuff is hard, porcellaneous, and thoroughly fractured, and only close examination reveals that it is part of the same unit as the basal vitrophyre.

This ash-flow was deposited in a small gully eroded into metamorphic and granitic rocks. The metamorphic rock is a biotite-rich quartzofeldspathic schist. It is probably a roof pendent in the granodiorite which outcrops to the east.

The carbonaceous zone lies in the bottom of the small gully; it cannot be traced laterally for any distance. It contains two types of organic material: highly carbonized wood fragments and wood which has been silicified, but not carbonized. Both kinds of wood fragments are intimately mixed in the carbonaceous zone. The wood fragments are rather large, being about 15 cm long and 10 - 15 cm in diameter.

Visible uranium minerals were not identified by the author, but Garside (1970, unpublished data) reports that sabugalite and autunite occur along fractures and layers in the wood, and disseminated in the weathered metamorphic rocks. The secondary, hydrated minerals probably represent a redistribution of uranium in response to destruction of the deposit by erosion and associated oxidation. Mineralization is not related to either the small normal fault or the numerous fractures, suggesting that it is not struc-
turally controlled.

Alteration is very poorly developed. A weak iron oxide staining of the carbonaceous zone is the only change other than normal postdepositional welding and crystallization.

The prospect is neither large nor well exposed. However, it substantiates the earlier observations that uranium mineralization may be located in the carbonaceous zones of ash-flow tuffs. It is similar to the other occurrences in that an unconformity is present, and alteration is generally weak. It also shows that the presence of a basal vitrophyre does not necessarily inhibit uranium mineralization.

Development work at the Spanish Springs Valley Prospect consists of one large and one small bulldozer trench. The prospect is located on land owned by North American Rockwell Corporation.

DELONGCHAMPS PROSPECT

At the DeLongchamps Prospect, secondary uranium minerals have developed along a diabase dike in the Hartford Hill Rhyolite. In the area around the prospect, the dike cuts at least three cooling units, including a siller ash-flow tuff with a carbonaceous zone named the Garrett Ridge Sillar. Because of the presence of the dike, the origin of the uranium mineralization may not be simply infiltrational. Effects of possible alteration and introduced uranium associated with the diabase dike are difficult
to distinguish from similar effects related to infiltration uranium occurrences. Consequently, this ash-flow tuff has been studied in detail, and particular emphasis placed upon the carbonaceous zone at the base of the Garrett Ridge Ash-Flow.

The Delongchamps Prospect is the best developed prospect of those studied. In the 1950's bulldozer trenches were cut along the outcrop of the mineralized tuff adjacent to the diabase dike, and 120 foot adit was driven along the footwall of the dike. Recent work includes a large bulldozer cut and two short adits about 30 feet long. Bulldozer roads and trenches have provided many relatively fresh outcrops of both the carbonaceous zone in the Garrett Ridge Sillar and older and younger ash-flow tuffs.

Beneath the Garrett Ridge Sillar is a densely welded ash-flow tuff which displays a strong eutaxitic texture of black, collapsed pumice fragments set in a tan, porcellaneous, crystal-rich matrix (12/88/3/0/7). Intense secondary crystallization has developed small lithophysae in the collapsed pumice fragments, although remnants of shard structures are megascopically visible in the matrix.

The degree of welding in this lower unit is atypical of the upper zones of ash-flows; it usually occurs near or below the middle third of the section. Erosion has stripped off more than just the nonwelded upper ashy zone, in this case it has cut down into the zone of dense welding.

Above the densely welded tuff lies an old erosion
surface marked by well rounded cobbles of volcanic rocks (fig. 6). The cobbles are dominantly andesitic volcanic rocks and some granitic rocks. These probably were transported from near the margins of the ash-flow field or from regions of particularly deep erosion. Their presence certainly indicates that an unconformity is present. The Garrett Ridge Sillar thickens from 100 feet on the ridge (present topography) to 150 feet in the canyon on either side. This is also conclusive evidence for erosion prior to deposition of the sillar, for ash-flows tend to have extremely flat upper surfaces because of their fluid-like nature during dispersal, and tend to "puddle" in areas of low relief. Marked differences in thickness are probably due to deposition over preexisting topography.

Above the zone containing cobbles lies a two foot thick zone of soil and ash (fig. 6). The soil was derived from the old erosion surface and was caught up and mixed with ash in the turbulent ash-flow. All of the glassy material has completely devitrified to a bentonitic clay. Small carbonized wood fragments are scattered throughout the top of this zone.

Separated from the soil/ash zone by a sharp contact is a resistant, white, crystal-rich zone of ash-flow tuff (95/0/5/0/35). Frosted quartz crystals are set in a devitrified porcellaneous matrix which contains no carbonaceous debris. This distinctive unit is only 18 inches thick.
Figure 6. Volcanic cobbles below the Garrett Ridge Sillar. Above the rock pick handle is a two foot thick zone of soil and ash which has devitrified to form bentonitic clay. Delongchamps Prospect, Virginia Mountains, Nevada.
Above another sharp contact lies the first portion of the ash-flow that contains significant organic debris. It is an eight foot zone of hard, light gray, ash-flow tuff. The carbonized wood fragments come in three distinct size ranges; the first averages 1x1x2 mm, the second 7x10x20 mm, and the larger fraction consists of limbs and logs from 15 to 50 cm in diameter and up to 175 cm long (figs. 7, 8, & 9). All of the carbonized material has been compressed and flattened. By volume, carbonized organic material constitutes from 5 to 10 percent of the eight foot carbonaceous zone. The composition of the ash-flow (10/30/0/3/1/30) remains the same from this zone to the top of the sillar; only the color changes. The gray color in the carbonaceous zone may be due to minute organic material scattered through the matrix. Groundmass material has been thoroughly crystallized, the shards are still glassy. Even near the base, there is no evidence of welding, although there is some compaction of the ash-flow.

The degree of carbonization varies; some logs are entirely reduced to charcoal, while others of the same dimensions are hardly carbonized and are only slightly silicified. This may be a function of the length of time that the wood was transported in the ash-flow, the more completely carbonized material being transported for a longer distance and being exposed to the intense heat for a longer period of time. The noncarbonized debris might represent trees that were growing when they were caught up, the water
Figure 7. Photograph of medium-sized carbonized wood fragments from the carbonaceous zone of the Garrett Ridge Sillar. View is parallel to the plane of foliation caused by compaction of the ash-flow. Delongchamps Prospect, Virginia Mountains, Nevada.
Figure 8. Carbonaceous material from the same location as figure 7, except that this view is perpendicular to the foliation caused by contraction of the ash-flow tuff, Delongchamps Prospect, Virginia Mountains, Nevada.
Figure 9. Photograph of large, relatively uncarbonized log from the carbonaceous zone at the Dalongchamps Prospect, Virginia Mountains, Nevada.
content preventing thorough carbonization. The logs that are highly carbonized may represent dead dry logs that were resting on the ground prior to transportation. Regardless of their origin, the relationship is significant because the more thoroughly carbonized remains would be the most favorable location for the precipitation of secondary uranium.

Above the carbonaceous zone lies the remainder of the ash-flow tuff. The percentage of organic debris above the carbonaceous zone is less than one percent. The ash-flow tuff is a hard, pale green unit which has been thoroughly devitrified; shards, groundmass, and pumice fragments are coarsely crystalline. The devitrification of the shards is probably due to the influence of upward migration of volatiles released from the crystallization of the glassy groundmass material and pumice fragments in the lower portions of the ash-flow. The pumice fragments are usually small and very slightly compressed. The whole of the ash-flow is fractured, probably in response to normal faulting which is characteristic of the area. Exposures of this upper portion of the ash-flow tuff are very poor and vertical variations are difficult to document. This is characteristic of sills which are indurated by secondary crystallization and lack well defined zones of welding; they tend to be very homogenous throughout.

The basal portion of the sillar can be traced without change for about 200 feet laterally in a large bulldozer cut.
All of the zones are present and do not vary in thickness. While this represents only a very small portion of the ash-flow, there is other evidence that the carbonaceous zone may be widespread. Brooks (1956, p. 13) states that carbonized and petrified wood is present at the base of the ash-flow tuff for at least 2000 feet in a north-south direction. The zone of organic debris covers a sizeable area and is not just a small isolated occurrence.

The Delongchamps Prospect provided the only identifiable plant fossils. A well-preserved leaf of the oak Quercus simulata Knowlton and scattered fragments of the genera Populus and Metasequoia (?) are present (J.R. Firby, personal communication). That such delicate leaves would be preserved is very surprising since the motion of ash-flows is usually referred to as turbulent or chaotic. Extreme turbulence was present in most parts of the ash-flow, as evidenced by frosted quartz grains, fractured and broken phenocrysts, and a relatively homogenous original mineralogy. However, there is evidence which suggests that there may be some laminar flow at or near the base of some ash-flows. The long dimensions of the carbonized limbs and logs at all the prospects are oriented parallel to the base of the ash-flow and within 30° of the same compass bearing. If the flow was very turbulent, then the limbs should have a much more random final orientation, and perhaps importantly, would be distributed throughout the ash-flow in a more homogenous fashion. Biotite flakes in the Dry
Valley Ash-flow Tuff are oriented parallel to the base of the ash-flow and not in a haphazard fashion. Clearly, there is some type of laminar flow which operates at or near the base of the moving ash-flow. This flow may have a pronounced effect on the porosity and permeability of the ash-flow near the base. If the shards, phenocrysts, and pumice fragments are aligned in some fashion, migrating groundwater would tend to move preferentially in certain directions.

ANALYTICAL RESULTS

A number of samples were analyzed fluorimetrically for uranium. The quantity of samples taken was limited by the generally poor exposures and discontinuous nature of the carbonaceous zones. The uranium content and the volume percent of organic debris of the samples is given in Table 1.

The location and description of the samples is presented in Appendix II.

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Table 1. Uranium content and amount of organic material present in the sample from various portions of the carbonaceous zones.

The samples contained between 24 ppm (0.0024%) and 2600 ppm
(0.26%) uranium, and the variation in the degree of enrichment in different portions of the carbonaceous zone may vary even more widely than this. Various parts of the carbonaceous zone have been leached selectively, giving certain samples the appearance of being "enriched" in uranium. A channel sample taken from the carbonaceous zone at the Divide Prospect contains 120 ppm uranium, but a sample of carbonaceous debris along (no tuff matrix) from the same location contains 2500 ppm uranium. Similar results were obtained from material at the Independence Prospect, suggesting that the uranium is located in the organic debris rather than in the ash-flow tuff. Samples across other sections of nearly pure carbonaceous debris (nos. 317 and 319) contained only 14 and 24 ppm uranium. Samples that are nearly pure organic debris are both very high and very low in uranium, suggesting no correlation between volume percent organic material and the amount of uranium present. Samples containing large amounts of organic debris are not necessarily richer in uranium than samples with only a few percent of organic material.

The samples from the Spanish Springs Valley Prospect show that carbonized wood may contain more uranium than silicified wood. The uncarbonized wood contains only 24 ppm while the carbonized wood fragments contain up to 196 ppm uranium.

The limited number of samples precludes detailed conclusions, but the results of the analytical work suggest
the following generalizations:

1. The uranium is located in the carbonaceous material of the ash-flow tuffs.
2. The uranium content is not a function of the percentage of organic debris in the sample.
3. Carbonized wood tends to be enriched more than silicified, uncarbonized wood.

SUMMARY OF IMPORTANT CHARACTERISTICS

Each of the four prospects is slightly different and has its own unique characteristics; however, they are all fundamentally similar. The significant characteristics can be generalized as follows:

1. Some ash-flow tuffs have a basal zone of carbonized organic debris; when present, uranium mineralization is located in the carbonaceous zone.
2. Such ash-flows always rest on an unconformity.
3. Ash-flow tuffs with mineralization are very thoroughly crystallized and generally not strongly welded.
4. The uranium deposits lack any discernable structural control.
5. The deposits show none of the usual hypogene effects such as sulfide mineralization or hydrothermal alteration.
6. The only visible alteration is the development of iron oxides along fractures or as a halo around the carbonaceous zone.
7. Primary uranium minerals may be present, but were not identified; scattered, hydrated uranium minerals are rare.

8. Analysis for uranium show that mineralization is extremely irregular.

9. There is no apparent correlation between the amount of organic material present in a sample and the uranium content.

DISCUSSION

There are several geologic events involved in the formation of infiltration uranium mineralization in ash-flow tuffs. In reality, these processes are interrelated, but will be separated for the purposes of discussion. The following geologic processes influence the genesis and location of infiltration uranium deposits in ash-flow tuffs.

THE UNCONFORMITY

An unconformity, however small, is a necessity in the formation of an organic-rich basal layer of ash, and eventual concentration of uranium. A surface of nondeposition is necessary for the development of plant life which is the source of organic debris in the basal section of certain ash-flow tuffs. Only very rough estimates of the amount of time necessary for vegetation to begin regrowing can be made, and these would depend on soil, vegetation types, and climate. Ground plants began to establish themselves on miller deposits in the Valley of Ten Thousand Smokes in
1916, four years after the deposition of the tuff (Griggs, 1922, p. 157). It would of course take longer for the larger plant forms such as trees and shrubs to be established, but the necessary length of time would probably be on the order of a few tens of years. Since eruption of the pyroclastic sheets spanned the middle third of the Tertiary, many such time gaps are present. It is not suggested that each ash-flow is bounded by an unconformity, for the pattern of formation is clearly that of a series of closely spaced eruptions. The validity of this pattern is established in the stratigraphic column where there are many nonwelded basal sections, but relatively few sections containing carbonaceous inclusions. Technically, even the closely spaced ash-flow events are separated by a very small unconformity because the nonwelded upper ash zone is nearly always swept off by the succeeding flow, but these are probably not unconformities in the normal erosional/depositional sense.

When Tertiary ignimbrites rest on Mesozoic or Paleozoic rocks, an unconformity of a few tens to a few hundreds of millions of years duration is present. Consequently, beneath the initial Tertiary ash-flow event is a favorable location for carbonaceous zones. Because this particular unconformity is much more easily found than unconformities between ash-flows, and because it is very likely to contain the important carbonaceous zone, its location is of considerable interest in regional exploration.
Because unconformities are so necessary for secondary uranium deposits of this kind, recognition of their existence is essential. Several criteria may be used to establish their presence, an important one being the presence of abundant foreign inclusions at the base of the ash-flow. These foreign components are probably picked up from "lag gravels" of lithic fragments and/or crystals derived from the weathering of pre-existing tuffs. The lithic fragments tend to be rounded and weathered; they are usually easily distinguished from unweathered, angular, cognate inclusions. Much of the lithic material in the carbonaceous zone at the Independence Prospect was derived in this manner.

A second criterion is an ash-flow of drastically unequal thickness. Ash-flow tuffs are noted for their distribution over wide areas, due primarily to their fluid-like movement during deposition. When deposited over a terrain with topographic relief they flow into the low areas and tend to "smooth out" the topography. Succeeding flows, deposited in rapid succession, have a sheet-like form, the horizontal dimensions being many times greater than their vertical thickness. Ash-flow tuffs which vary in thickness over short distances were probably deposited on an irregular erosion surface, as for example at the Deiongchamps Prospect where the Garrett Ridge Sillar varies from 100 to 150 feet in thickness in about 300 feet horizontally. The unconformity is also marked by stream-rounded cobbles and wood fragments at the base of the
ash-flow (Brooks, 1956, p. 18).

A significant unconformity may be marked by a drastic change in lithology or welding. At the Divide Prospect the ash-flow tuff rests directly on Mesozoic granitic rocks producing a marked unconformity. Where the unconformity is between ash-flow tuffs it is less obvious, except where there is unusual change in the degree of welding between ash-flows. At the DeLongchamps Prospect the non-welded base of the ash-flow rests on a highly welded ash-flow tuff. Since welding of that intensity in the lower ash-flow is not to be expected at the very top of an ash-flow, it strongly suggests that erosion has stripped off the non-welded top and much of the zone of partial welding. This particular criterion may be difficult to establish and should be verified with other observations.

THE PRESENCE OF ORGANIC TERRAINS

One necessary requirement for infiltration uranium deposits of this kind is a powerful concentrating agent, in this case the carbonaceous debris. Organic material or "carbon trash" is the classic ore precipitant in secondary uranium deposits, especially deposits on the Colorado Plateau. In ash-flow tuffs, carbonized wood material serves the same purpose, and so organic debris must be present if secondary uranium is to be concentrated.

Carbonized wood implies that vegetation was established in the path of the ash-flow. The dispersal mechanism of ash-flows suggests that organic material, even if growing
in small, isolated patches, would be spread throughout the base of the ash-flow. That is, whatever organic debris was available would be dispersed through the basal section of the ash-flow. If however, the ash-flow was deposited on a terrain with little or no established plant life, there would be no carbonaceous basal ash and probably no infiltrational uranium mineralization. Therefore, the distribution of flora in the middle and late Tertiary in Nevada is significant.

The distribution of plant life is a function of several factors, the dominant one being climate. The changes in Tertiary climatic conditions have been rather drastic. In general, there has been a trend from a subtropical warm climate to a more temperate and humid climate eventually to the relatively arid climate of the present. Ash-flow tuff volcanism was well under way by the middle Tertiary. At that time there was not a ubiquitous Tertiary flora, but the pattern was one of "pockets" or basins of flora consisting of vegetation from the zone between woodlands and grasslands (J.R. Firby, personal communication). Axelrod (1966, p.25) inferred that the Eocene Copper Basin flora of northwestern Nevada received 50-60 inches of rainfall per year and had a mean temperature of about 51°F. The Miocene Trapper Creek flora of southeastern Idaho suggests an annual temperature of about 65°F (Axelrod, 1964, p.1). Younger floras show that the trend continued into the late Tertiary. Four Miocene-Pliocene floras of west-central Nevada
consisted of live-oak woodlands with conifer forests on bordering slopes, indicative of a biseasonal rainfall of from 25-30 inches yearly and rather mild winters (Axelrod, 1956, p. 14-15). Clearly, the change has been towards a cooler, more arid climate. With the inception of widespread Basin and Range faulting in the Pliocene came the formation of isolated depositional basins. In the Pliocene, the major uplifting of the Sierra Nevada block had a drastic effect on Pliocene flora. A strong rain-shadow was created by the Sierra Nevada which greatly accelerated the gradual change to an arid climate, finally producing the climate of today.

The distribution of flora in "pockets" and the general climatic changes in the Tertiary has direct bearing on the location of infiltration uranium deposits in Tertiary ash-flow tuffs. Ash-flows which were transported across and/or were deposited in floral terrains are likely to contain the basal carbonaceous zone. In pre-Miocene time, the depositional basins and floral basins (pockets) may or may not have coincided. The search for uranium deposits of this kind should be concentrated in areas where ash-flow tuffs and floral terrains coincide.

The effect of climate change is significant when dealing with deposits associated with Pliocene and younger ash-flow tuffs in which the distribution and density of plant life has been greatly reduced. Consequently, ash-flows erupted over such terrains may be relatively barren
of carbonized wood and plant material. This is not to suggest that all young ash-flows are void of organic debris, but that on the whole, they seem relatively bare of the necessary quantities of organic debris.

Much of the Tertiary flora is spatially associated with water, especially streams, lakes, and marshes. If fossil material from such environments was present in the basal ash, and if it could be assumed that it was not transported for any great distance (as the Delongchamps Prospect), it would be advantageous to trace the stream or lake boundary laterally in an attempt to delineate other zones of carbonaceous debris. In certain ash-flows this may be possible because some of the organic material, leaves particularly, cannot withstand long transportation, and are probably deposited close to their source area.

WELDING

The welding that may occur in ash-flows has a profound influence on the location, thickness, and porosity of the nonwelded basal layer. Whether any given ash-flow will weld depends; according to Smith (1960a, p. 823) on many variables; the important ones being (1) temperature, (2) amount and composition of the volatiles, (3) composition of the ash, (4) lithostatic load, (5) rate of cooling, and (6) rate of crystallization. Smith goes on to say that the two most important controls are probably emplacement temperature and the thickness of the flow or cooling unit (Smith, 1969, p. 823). The number of variables results in an infinite
number of welding zone geometries.

Ash-flow tuffs vary from completely nonwelded units to totally welded units. The former are common but the latter are rare. Tuffs that are densely welded from top to bottom are a special case. Smith (1960b, p. 153) has divided welded ash-flow tuffs into three zones: the zone of no welding, the zone of partial welding, and the zone of dense welding.

The zone of no welding is taken as that part of an ash-flow in which no welding has taken place, and may comprise the entire unit or only a small part. Most single ash-flow cooling units have a nonwelded top and bottom, although in some of the very hot flows the nonwelded bottom may not be present under the entire sheet. In these very hot ash-flows, densely or partly welded tuff may extend to the base of the unit.

The zone of partial welding includes all material ranging from that which shows incipient welding to that which has lost virtually all its pore space. This zone shows a wide range in textures because of the differences in porosity and degree of deformation of its glassy parts.

The zone of dense welding is marked by complete coalescence of the glassy fragments with elimination of all pore space. The resulting rock is dense black glass or vitrophyre; this zone is sometimes referred to as the vitrophyre zone. Such a zone is present at the Spanish Springs Valley Prospect.

As far as infiltration uranium deposits are concerned,
the nonwelded, ashy zones are most important. The first zone of no welding is at the top of the ash-flows where lithostatic load is at a minimum, and heat loss is at a maximum because of contact with the atmosphere. The nonwelded top is seldom found because it is soft, porous, and exceedingly vulnerable to erosion. In most places it has been eroded off or swept into the succeeding ash-flow (Cook, 1965, p. 35). The other location for an ashy layer is at the base of the ash-flow, below a zone of either partial or dense welding. The lack of welding in this zone is ascribed to rapid cooling of the ash because of ground contact. Martin (1957, p. 67) studied a group of ash-flow tuffs (both welded and nonwelded) and concluded that the nonwelded zone may be absent or it may be more than 50 feet thick, or more, from 4 to 15 feet in thickness.

This porous basal ash is overlain by a zone of partial or dense welding in which porosity and permeability are lower. Since the upper ash zone is usually removed from the preceding ash-flow, many ash-flow tuffs rest on a surface of slight to moderate welding. The degree to which the upper surface of the lower ash-flow is welded depends on how much erosion has taken place between deposition of the two ash-flows. The end result, however, is a porous, permeable ashy zone which is bounded above and below by a welded zone. This porous zone provides a natural channel way for the movement of groundwater solutions.

Another favorable location for infiltration deposits
is in unwelded tuffs. These ash-flow tuffs are either completely nonwelded or contain a zone of only weak welding. In any case, they are units which are porous and relatively permeable throughout. It is in this type of unit that at least two (Independence and Delongchamps) uranium prospects occur. Relatively thin sillars of 100 to 150 feet thick are probably much more common in piles of welded tuff than previously suspected.

CRYSTALLIZATION OF THE GLASS

Uranium makes up about 1 to 2 ppm of the earth's crust. It is an even less common constituent of basic igneous rocks, averaging less than 1 ppm (Holland and Kulp, 1954, p. 203). In high silica igneous rocks, the concentration of uranium is greater; Rosholt et al. (1971, p. 1864) gives an average of ten samples from three ash-flow tuffs and four rhyolitic lava flows as about 6 ppm. The relatively large size of the uranium atom (0.97 Å) and high charge usually precludes all but very limited substitution in common rock-forming minerals during magmatic processes. Uranium tends to be partitioned into late-stage, and volatile-rich phases. As a result, a differentiating magma would yield a uranium-enriched high silica magma which, if cooled under volcanic conditions, would produce a rock of a rhyolitic to quartz latitic composition. The inability of uranium to be concentrated in phenocrysts means that in ash-flow tuffs, virtually all the uranium is located in the
glassy matrix. The question of postdepositional mobility of uranium in volcanic glass is therefore very important.

Following deposition, volcanic glass, whether in ash-flow tuffs, ash-fall tuffs, or rhyolitic lava flows, tends to undergo two types of chemical changes. Pyroclastic deposits are readily altered because of their high porosity, the large size of their particles, and the inherently unstable character of their glassy fragments.

The first important chemical change that may occur in natural glasses is hydration, the addition of water to volcanic glass during cooling. Most Tertiary volcanic glasses contain a few tenths of a percent magmatic water initially; the remainder of the water (up to about 10 percent) is absorbed during cooling. The amount of hydration is a function of time and the surface area of the glass particles.

The second alteration that affects natural glasses is devitrification or crystallization. Nearly all glass is metastable and tends to devitrify with time. A large proportion of ash-flow tuffs have undergone devitrification, and invariably the products are extremely fine-grained cristobalite and feldspar (Ross and Smith, 1961, p. 36). Devitrification is generally more prevalent in ash-flows which have undergone compaction and welding. Crystallization varies from selective, devitrification of pumice fragments but not shards (or visa versa), to complete destruction of tuff structures.
As some ash-flow tuffs devitrify, the development of vapor-phase crystallization indurates the tuff without the intervention of welding. Vapor-phase crystallization involves the growth of alkali feldspar, tridymite, fayalite, and cristobalite in the pore spaces. The products are generally coarser grained than those of devitrification, and generally develop in the porous upper portions of ash-flows. Vapor-phase crystallization is related to the release of volatiles during crystallization of shards and pumice fragments lower in the ash-flow.

In summary, ash-flow tuffs are subject to hydration and/or devitrification following deposition. The uranium that is present is located in the glass and not in the phenocrysts. The question arises as to which process, devitrification or hydration, is responsible for the release of uranium from volcanic glasses. The studies of infiltration uranium deposits in the intermountain basins in Wyoming suggest that the source of the uranium is in stratigraphically higher hydrated volcanic ash beds.

Resholt et al. (1971) compared analyses of hydrated and non-hydrated glass pairs from Tertiary silicic volcanic rocks of the western United States. They found that the uranium content of the hydrated glass, when corrected for water hydration, is nearly identical with that of the parent non-hydrated glass. They concluded that no measurable quantities of uranium were removed or added to the glass during or after hydration. The uranium content of non-crystallized
specimens, however, is only 20 to 70 percent of that in the undevitrified glass from the same unit. In other words, the crystallized specimens had lost from 30 to 80 percent of the uranium originally present in the rock.

During and after hydration, the behavior of alkalies and certain other elements must be contrasted with uranium, because during hydration the former are subject to leaching and/or ion exchange (Lipman, 1965; Noble, 1967; Lipman et al.; 1969). Thus Rosholt et al. (1971, p. 1065) concluded that, even during weathering processes, uranium is not mobile in glassy phases of rocks, probably because of a uniform distribution of uranium in a non-crystalline matrix.

In Rosholt's study, the loss of uranium was attributed to groundwater leaching which was facilitated by oxidation of part or all of the uranium during crystallization. Similar results have been reported by Shatkov et al. (1971) and Welke et al. (1969). Recent work has shown that halogens are released and lost during primary crystallization of groundmass material in silicic volcanic rocks, and a part of the halogen loss has been attributed to the escape of volatile metal halides (Naboko, 1959; Smith, 1960a; White and Waring, 1963; Noble et al., 1967). Rosholt et al. (1971, p. 1066) suggest that the correlation between fluorine and uranium losses may be due, in part, to the fact that one of the volatile metal halides may be UF₆. It must be said that only part of the uranium is released with the volatiles because of the susceptibility of oxidized uranium to leaching.
by groundwater.

Regardless of how the uranium is subsequently transported, the fact remains that it is necessary to crystallize the glass in silicic volcanic rocks to release substantial amounts of the enclosed uranium. With regard to the Hartford Hill Rhyolite, Bonham (1963, p. 25) observed that the ash-flow tuffs are almost completely devitrified because of near pervasive hydrothermal solutions. Such thoroughly crystallized ash-flows are necessary for the formation of uranium deposits in the carbonaceous zone of ash-flow tuffs. Nondevitrified ash-flows, no matter how favorable other factors might be, are not likely to be the source of the uranium for such a deposit because the uranium is not released, even during weathering.

MIGRATION AND CONCENTRATION OF URANIUM

The Independence, Divide, and Spanish Springs Valley prospects are altogether lacking in hydrothermal features. Veining, crosscutting relationships, structural control, evidence of sulfides, or hydrothermal alteration are lacking, suggesting that the formation of the deposits was essentially an internal process, with the leaching, transportation, and deposition of the uranium occurring within the ash-flow itself.

Uranium has many valence states (+2, +3, +4, +5, and +6), but only +4 and +6 states are of geologic interest. The uranium ion, $U^{4+}$, is the most abundant species in nature,
and is stable under reducing conditions; in magmas, or in
sedimentary environments in which organic debris is pre-
served. The U\(^{4+}\) oxide (UO\(_2\)) is only very slightly soluble
in water. The dissociation constant for the reaction:
\[
\text{UO}_2 + 2H_2O \rightarrow U^{4+} + 4OH^- 
\]
is but 10\(^{-52}\) at 25°C and 1 atmosphere pressure (Garrels,
1954, p. 12). The great stability of UO\(_2\) under reducing
conditions probably accounts for the preponderance of
uraninite as the primary uranium ore mineral in other infil-
tration deposits. The U\(^{4+}\) ion in aqueous solution can be
oxidized easily at a finite rate to the uranyl ion (U\(^{6+}\)O\(_2^{2+}\))
rather than to the U\(^{6+}\) ion.

The transition from +4 to +6 has a redox potential
within the normal range of geologic environments:
\[
U^{4+} + 2H_2O \rightarrow \text{UO}_2^{2+} + 4H^+ + 2e^- \quad E = +0.33 \text{ volt}
\]
and there are a variety of oxidizing agents in many natural
systems which are sufficient for the task. The UO\(_2^{2+}\) ion
is so stable that it maintains its identity through various
chemical transformations from solid to solution and vice
versa (McKelvey et al., 1955, p. 10). the (UO\(_2^{2+}\)) ion does
not react strongly with most anions and hence forms few
insoluble compounds. It forms insoluble solids with As,
V, and P, but these are not major rock-forming elements and
are not abundant in natural waters. The (UO\(_2^{2+}\)) ion forms
soluble complexes with carbonate and sulfate, both of which
are plentiful in natural waters. The ease with which U\(^{4+}\)
is oxidized in normal geologic situations and the high solu-
bility of uranium sulfate and carbonate complexes in groundwater accounts for the mobility of secondary uranium in the near-surface environment at relatively low temperatures and pressures.

The leaching of uranium from ash-flow tuffs is accelerated by oxidation of part or all of the uranium during crystallization (Rosholt et al., 1971, p. 1061). After complexing with common groundwater constituents, the uranium-bearing solutions migrate through permeable portions of the ash-flow tuffs. Since porosity is related to the degree of welding, the areas of maximum groundwater flow would be in the nonwelded, ash; sections; in welded zones, flow would be at a minimum because of loss of pore space. Fractures and cooling joints are common in rigid welded zones. These probably allow the percolation of groundwaters downward through the impermeable welded portion to the porous basal ash.

In ash-flow tuffs, uranium may be "fixed" in three states: (1) in a reduced state as uraninite, an oxide, or coffinite, a hydroxy-silicate, or (2) as a $\text{UO}_2^{++}$ compound with either As, V, or P, or (3) adsorbed on clays and colloids. Adsorption on clay minerals probably accounts for only a minor amount of the uranium. To determine whether the uranium is stabilized in the oxidized or reduced state requires the identification of uraninite/coffinite or the hydrated secondary minerals. The $\text{U}^{++}$ minerals are exceedingly difficult to identify because they are black.
powdery, usually very fine-grained, and intimately intergrown with the carbonized wood that they replace. The colorful hydrated uranium minerals were only rarely present at the prospects, and none in large enough quantity for identification.

Carbonaceous trash, or organic debris, is considered the classic ore precipitant in secondary uranium deposits, especially in the very important deposits on the Colorado Plateau and the Tertiary Basins of Wyoming. The carbonaceous material in ash-flow tuffs also provides a mechanism for concentrating uranium from relatively dilute groundwater solutions.

The basic chemistry probably involves oxidation and reduction. The carbon in the organic debris acts as a reducing agent which causes the uranium to go from a soluble $\text{UC}_2^{++}$ complex to an insoluble, stable $\text{UO}_2$ compound. The organic material is oxidized and the uranium is reduced as the uranium minerals replace carbonized wood fragments. This reaction, which has been demonstrated in both natural and laboratory systems, accounts for the very close spatial relationship between uranium and organic debris.

The organic carbon is probably involved in more than one oxidation-reduction couple. Carbon may also be involved in an oxidation-reduction couple with the iron to precipitate the iron oxides associated with the carbonaceous zones. There may be other couples operating at the same time, so that even though the basic chemistry is simple, the
The general lack of visible uranium minerals may be due to the fact that some of the uranium is present in metallo-organic compounds. Metal ions are fixed in complicated, three-dimensional ring complexes or organic compounds. The exact nature of such compounds is poorly understood and the distribution of the uranium ions in the intricate organic structures is difficult to determine. Uranium in organic complexes is normally thought of in connection with petrolierous or thuctlicite uranium ores, but in organic debris which has not been highly carbonized, a part of the uranium may be in the form of metal chelates or as coordination compounds. Upon oxidation, the organic framework is destroyed and the uranium may be released to form hydrated, colored, secondary minerals.

As previously noted, the alteration products are rather simple and, in general, poorly developed. If the uranium-bearing solutions were highly acidic or strongly basic, they would have had a very pronounced effect on the ash-flows. Natural glass is inherently unstable and in the presence of reactive solutions it would be converted to clay minerals. In all of the ash-flow tuffs, the products of the glassy portions were cristobalite, tridymite, and feldspar rather than clay minerals. The universal lack of alteration products supports the conclusion that mineralization was at very low temperatures, pressures, and concentrations.
THE CONCEPTUAL MODEL

There are many kinds of conceptual models. Some are essentially genetic, built around the node or origin of a particular kind of deposit. Others provide a framework for describing a deposit in terms of associated lithology, alteration, mineralogy, structure, etc.; a descriptive conceptual model. The writer will now undertake development of such a model for infiltration uranium deposit in an ash-flow tuff.

The basal nonwelded ashy zones of ash-flow tuffs do not crop out well, and their discovery might be dependent upon finding carbonaceous float material or delineating zones of anomalous radioactivity.

Infiltration deposits in ash-flows should not be confused with structurally controlled deposits in the same rock type. Structurally controlled deposits are spatially related to faults and fractures, may exhibit veining or crosscutting, and are surrounded by halos of hydrothermal, usually propylitic, alteration. Secondary infiltrational uranium may also concentrate in shear zones in ash-flow tuffs, but as with vein deposits, they tend to be oriented at a high angle to bedding in contrast to deposits in carbonaceous zones which are strata conformable.

The carbonaceous zone always overlies in unconformity. The unconformities may be relatively indistinct, spanning the time between ash-flow eruptions; while other represent much longer periods of time. The latter are probably
regional in extent, but the former may be relatively local.

Carbonaceous zones may be of different shapes and sizes. They may consist of discontinuous lenses of organic debris of limited aerial extent, or a uniform zone which can be traced laterally for a few thousand feet. The vertical dimension is also variable; it may be a few inches thick or a zone up to 20 feet thick. The carbonaceous zone may be very uniform in the vertical dimension over many hundreds of feet; more often it is highly erratic. The carbonaceous zone is made up of carbonized wood material which ranges in size from microscopic fragments up to individual logs. Rarely, leaves, leaf stems, and pine needles are present. Most of the debris is of limb size material which has been compressed in the vertical dimension by compaction. The carbonaceous zone consists of both carbonized and noncarbonized material, often intimately intermixed. All gradations from complete carbonization of organic material to a complete lack of any such effects may be present in the same deposit. The woody material may be thoroughly mixed with ash from the ash-flow, or form discrete lenses of pure organic debris.

The uranium mineralization is always associated with the carbonaceous zone which is always located at the very base of the ash-flow. Whether in a sillar or a welded ash-flow tuff, the carbonaceous zone lies above the unconformity as part of the basal ash. Almost always, the basal ash is nonwelded or only slightly welded. Occasionally the organic
zone may be located below a basal vitrophyre, but this is not typical. In other words, the carbonaceous zone tends to be located in the porous, permeable, basal ash.

The release of uranium from the glassy phases of ash-flow tuffs is due to devitrification of the glass. Infiltration deposits are located in ash-flows which have undergone relatively complete crystallization. Devitrification is usually concentrated in the upper portions of ash-flows, but in ash-flows with uranium mineralization, devitrification has affected even the lowest portions. The sequence of devitrification seems to be pumice fragments, groundmass material, and then shards; the extent of crystallization can usually be seen in hand specimen.

Because the mineralizing solution consisted of uranium-bearing groundwater, alteration is very weakly developed. Iron oxides are the only ubiquitous alteration products. They occur as either a halo around the carbonaceous zone or as a stain in and around the carbonaceous zone and are very localized. It is not a type of alteration that forms large, broad, readily visible zones of discoloration.

In general, visible uranium minerals are rare. Some hydrated, secondary minerals can be identified, but primary oxides or silicates are exceedingly difficult to identify. Uranium minerals related to infiltration mineralization may be quickly leached and removed from the carbonaceous zone in response to weathering and erosion of the deposit.

Ash-flow tuffs in Nevada were deposited primarily in
the last half of the Tertiary. Because the amount of available vegetation has decreased since the Middle Tertiary, the oldest ash-flows are the best sites for large carbonaceous zones. Also, the moist, humid climate provided for thorough leaching and weathering of devitrified ash-flows.

All of the ash-flow sheets have been affected by Basin and Range faulting. Older ash-flows are probably distributed evenly between the basins and the ranges, but very young ash-flow tuffs may be primarily restricted to the basins. Uranium may be leached from ash-flows on the up-thrown block and concentrated in carbonaceous zones located in the basins.

VARIATIONS IN THE BASIC CONCEPTUAL MODEL

The basic model, infiltrational uranium being concentrated in the carbonaceous zones at the base of the ash-flow tuffs, may be extended into other geologic settings. Ash-flow tuffs are frequently interbedded with other volcanic rocks, tuffaceous sediments, and other clastic sediments. They may be faulted into contact with intrusive rocks, marine sediments, and metamorphic rocks. In many of these geologic situations, infiltration uranium may be released from other rock types, transported, and then concentrated in zones of organic debris in ash-flows.

Many thick piles of ash-flow tuffs can be traced laterally into clastic wedges of tuffaceous sediments.
derived from the weathering of the ash-flows. In some cases, this is in response to the uplift of pyroclastic terrain along Basin and Range faults as the sediments are deposited in basins adjacent to the uplift. These tuffaceous sediments often contain organic debris, which may be derived from carbonaceous zones at the base of the ash-flows. During weathering, uranium leached from the crystallized zones of the ash-flow tuffs may be transported and concentrated in carbonaceous tuffaceous sediments. If the ash-flow field was the site of uranium deposits of the type discussed in this paper, then weathering and oxidation of these deposits would yield large quantities of the uranyl ion which might be concentrated in the tuffaceous sediments. The mobility of uranium allows it to move from one host to another with ease, and the concentration of economic quantities need not be confined to a single geologic environment.

In many places in northwestern Nevada, ash-flow tuffs and pre-Tertiary granitic rocks have been juxtaposed along normal faults. This introduces a second major source of uranium by weathering and leaching the granitic rocks and associated pegmatites. Plutonic rocks of the granite family are often rich in uranium, normally containing about as much as rhyolitic rocks. Most of the uranium is easily leachable during weathering, and could be concentrated in ash-flow tuffs if the uranium-bearing groundwaters were to move along permeable zones in the pyroclastic rocks after leaving the
granitic terrain. After percolating through the weathered granitic rocks, solutions might move along faults and shear zones until reaching the relatively permeable ashy zones of ash-flows. Introduced uranium would be added to that associated with leaching of the devitrified glass of the ash-flow, to be concentrated in the basal carbonaceous zone.

Many metalliferous deposits contain uranium in significant, but uneconomic quantities. Where ash-flow tuffs cover the flanks of the ranges which contain these deposits, they should be considered as particularly favorable host rocks for uranium derived from the weathering of the base-metal deposits.

Because the carbonaceous zones is a powerful concentrating environment for groundwater transported uranium, the relationship of this zone to potential sources of uranium should be considered. In some cases, the uranium will be derived primarily from the crystallization of the natural glass in the ash-flows themselves. In other cases, however, uranium may be derived from other sources, and transported to the site of concentration by groundwater.

ORE DEPOSIT POTENTIAL

The question remains as to whether or not infiltration uranium deposits in ash-flow tuffs are, or will be, economically attractive. Present day weathering and leaching of the exposed carbonaceous zones affects the chemical analysis, and hence conclusions concerning the distribution and intensity of uranium mineralization. Because of the
nobody of the uranium, truly representative samples were probably not obtained, nevertheless, certain generalizations about the possible size and grade of infiltration uranium deposits can be made. What constitutes "ore" depends on many factors other than tonnage and grade, but these two are the primary considerations. Based on the grade used in the 1950's, where 0.20% U₃O₈ was the economic cut-off, the 2500 and 2600 ppm values are "ore grade" material. The values for most of the channel samples, however, are certainly below what would be considered a minimum grade. Even from the limited number of samples it seems reasonable to conclude that mineralization of ore grade (.25 and .36% U) may be obtained by the model presented. Whether such mineralization is present in quantities to warrant development is more difficult to determine.

A six foot thick carbonaceous zone is present at the Delongchamps Prospect for over an area of at least 2000 x 500 feet. Assuming that this volume of rock was mineralized to an economic grade (0.20% U₃O₈), the resulting deposit would probably be considered a medium grade, medium size deposit.

Uniform, widespread carbonaceous zones could be sites for large relatively low-grade uranium deposits, that sufficient uranyl ion could be introduced into the sequence. If less uranyl ion is introduced into the system, a large carbonaceous zone would probably yield mineralization which is too low-grade to be economic. In this case, an irregular
discontinuous carbonaceous zone might be preferable over a large uniform zone because it would yield smaller deposits of economic grade.

High grade uranium mineralization may be developed in an environment where there is some variation in the basic model. Where associated with granitic rocks, or weathered uranium-bearing metalliferous deposits, additional amounts of uranyl ion may be introduced into the system. In these situations, relatively high-grade deposits might result.

Ash-flow tuffs are originally laid down horizontally, an orientation favorable for development by open-pit methods. Mineralized ash-flows are often covered up by a few hundred to a few thousand feet of younger ash-flows, which means that they could not be developed by open-pit techniques. When mineralized ash-flow tuffs occur as easily accessible erosional remnants, the size of the remaining ash-flow and carbonaceous zone is correspondingly small.
ACKNOWLEDGMENTS

Gratitude for assistance in many aspects of this study is due Dr. Anthony L. Payne, who introduced the general problem of infiltration uranium deposits in the Basin and Range Province, and whose guidance and help is acknowledged.

Appreciation is extended to Larry Garzide of the Nevada Bureau of Mines for the generous use of unpublished data concerning uranium occurrences in Nevada. Thanks is also given to Edward Post of Skyline Labs, Inc., of Denver, Colorado, for special handling of the uranium analysis. J. Gibbons, D. Kappes, and W. Kemp offered many helpful suggestions, and Dr. James Firby of the University of Nevada kindly identified the leaf fossils and provided information concerning the distribution of Tertiary flora.
**APPENDIX I \ TERMINOLOGY**

**Ash-flow** - A turbulent mixture of gas and pyroclastic materials of high temperature, ejected explosively from a crater or fissure, that travels swiftly down the slopes of a volcano or along the ground surface. The solid material in an ash flow, although unsorted, is dominantly of particles of ash size (less than 4 mm in diameter) but generally contains different amounts of lapilli and blocks. The flowage principle is used in industry for the transportation of solids suspended in a gas, and is known as fluidization. Reynolds (1951, p. 580) has applied the concept to the dispersal of ash-flow materials (Ross and Smith, 1961, p. 3).

**Ash-flow tuff** - The consolidated deposits of volcanic ash resulting from an ash-flow are called ash-flow tuff. Ash-flow is here used as an adjective to indicate the mechanism of dispersal, and tuff indicates the state and size of the material. Ash-flow tuff is an inclusive, general term for consolidated ash-flow beds that may or may not be either completely or partly welded. (Ross and Smith, 1961, p. 3).

So defined ash-flow tuff is a rock unit term, freed from welding, size-range, and composition restrictions.

**Nonwelded tuff** - The term "nonwelded tuff" will be applied to those ash-flows or parts of ash-flows that have
not become welded. The mode of deposition and consequent cooling of ash-fall materials precludes welding, in contrast to ash-flow materials which may or may not become welded. Thus there should be no confusion, and it seems unnecessary to use the term "unwelded ash-flow" materials each time they are mentioned. That is, "nonwelded tuffs" are always to be understood as the corollary of welded tuffs (Ross and Smith, 1961, p. 5).

Welding - Welding is briefly defined as that process which promotes the union or cohesion of glassy fragments. The degree of welding may range from incipient stages marked by the sticking together or cohesion of glassy fragments at their points of contact within the softening range to complete welding marked by the cohesion of the surfaces of glassy fragments accompanied by their deformation and the elimination of pore space, and perhaps ultimate homogenization of the glass (Smith, 1960, p. 15).

Welded tuff - Tuffs in which the individual fragments remained plastic enough to become partly or wholly welded. Welded tuff is self explanatory and should be considered a rock unit term, not a rock type term with composition connotations.
<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Description and Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>PJH-316</td>
<td>Channel sample of carbonaceous zone (72 inches) at west end of Independence Prospect. Zone contains about 30% organic debris (by volume) in a green iron-stained ash-flow tuff.</td>
</tr>
<tr>
<td>PJH-317</td>
<td>Channel sample of carbonaceous zone (8 inches) 500 feet along strike of the ash-flow from sample no. 316. Zone is nearly pure (90%) carbonized organic material. Independence Prospect.</td>
</tr>
<tr>
<td>PJH-318</td>
<td>Channel sample across thick, carbonized log (10 inches) approximately 300 feet along strike from sample no. 316. Independence Prospect.</td>
</tr>
<tr>
<td>PJH-320</td>
<td>Sample from west end of Independence Prospect, same location as no. 316. Select sampling of carbonaceous debris without tuff matrix.</td>
</tr>
<tr>
<td>PJH-323</td>
<td>Hand sample of tuff from carbonaceous zone. Contains 1-2% carbonized organic debris. From below no. 318. Independence Prospect.</td>
</tr>
<tr>
<td>PJH-406</td>
<td>Channel sample from below weathered granodiorite boulder in the carbonaceous zone (5 feet) at the Divide Prospect.</td>
</tr>
<tr>
<td>PJH-409</td>
<td>Sample of carbonized organic material only - no ash-flow tuff included. From center of the carbonaceous zone at the Divide Prospect.</td>
</tr>
<tr>
<td>PJH-507</td>
<td>Channel sample across the carbonaceous zone (36 inches) at the Spanish Springs Valley Prospect.</td>
</tr>
<tr>
<td>PJH-508</td>
<td>Select sample of dark, carbonized wood from the carbonaceous zone at the Spanish Springs Valley Prospect.</td>
</tr>
<tr>
<td>PJH-509</td>
<td>Select sample of tan, silicified wood from the carbonaceous zone at the Spanish Springs Valley Prospect.</td>
</tr>
</tbody>
</table>
REFERENCES CITED


McKelvey, V. E., Everhardt D. L., and Garrels, R. M., 1955,


