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Solution-collapse breccia pipes of Spanish Valley, southeastern Utah

By

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Abstract

More than 70 breccia pipes lie along northwesterly trends near Spanish Valley in Grand and San Juan Counties, a few kilometers southeast of Moab, Utah. The structures generally are roughly oval in plan and only several tens of meters in diameter, but are inferred to extend downward about 1,000 m. The pipes contain a breccia that has been dropped as much as several hundreds of meters by solution collapse. Much sandstone in the breccia has been decemented and in places has flowed, as shown by foliation and sandstone dikes. Contacts of the breccia and country rock are sharp. The country rock is unaltered.

The structures apparently formed in the Tertiary and may be contemporary with igneous intrusions of the nearby La Sal Mountains. The breccia pipes probably result from solution of deeply buried salts and carbonate rocks by migrating waters heated by the igneous intrusions, followed by upward stoping of younger strata.

The breccia pipes of Spanish Valley and environs are not known to be mineralized, but they resemble uranium- and copper-bearing breccia pipes elsewhere on the Colorado Plateau.

Introduction

Along the northeast side of Spanish Valley and along Pack Creek Canyon, a few kilometers southeast of Moab, Utah, are more than 70 breccia pipes (figs. 1 and 2). They are roughly oval in plan, commonly a few tens of meters in diameter, and contain a broken mass of rock that has been dropped a few tens to hundreds of meters (table 1). The vertical exposure of any of these structures is less than 60 m, but the breccia columns probably extend downward about 1,000 m.

The breccia pipes of Spanish Valley and environs were recognized during the geologic mapping of the Mount Peale 2NW and 2NE 7.5-minute quadrangles, San Juan County, Utah (Weir and Puffett, 1960a; Weir and others, 1961). The northeast flank of Spanish Valley in Grand County, as far north as Mill Creek Canyon, was searched for outcrops of pipe breccia in the area mapped by Baker (1933). The Spanish Valley structures were re-studied by the senior author in 1994. Several notes on the collapse-formed structures have been published (Weir and others, 1956; Puffett and others, 1957; Weir, Puffett and Dodson, 1961).

Geology of Spanish Valley and Environs

Stratigraphy

Jurassic and Cretaceous rocks make up most of the outcrops around Spanish Valley (fig. 2). Near Moab, Triassic and Upper Paleozoic rocks also crop out (Baker, 1933; Doelling, 1985). Quaternary alluvial deposits cover the valley floor and tops of mesas.

Table 2 presents a generalized section of the sedimentary rocks exposed in and near the area. The wide range of thicknesses given for some units is based on the concept of the structure of the area shown in the cross sections (fig. 3).

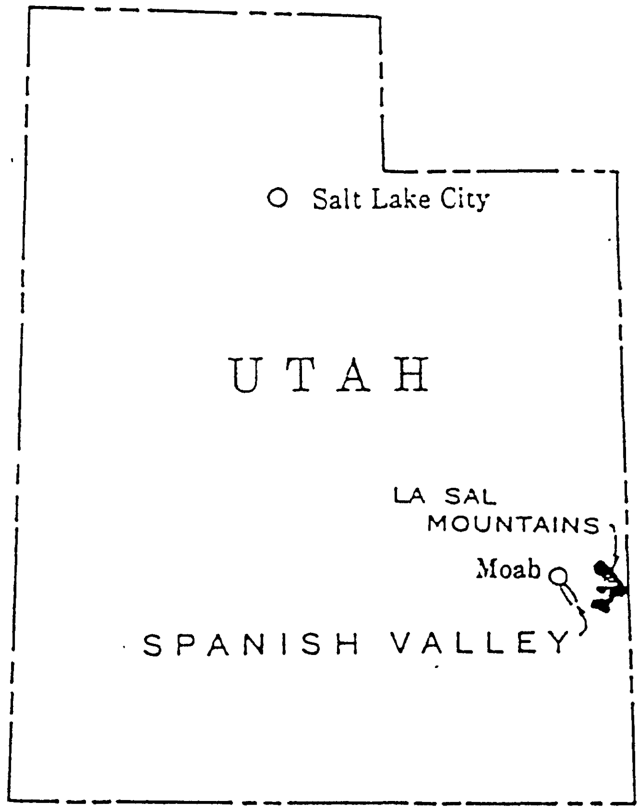
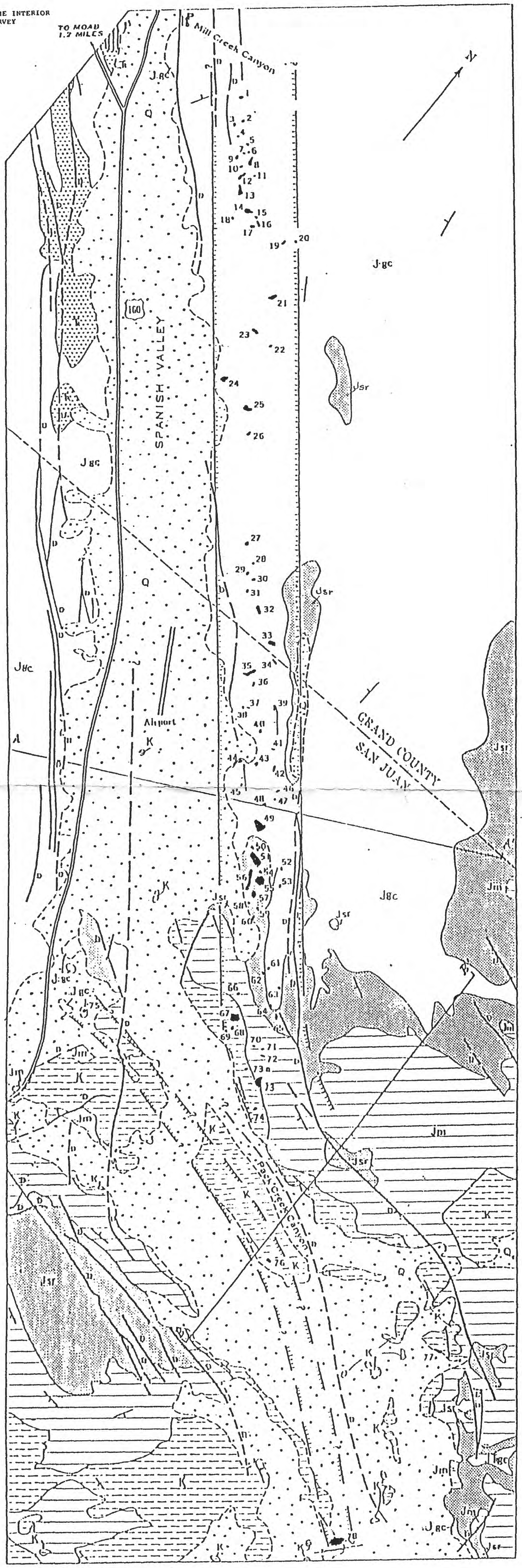


FIGURE 1.--Location of Spanish Valley and La Sal Mountains, southeastern Utah.



EXPLANATION.

Q — Quaternary deposits

K — Cretaceous formations

Jm — Morrison Formation (*Jurassic*)

Jsr — San Rafael Group (*Jurassic*)

J gc — Glen Canyon Group (*Jurassic*)

ħ — Chinle and Moenkopi Formations (*Triassic*)

P — Hermosa Formation (*Pennsylvanian*)

Strike and direction of dip of beds

High-angle fault
Dashed where inferred or concealed. D, *downthrown side*

Breccia Pipe with reference number
(See table 1)

Belt of breccia pipes

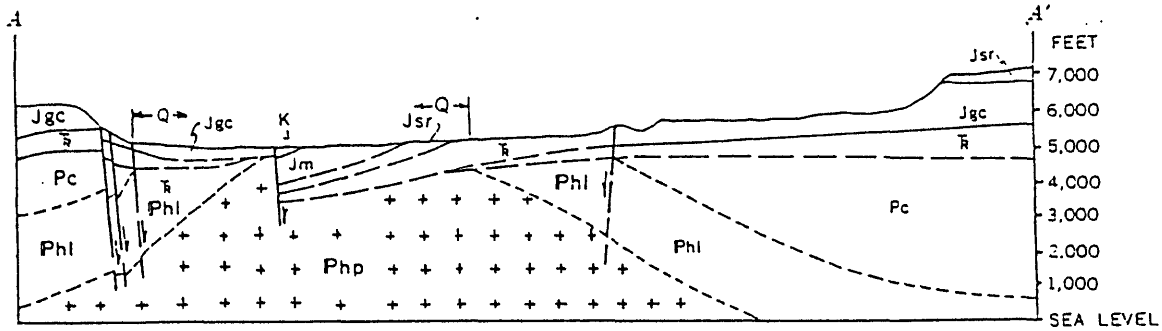
A — A'
Location of sections
(See figure 3)

THIS REPORT IS PRELIMINARY AND HAS NOT BEEN REVIEWED FOR CONFORMITY WITH U.S. GEOLOGICAL SURVEY STANDARDS OR WITH THE NORTH AMERICAN STRATIGRAPHIC CODE.

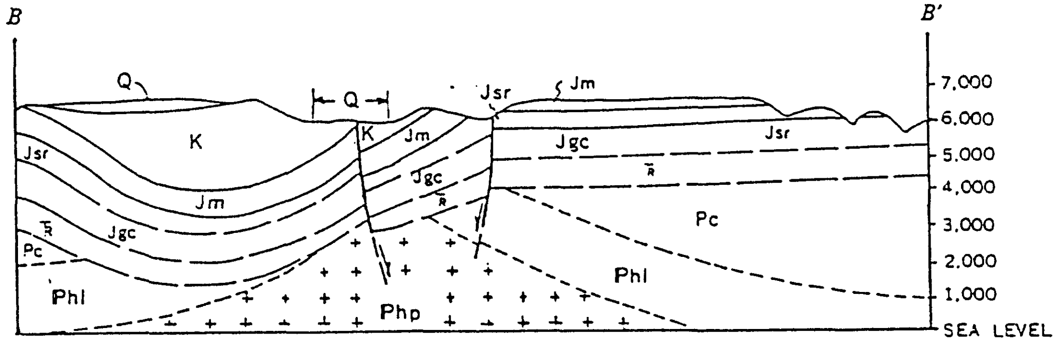
Geology of Spanish Valley in Grand County after Baker, 1933; San Juan County by Weir, Puffett, and Dodson, 1956–59

0 — 1 — 2 MILES
0 — 1 — 2 — 3 KILOMETERS

FIGURE 2.--Simplified geologic map of Spanish Valley and environs, Grand and San Juan Counties, Utah.



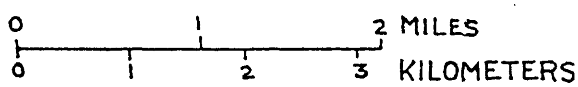
A. SPANISH VALLEY



B. PACK CREEK CANYON

EXPLANATION

Q = Quaternary deposits
K = Cretaceous formations
Jm = Morrison Formation
Jsr = San Rafael Group
Jgc = Glen Canyon Group
Tr = Chinle and Moenkopi Formations
Pc = Cutler Formation
Phu = Hermosa Formation, upper member
Php = Hermosa Formation, Paradox Member



Scale

FIGURE 3.--Cross sections: A. Spanish Valley
B. Pack Creek Canyon.

Table 1. -- Solution-collapse breccia pipes of Spanish Valley and environs, Grand and San Juan Counties, Utah. (Locations shown on figure 1.)

Number	Host Rock 1/	Youngest Breccia	Displacement 2/ (Meters)
1-5	Jn	Jms	210
6	Jn	Jeu	80
7-17	Jn	Jms	210
18	Jn	Jmt	145
19	Jn	Kbc	410
20	Jn	Jeu	80
21	Jn	Jms	210
22	Jn	Jed	10
23	Jn	Kbc	410
24-25	Jn	Jms	210
26	Jn	Jmt	145
27	Jn	Jmb	330
28	Jn	Kbc	410
29	Jn	Kd	440
30	Jn	Jms	210
31	Jn	Jed	10
32	Jn	Kbc	410
33	Jn	Kd	440
34	Jn	Jeu	80
35	Jn	Jmt	145
36	Jn	Jeu	80
37-38	Jn	Kbc	410
39	Jn	Jms	210
40	Jn	Kbc	410
41	Jn	Jms	210
42-45	Jn	Kbc	410
46	Jn	Jms	210
47	Jn	Kd	440
48	Jn	Jms	210
49	Jn	Kbc	410
50	Jeu	Kd?	440?
51	Jeu	Kbc	330
52	Jn	Jmb	330
53	Jn	Jmt	145
54	Jeu	Jms	130
55-57	Jeu	Kbc	330
58	Jeu	Jeu	30
59-60	Jeu	Kbc	330
61	Jn	Jmb	330
62	Jeu	Jmb	250
63	Jn	Jms	210
64	Jed	Jms	200
65	Jeu	Kbc	330
66	Jmb	Km	200?
67-69	Kbc	Km	100?

Number	Host	Youngest Breccia	Displacement
70	Jmb	Km	200?
71	Jms	Km	400?
72	Jms,Jmb	Km	400?
73	Jmb,Kbc	Km	400?
74	Kbc	Km	100?
75	Jn	Jms	210
76	Kms	Km	50?
77 3/	Jmb?	Km?	200?
78	Kms	Km	10?

1/ Abbreviations of stratigraphic units:

Kms -- Sandstone member, Mancos Shale
Km -- Mancos Shale
Kd -- Dakota Sandstone
Kbc -- Burro Canyon Formation
Jmb -- Brushy Basin Member, Morrison Formation
Jms -- Salt Wash Member, Morrison Formation
Jmt -- Tidwell Member, Morrison Formation
Jeu -- Upper part (Moab and Slick Rock Members), Entrada Sandstone
Jed -- Dewey Bridge Member, Entrada Sandstone
Jn -- Navajo Sandstone

2/ Estmated displacements of breccias based on stratigraphic thicknesses in nearby areas. Because thick units lack internal marker beds the true displacement of breccias older than the Mancos Shale may differ from the estimate by several tens of meters. Because the Mancos Shale is exceptionally thick, displacements of Mancos breccia are conjectural.

3/ Doubtful collapse, poorly exposed. May be closely spaced fault slices.

Structure

Spanish Valley overlies the central part of the south half of the Moab anticline. A ridge of thickened salt of Pennsylvanian age, the Paradox Member of the Hermosa Formation, underlies the northwest-trending valley and forms the core of the anticline. At the south end of Spanish Valley the buried ridge of salt bends easterly and underlies Pack Creek Canyon (Case and others, 1963, p. 108).

The exposed geologic structures of Spanish Valley and Pack Creek Canyon do not generally conform to the inferred buried structure, although trends of major elements are about the same. The major surface structural feature of Spanish Valley is a broad, faulted northwest-trending, asymmetric syncline; the subsurface feature is a northwest-trending asymmetric anticline (fig. 3 A). Many northwest-trending joints and minor high-angle faults cut exposed rocks on the flanks of the syncline. Similar fractures probably cut rocks in the trough of the syncline, concealed under the valley fill.

Table 2. -- Generalized section of sedimentary rock formations overlying the Pennsylvanian salt sequence in the Spanish Valley area, Utah.

SYSTEM	SERIES	UNIT	THICKNESS (Meters)	CHARACTER
Quaternary	Holocene and Pleistocene		0-30	Alluvial, eolian, and landslide deposits.
Cretaceous	Upper	Mancos Shale	750	Gray shale.
		Dakota Sandstone	15-30	Brown sandstone and black shale.
	Lower	Burro Canyon Formation	30-60	Gray sandstone and conglomerate; variegated shale.
Jurassic	Upper	Morrison Formation: Brushy Basin Mbr.	110-125	Variegated mudstone.
		Salt Wash Member	100-125	Gray to buff sandstone; variegated mudstone.
		Tidwell Member	5-10	Red silty shale and red and gray chert.
		SAN RAFAEL GP. Entrada Sandstone: Moab Tongue	25	Yellowish-gray, crossbedded sandstone.
		Slick Rock Member	85-100	Orange to buff, crossbedded sandstone.
		Dewey Bridge Member	15-20	Red silty mudstone.
		Page Sandstone	0-20	Buff crossbedded sandstone.
	Lower	GLEN CANYON GP. Navajo Sandstone	30-150	Grayish-yellow crossbedded sandstone.
		Kayenta Formation	30-65	Gray and red sandstone and siltstone.
		Wingate Sandstone	30-90	Reddish-brown, crossbedded sandstone.
Triassic	Upper	Chinle Formation	90-120	Red silty mudstone and sandstone; basal gray sandstone.
	Middle? and Lower	Moenkopi Formation	0?-90	Reddish-brown mudstone, and siltstone, and sandstone.
Permian	Lower	Cutler Formation	0?-1200	Gray and red sandstone and conglomerate.
Pennsylvanian	Upper	Hermosa Formation: Upper Member	300-750	Gray limestone and sandstone.

Folds and faults bordering Pack Creek Canyon trend more easterly than the folds and fractures of Spanish Valley. Pack Creek Canyon lies on the flank of a faulted, southeast-trending surface syncline (fig. 3 B).

The complex structure of Spanish Valley and environs is due to flowage of the salt sequence of the Paradox Member of the Hermosa Formation (Pennsylvanian). The original thickness of the Paradox Member probably was about 1,000-2,000 m, but present thickness of the distorted beds of the member in salt-cored structures may be more than 4,200 m (Cater, 1970, p. 9; Hite and Lohman, 1973, p. 15). The chief period of salt movement extended from the late Paleozic to the middle Mesozoic. The salt-cored folds were intensified by regional compression in the Tertiary. Minor flowage of the salt occurred intermittently into the Cenozoic and may be continuing locally today (Cater, 1970, p. 65; Huntoon, 1988, p. 84-85). The surface synclines and faulted rocks result chiefly from Cenozoic solution of the upper part of the roll of salt underlying the valleys and the accompanying collapse of the overlying strata.

Several kilometers east of the area shown in figure 2, the sedimentary rocks are turned up around the igneous intrusions of the La Sal Mountains. The intrusions consist of three groups of stocks and laccoliths of Tertiary age. The southern group of intrusions is elongated parallel to the syncline of Pack Creek. Many of the laccoliths spread in the salt sequence of the Hermosa Formation, though some spread in younger strata (Hunt, 1958, p. 316, 318).

Geologic setting

Most breccia pipes of Spanish Valley lie in a belt, about a kilometer wide and 16 km long, that parallels the valley (fig. 2). Pipe 75 and the somewhat doubtful pipe 77 lie outside this belt; they may lie in a southeasterly trending belt that includes pipe 76 and that roughly parallels Pack Creek Canyon (fig. 2).

The oldest formation exposed near the breccia pipes is the Navajo Sandstone of Early Jurassic age. Our knowledge of the buried pre-Navajo rocks is largely based on study of outcrops near Moab (Baker, 1933; Doelling, 1985) and studies of better exposed salt anticlines in the region (Shoemaker and others, 1958; Cater, 1970). Paleozoic units younger than the mobile salt sequence of the Paradox Member of the Hermosa Formation, especially the Cutler Formation, probably thicken greatly off the flanks of the anticline. The pre-Navajo Mesozoic formations probably thin abruptly and may pinch out on the flanks of the Moab salt anticline.

The Mesozoic section contains many unconformities that truncate underlying strata. An angular discordance between the Burro Canyon Formation (Early Cretaceous) and the Dakota Sandstone (Late Cretaceous) near Pack Creek suggests that a movement of the anticlinal salt core occurred here in the late Mesozoic.

The belt of breccia pipes along Spanish Valley lies on the east flank of a surface syncline. The conjectural belt along Pack Creek lies mostly on the north side of a surface syncline. The belts locally cut across trends of surface folds and faults. Underlying the belts, in places less than 600 m below the surface, are limestone beds of the upper member of the Hermosa Formation (Late Pennsylvanian), truncated by a pre-Mesozoic unconformity, and adjacent contorted beds of intrusive salt of the Paradox Member of the Hermosa. The subsurface trace of these Paleozoic limestone and salt units probably controls the distribution of the breccia pipes.

Characteristics of the breccia pipes

Outcrops

Most breccia pipes are not readily identified at distances of more than a few score meters. They commonly form inconspicous mounds or depressions that have a relief of only a few meters. A few pipes occupy heads of short, steep-walled canyons or form prominent hills or conspicuous pinnacles (fig. 4). Many breccia pipes are partly covered by landslide and alluvium, and resemble remnants of landslides. The fault boundaries of the breccia pipes, however, clearly differentiate the pipes from landslides.

Boundaries

Boundaries of the breccia pipes are near-vertical contacts, which consist of short, straight faults that enclose a core of down-dropped rock. Although displacements on these faults are large (table 1), slickensides are absent and the bounding strata show no drag. Some boundary faults dip steeply inward, but they probably average about vertical as suggested by exposures of jagged or wavy fault surfaces (fig. 5).

Dimensions

Diameters of the breccia pipes range from about 30 to 450 m. Displacements downward within the structures, as indicated by stratigraphic separation of breccia material, range from about 30 to more than 700 m (table 1). No evidence of upward movement of breccia material has been recognized.

Displacements of the breccia material are commonly greater than the diameter of the pipes, but displacements are not proportional to the diameters. Thus, some pipes only a few tens of meters across, contain rocks that have dropped many scores of meters (fig. 6). Nor are displacements closely related to the stratigraphic position of the exposed pipe. That is, pipes in the same host rock may show markedly different displacements even where the structures are relatively close. (Compare pipes 33 and 34 in figure 2 and table 1).

The lengths of the breccia pipes are unknown. If, as inferred, they all extend into deeply buried Paleozoic rocks, the lengths of the breccia columns are about 1,000 m.

Breccia

Along the bounding faults within most pipes is a border breccia, commonly about a meter wide, that consists of fine to coarse fragments of all the displaced rocks set in a paste of the country rock (fig. 7). Farther inward, material from the country rock is less common. The interior breccia is a mass of broken rock, locally containing huge blocks, 10 m or more across (fig. 8) in a calcitic sand matrix.

In most pipes the interior mass is a jumble of down-dropped blocks. In a few pipes the breccia is formed of discrete units of broken rock derived from formations younger than the country rock.

FIGURE 4.--Photo of pillar of chaotic breccia, composed of blocks and sand derived from the Navajo and Entrada Sandstones, near center of pipe 41 on northeast side of Spanish Valley, San Juan County, Utah. Pillar is about 8 m high; note pick (32 cm long) on block near base.

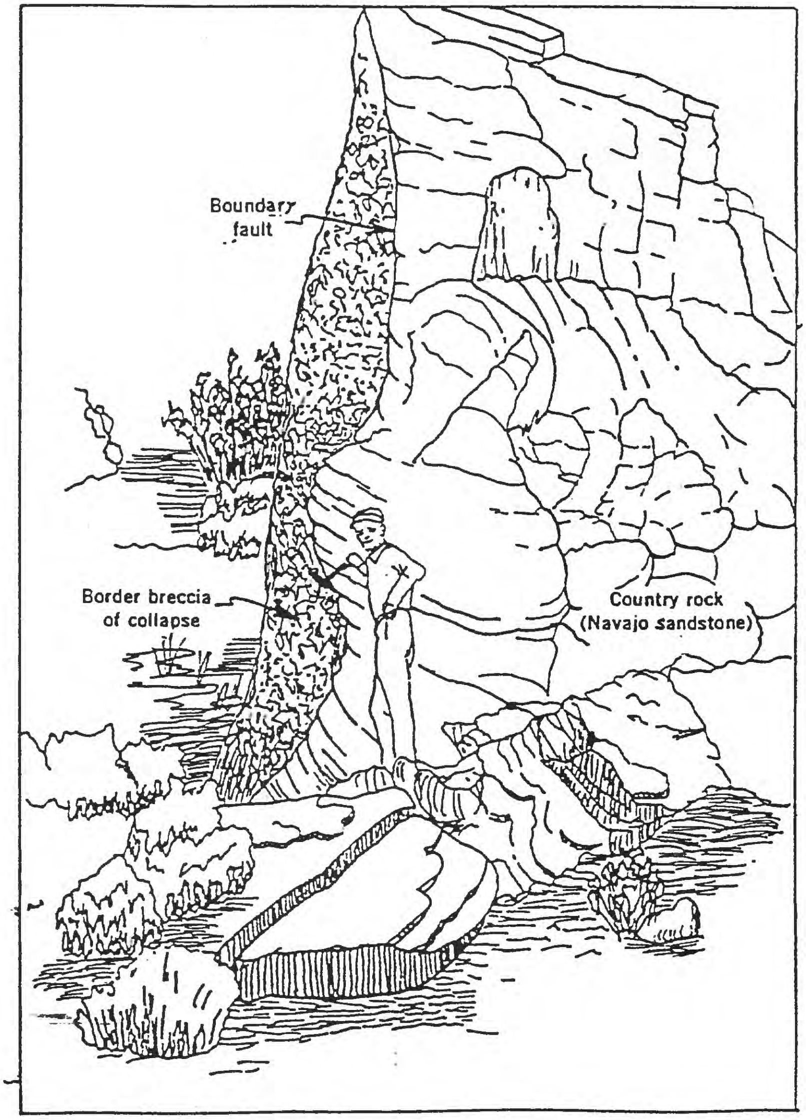


FIGURE 5.--Sketch of wavy boundary-fault surface exposed on rock pillar on south side of breccia pipe 41.

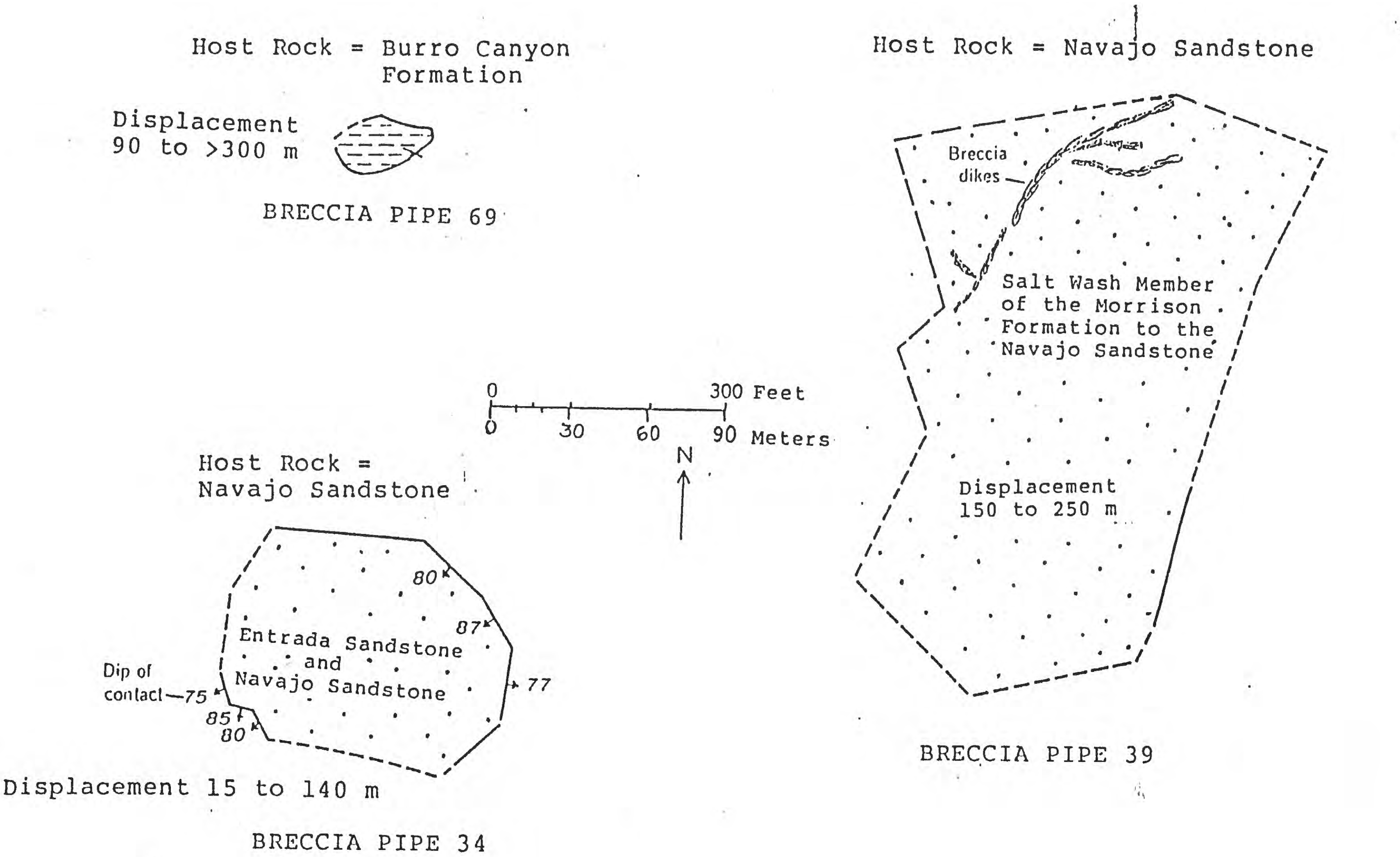


Figure 6. Plan maps of breccia pipes 34, 39, and 69, northeast side of Spanish Valley, San Juan County, Utah .

FIGURE 7.--Photo showing near-vertical view of jagged southeastern border of breccia pipe 33, Grand County, Utah. Rule, right center of photo, is extended 52 cm on border breccia of rocks derived from the Navajo and Entrada Sandstones and the Morrison Formation. Pick, lower right, is on unaltered host Navajo Sandstone.

FIGURE 8.--Photo of large block of Entrada Sandstone, estimated to be about 10 m x 10 m x 7 m, near center of breccia pipe 42, San Juan County, Utah.

The youngest rocks, which have the greatest displacement, are near the center of the structure.

Fragments in the breccia outcrops are derived from exposed formations -- from the Navajo Sandstone upward into the Mancos Shale. Neither Tertiary sedimentary or igneous rocks nor fragments of formations now buried were recognized in the breccia.

Breccias within the structures show no evidence of extreme crushing and shearing. Fragments are not slickensided and most quartz grains are not cracked. Dikelets, a fraction of a centimeter to a few centimeters wide, of fine breccia of calcitic sandstone locally cut blocks in the breccia mass (fig. 9). Near-vertical dikes of sandstone, commonly less than a meter wide, irregularly cut some breccia masses (fig. 6, pipe 39).

Sandstone in the intrusive fine breccia of the dikes is relatively fine grained, but otherwise differs little from sandstone in the broken rocks.

Alteration of breccia

Rock alteration within the pipes is minor except for local decementation of sandstone. The original calcite cement of some sandstone was partly removed as shown by many poorly indurated fragments in the breccia. Probably the net removal of calcite was small, for most broken rock is firm. However, some sand flowed freely as shown by sandstone veinlets and dikes and by sand grains abundantly scattered in the breccia matrix, especially near the bounding faults.

Within some pipes iron has been added or redistributed. The rocks in the breccia are redder than the same rocks cropping out nearby. Crusts and veinlets of limonite and more rarely of a purplish-black manganese oxide are conspicuous in sandstone breccia of a few pipes. In a few pipes plates of gypsum are in shaly units of breccia and along bounding faults. These features, however, are exceptional. Generally, the rocks within the collapse structures are like the same rocks in normal outcrop.

Country rock

Rocks containing the breccia pipes are for the most part undisturbed and unaltered. Dips in the strata surrounding the pipes range from horizontal to about 30°, but show no local changes near the pipes. The country rock is not brecciated nor crumpled around the bounding faults.

Where the country rock is sandstone, dikes of sandstone are locally common near the pipes (fig. 10). The dikes are as much as 10 m long but rarely more than several centimeters wide. They are made up of grains and small fragments of the country rock. Generally, the dikes are not connected to the breccia pipes. Rarely, the dikes branch off the bounding faults and locally fill joints.

Some joints in sandstone near the pipes contain a pseudobreccia resulting from the removal of cement along many criss-crossing planes. Such pseudobreccias may represent an early stage in the development of sandstone dikes, but we did not find transitions between the pseudobreccias and the dikes. Both the pseudobreccias and the dikes, in common with much matrix of the pipe breccias, have their origin in the removal of the original cement.

FIGURE 9.--Photo of dikelets of calcitic sandstone breccia cutting breccia fill of pipe 42, San Juan County, Utah. Rule is extended 35 cm.

FIGURE 10.--Photo of sandstone dike, composed of brecciated Navajo Sandstone, in country rock of Navajo Sandstone on southwest side of pipe 46, San Juan County, Utah. Tape, placed on dike, is extended 10 cm.

Color changes in country rock around the breccia pipes are not common, although Navajo Sandstone near some pipes is redder than typical Navajo. Small patches of dark-brown sandstone, probably due to iron-oxide stain, are locally conspicuous near some pipes. Purplish blotches, probably manganese-oxide stain, also locally mottle Navajo Sandstone along Spanish Valley. These color differences in the Navajo are also found in the formation far from known breccia pipes. Thus, the color alterations may be unrelated to the pipes.

Descriptions of two collapse structures

No one breccia pipe can be considered typical of the pipes along Spanish Valley. Pipes 33 and 76, described below, have several unique features. They were studied in detail, however, because they are among the few that are well exposed and because they share many features common to all the breccia pipes.

Breccia pipe 33

Pipe 33 is on the northeast side of Spanish Valley, about 13 km southeast of Moab near the border of Grand County. The breccia forms a light-gray hill that contrasts with the surrounding light-brown rock slope (fig. 11). The hill can easily be recognized across the valley from U.S. Highway 160, a distance of more than 2 km.

The pipe outcrop is pear-shaped in plan and has a maximum width of about 150 m (fig. 12). In places the bounding fault parallels or is a continuation of northwest-trending regional joints, but in general, the bounding fault crosscuts the joints.

Where exposed, the bounding fault dips steeply outward. The inner border of the pipe is a distinctive breccia, about a meter wide. The border breccia is made up of small fragments and large blocks from the Navajo and Entrada Sandstones and small fragments from the Morrison Formation (fig. 7). The clasts are mixed in a sand matrix derived by decementation of the country rock, the Navajo Sandstone. Neither border breccia nor Navajo Sandstone along the bounding fault show slickensides.

Pipe 33 differs from most pipes in that the collapsed fill is separable into units that are composed of material derived from one or only a few formations. The border breccia grades into a unit of jumbled blocks from the Navajo and Entrada Sandstones with a local minor admixture of fragments from the Morrison Formation. The blocks from these formations are crudely sorted in stratigraphic order inward from oldest to youngest.

The inner boundary of the Navajo-Entrada breccia is a roughly circular fault that dips steeply inward. Plates of gypsum line part of this fault, but slickensides are absent. Inward from the fault, on the east side of the structure, is a crescent-shaped fault slice containing red mudstone, chert, and sandstone from the Tidwell and Salt Wash Members of the Morrison Formation. The fault on the inside of this slice of Morrison fragments also dips steeply inward and merges with the nearly circular fault that forms the inner boundary of the Navajo-Entrada unit on the west side of the structure.

Inward from the nearly circular fault is a unit composed mainly of purplish-gray and greenish-gray mudstone and brown sandstone, mostly from the Brushy Basin Member of the Morrison Formation, and lesser amounts of red mudstone, red and gray chert, and light-brown sandstone from the Tidwell and Salt Wash Members of the Morrison.

FIGURE 11.--Photo of pipe 33, viewed looking eastward from floor of Spanish Valley, Grand County, Utah. Pipe crops out as a block-strewn, gray hill, composed of breccia of sandstone and shale. Hill is about 45 m high, 150 m wide. Country rock is Navajo Sandstone.

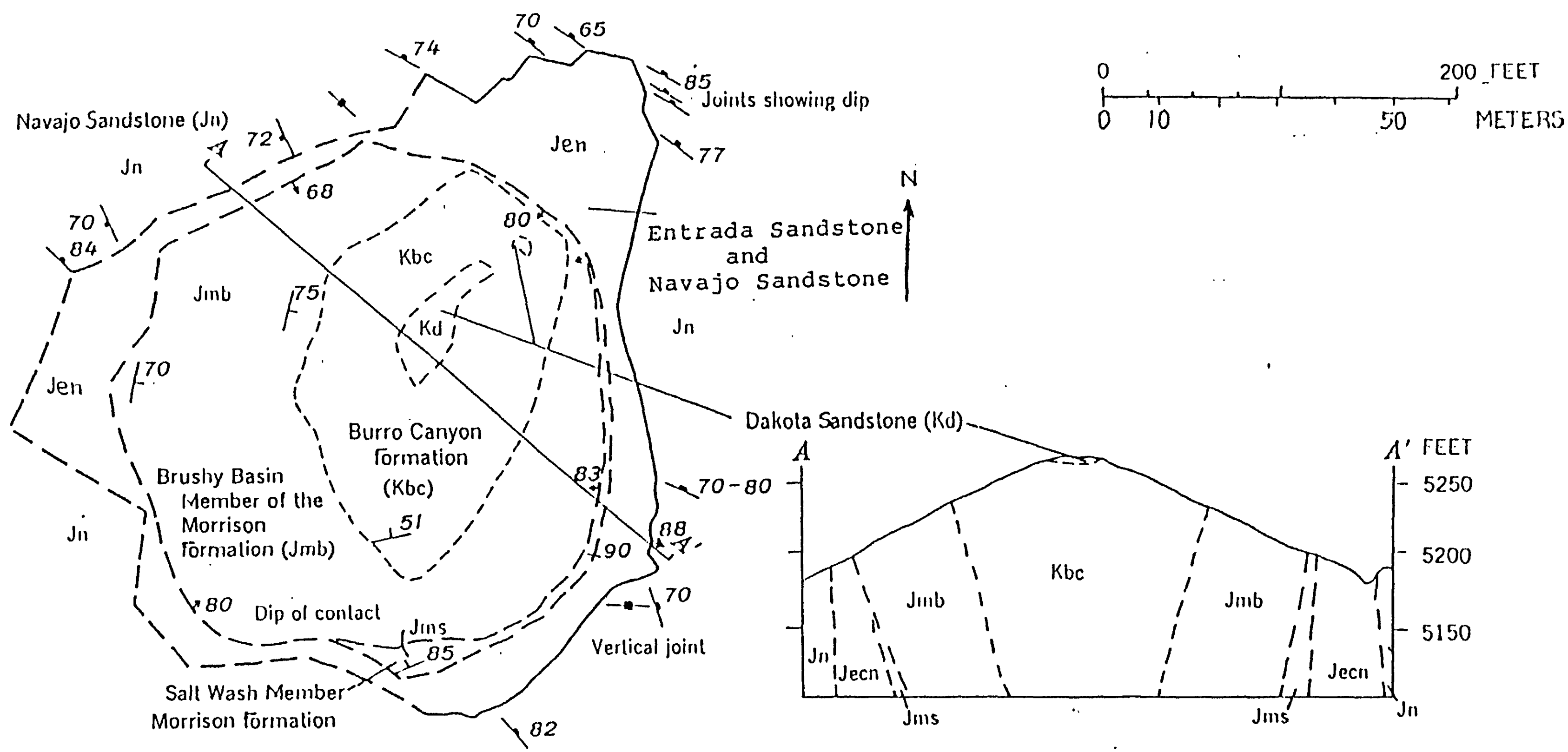


Figure 12. Plan and section of breccia pipe 33, Grand County, Utah.

This breccia unit grades inward to a unit composed chiefly of greenish-gray and olive mudstone and lesser amounts of gray sandstone and limestone from the Burro Canyon Formation. Within this Morrison-Burro Canyon unit beds dip steeply inward.

Above the Burro Canyon material are scattered flat-lying slabs of the basal conglomerate of the Dakota Sandstone. Black carbonaceous shale mixed with Burro Canyon debris was also derived from the Dakota.

The material within pipe 33 is derived from formations representing a stratigraphic column of at least 450 m -- the minimum downward displacement. The units within the collapse apear much thinner than the formations from which they were derived. The thinning was probably accomplished by slippage along steeply inward-dipping bedding planes, although displacement was recognized only on the faults described. We infer from the plan relations that the structure is a crude cylinder in which breccia units from different formations are arranged roughly like a stack of nested cups.

The boundary of the pipe is sharp. The country rock, the Navajo Sandstone, is not shattered, although in this region it is cut by many steeply dipping, northwest-trending joints. Veinlets and small dikes, composed of sand derived from the Navajo, are common near the pipe. The Navajo otherwise appears unaltered, except possibly for a few patches of dark-brown, limonite-stained sandstone.

Breccia pipe 76

Breccia pipe 76 (fig. 13) is in an unnamed sandstone member of the Mancos Shale. The member is about 100 m thick, lies about 450 m above the base of the formation, and has yielded marine fossils of middle Late Cretaceous age (Weir and Puffett, 1981, p. 95-101). The pipe lies at the head of a steep-sided gully on the south side of Pack Creek Canyon. Although this structure has a width of 120 m, it is not easily recognized from a distance. The exposed part of the bounding fault of the pipe dips inward 55° to 75°. Sandstone within the structure is a lighter brown and less firmly cemented than sandstone outside the bounding fault. Bedding of sandstone within the structure is mostly obscure, but is distinct in sandstone outside.

Near the north border of the pipe, interior sandstone is foliated parallel to the plane of the bounding fault (fig. 14). The outer boundary of the foliation is at the fault. The foliation results from streaking of clay fragments in the sandstone. The rock apparently was decemented, flowed, and then was recemented.

On the side, extending toward the center of the structure is a breccia of large sandstone blocks. Near the center of the exposed pipe is a small area of crushed black shale, which was probably derived from the Mancos Shale just above the sandstone member. On the basis of the exposed rocks in the fill, the downward displacement of breccia at the surface of this pipe may be only about 60 m.

The altered and foliated rock in pipe 76 is unlike other pipe fills in the area. Apparently the alterations are extreme effects of decementation, a process whose effects are detected to some extent in all the pipes. The moderate dips measured along the bounding fault are also uncharacteristic, and we infer that the fault steepens below the surface.

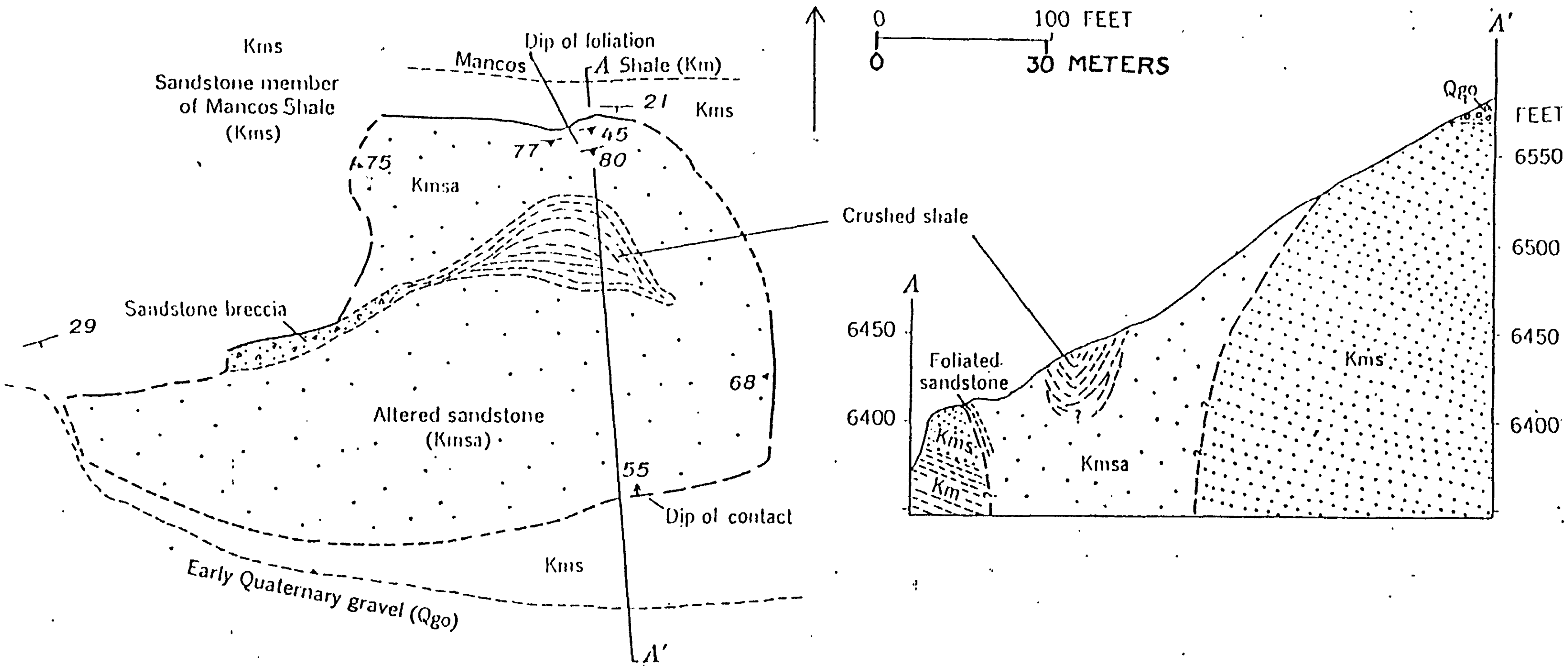


Figure 13. Plan and section of breccia pipe 76, San Juan County, Utah.

Age of the breccia pipes

The collapse of breccia in the pipes of Spanish Valley may have begun in the late Paleozoic and continued intermittently in the Mesozoic during periods of dissolution of the exposed salt core of the Moab Anticline. However, the period of greatest development of the breccia pipes was probably during the Tertiary. Unfortunately, the area lacks Tertiary deposits which would permit close dating of the pipes.

The youngest rocks recognized in any of the pipe fills are from the Mancos Shale of middle Late Cretaceous age. Many of the pipes lie near and were formerly overlain by alluvial gravels of early Pleistocene age (Richmond, 1962, pl. 1; Harden and Colman, 1988, p. 350, 352).

Figure 15 shows the relation of pipe 33 to these gravels and to the pre-Pleistocene surface. The gravels rest on an erosional surface cut on Jurassic rocks on a ridge on the northeast side of Spanish Valley. As the nearby pipe 33 contains blocks of Dakota Sandstone (Late Cretaceous), more than 700 m of section younger than the country rock was removed by erosion between the time the pipe was formed and the time the pre-Pleistocene surface was cut. This part of Utah perhaps was within the basin of sedimentation marginal to the Green River Lake during the Eocene, but since that time it has mostly been an area of erosion (Hunt, 1956. figs. 56, 57). Thus, after the formation of the breccia pipes, the removal of the Cretaceous and Jurassic rocks could have taken place at any time in the Tertiary since the Eocene. On the meager evidence, all we can say is that the pipes may be as old as latest Cretaceous and are not younger than Pliocene.

Contemporaneous events.

The formation of the breccia pipes may be contemporaneous with one or more of the following events that took place after deposition of the Cretaceous Mancos Shale and before the deposition of the Pleistocene gravels: 1) the late development of the folds in the area, 2) the emplacement of the igneous rocks of the La Sal Mountains and the associated minor copper and gold mineralization, and 3) the deposition or redeposition of uranium and vanadium minerals in favorable host rocks.

Folds of Spanish Valley

The folds of Spanish Valley and environs are related to the movement of the Paleozoic salt into the core of the Moab and Pack Creek anticlines. The salt anticlines in this part of the Colorado Plateau were formed in the Paleozoic and continued to grow intermittently through the Mesozoic. Regional compression intensified the folds in the late Cretaceous or early Tertiary (Baars and Doelling, 1987, p. 275-276). Growth of the salt cores virtually ended in the Tertiary, although minor adjustments were made in the Cenozoic (Cater, 1970, p. 65).

The near-vertical bounding faults of breccia pipes on the flanks of the folds suggest that the pipes are vertical, not inclined by folding. Moreover, the pipes appear younger than the regional joints that parallel the folds, because the bounding faults commonly in part follow and in part crosscut the joints. Thus, we believe the breccia pipes are younger than any significant folding in the area.

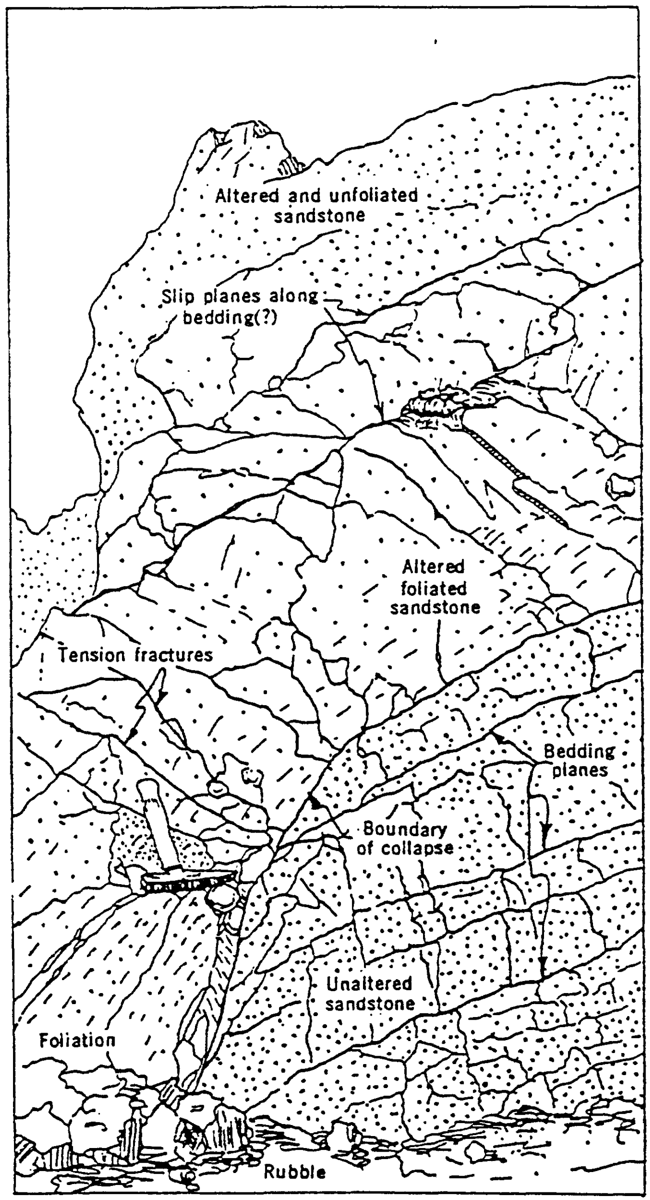


Figure 14. Sketch showing foliated sandstone of breccia pipe 76.

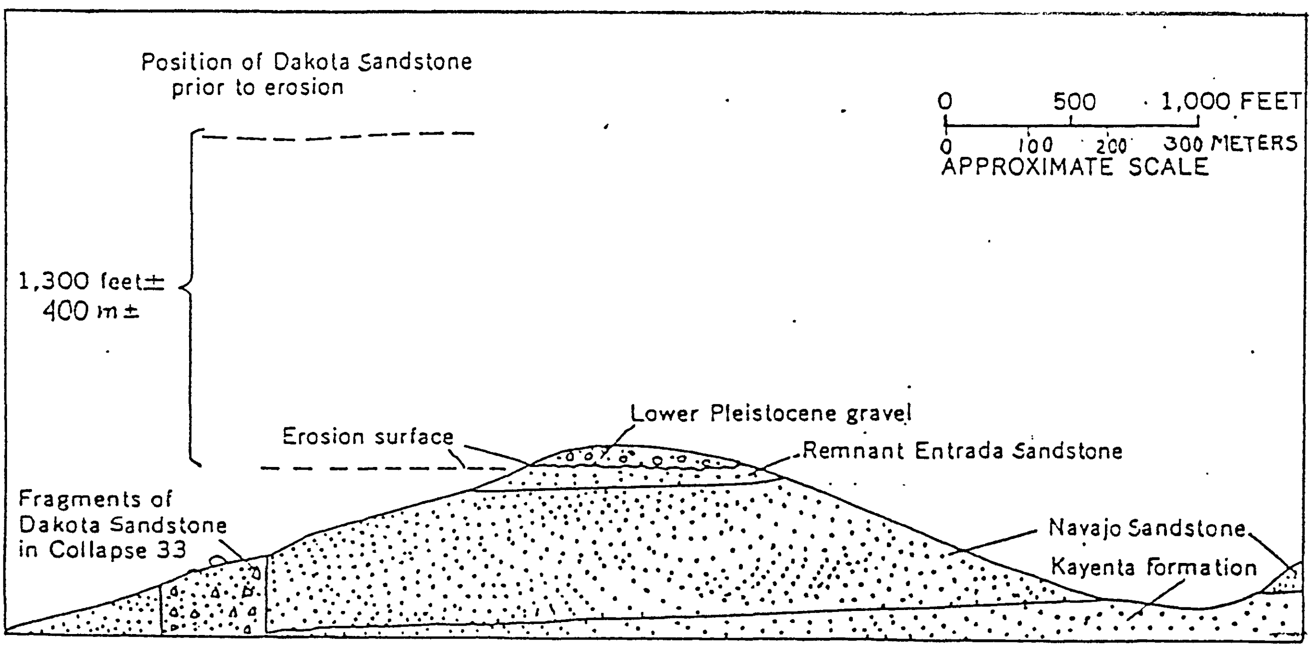


FIGURE 15.--Relation of pre-Pleistocene surface to pipe 33, Grand County, Utah.

The La Sal Mountains

The stocks and laccoliths of the nearby La Sal Mountains intrude rocks as young as Late Cretaceous and are locally overlain by Pleistocene deposits (Hunt, 1958). On the north side of the mountains a conglomerate of Pliocene (?) age contains fragments derived from the intrusions. Thus, on stratigraphic grounds the possible age of the intrusions ranges from latest Cretaceous to late Tertiary.

On the basis of $^{40}Ar/^{39}Ar$ and fission-track ages, Nelson and others (1992, p. 1549) date the La Sal intrusions as 25.1 to 27.9 Ma, late Oligocene. These dates agree with ages determined for other laccolithic centers in the Colorado Plateau, which range from 31 to 20 Ma, middle Oligocene to early Miocene. Erroneous older K-Ar dates are ascribed to excess ^{40}Ar and contamination from xenocrysts (Nelson and others, 1992, p. 1560).

Uranium-vanadium deposits

Near Spanish Valley, large deposits of uranium minerals are in the Permian Cutler Formation (Campbell and Steele-Mallory, 1979), in the Triassic Chinle Formation (Huber, 1981), and in the Jurassic Morrison Formation (Kovschak and Nylund, 1981). Vanadium minerals are common to abundant in the uranium ores. The ore deposits are in restricted stratigraphic layers within the host formations. They appear to be localized in belts of favorable sedimentary facies. Thus, mineralization of the host rocks not long after their deposition has been favored (Butler and Fischer, 1978, p. B7; Campbell and Steele-Mallory, 1979, p. 31.)

Interpretations of data from isotopic studies of Colorado Plateau uranium ores yielded different ages and suggested different origins of these deposits. Stieff and others (1953) inferred that the Plateau uranium in the Morrison and Chinle Formations were deposited from hypogene solutions in the Late Cretaceous or early Tertiary. Miller and Kulp (1963) interpreted similar data to suggest that in some areas uranium ores in the Chinle were deposited at low temperatures from groundwater in H_2S-rich beds soon after the formation of the host rocks in the late Triassic, about 210 m.y. ago. Their data further suggest that uranium ores in the Morrison and, in some areas, uranium ores in the Chinle were deposited during the Cretaceous, about 110 m.y. ago. Under favorable conditions, the uranium may have been often remobilized and redeposited (Miller and Kulp, 1963, p. 626).

Copper deposits

Copper has been mined from the Burro Canyon Formation (Lower Cretaceous) and the Dakota Sandstone (Upper Cretaceous) near faults in Lisbon Valley, about 30 km southeast of Spanish Valley (Weir and Puffett, 1960b, p. 137-141; Hasenohr, 1976, p. 71). Copper carbonates and sulfides coat grains and fill interstices and cracks in grains, replace silica and carbonate cement, and fossil plant material, and line joints and minor faults. The origin of the copper deposits of Lisbon Valley is problematical. They have been considered to be syngenetic (Fischer, 1937) or low-temperature hydrothermal (Weir and Puffett, 1960b; Kennedy, 1961.) Hasenohr (1976, p. iii, 72-73) favored deriving the copper and related minerals at depth and moving them up along a fault in connate brines to be deposited in favorable structural and sedimentary settings.

Small deposits of copper carbonates and sulfides and gold-bearing pyrite in the La Sal Mountains are mostly in altered diorite porphry (Hunt, 1958, p. 355-359; Weir and Puffett, 1960b, p. 141). They are hydrothermal deposits, part of a late phase in the igneous history of the mountains.

Origin of the breccia pipes

Facts and inferences

The nature and origin of the breccia pipes of Spanish Valley must be inferred from small surface exposures. None of the outcrops shows more than about 60 m of the vertical extent of the breccia. The actual vertical extent of the breccia, however, is probably many hundreds of meters. This we infer from the great displacement of some breccia fragments (more than 700 m in pipe 71) and the great stratigraphic range of the host rocks, which represent a normal section of more than 1,000 m.

The breccia columns perhaps extended through the entire stratigraphic section to a higher land surface in Tertiary time. No cap rocks have been recognized over any of the pipes, though cap rocks may have been removed during Tertiary erosion. The small displacement of only a few tens of meters in some pipes seems difficult to propagate through the thick Mancos Shale. The scarcity of breccia pipes in the Mancos may imply that some pipes may end upward within the shale.

The breccia pipes probably bottom in deeply buried, inclined Paleozoic rocks. None of the pipes has been drilled and none crops out in rocks older than the Navajo Sandstone (Lower Jurassic). The large downward displacements of breccias in some pipes, however, indicate that the structures penetrate all the pre-Navajo Mesozoic rocks, which are about 300 m thick. The underlying upper part of the Paleozoic section includes the clastic Cutler Formation, the calcareous upper member of the Hermosa Formation, and the salt sequence of the Paradox Member of the Hermosa Formation. Outcrops northwest of the map area of figure 2 suggest that the unit underlying the belt of breccia pipes along Spanish Valley is limestone of the upper member or salt of the Paradox Member of the Hermosa.

Features of the breccia fill that bear upon the origin of the pipes include the following. 1) Breccia fragments are from strata younger than the host rock. We found no evidence of upward movement nor injection of igneous material. 2) Some sandstone in breccia was decemented, flowed, and recemented as shown by sandstone dikes, foliation, and destruction of bedding. Small dikes of sandstone breccia and pseudobreccia in sandstone along joints indicate that the decementing process operated also on a small scale in the host rocks. Thus, solution of carbonate cement was an important factor in the formation of the breccia structures. (Mudstone in breccia does not clearly reveal decementation, but some fragments are contorted, showing that they were plastic during deformation.) 3) A centripetal dip is shown by breccia masses whose internal grouping was mapped in detail (figs. 12 and 13). All the breccias appear to have their greatest displacement near the center of the structure. That is, internal movement within breccia exceeds that between the breccia and the bounding fault. 4) The breccia mass is for the most part tightly packed and firmly cemented (though locally less well cemented than the country rock or the strata from which the fragments were derived). From this we infer that the brecciation resulted in relatively little increase in volume and no large cavities and that downward movement was fairly continuous. 5) The absence of slickensides on the breccia fragments and on the bounding faults suggests that shear planes within the breccia were lubricated by decemented sand and plastic clay and, in a sense, are solution faults.

Hypothesis

Solution of inclined limestone beds of the deeply buried upper member of the Hermosa Formation or of salt in the Paradox Member could create space for breccia collapsing from overlying formations. Caves in the limestone possibly formed during a time of pre-Triassic erosion, but no karst topography in the Hermosa has been reported. More likely, cavities in limestone of the Hermosa were formed by circulating solutions at some time in the Tertiary. The same solutions that dissolved the limestone of the Hermosa probably rose along fractures in younger formations and removed carbonate cement from sandstone beds. The lack of slickensides and crushed rock implies that the breccias were formed by continuous collapse of partly decemented rock rather than by intermittent gravity failure of roofs over caves.

The nature and source of the solutions that dissolved carbonate from the rocks are unknown. The lack of rock alteration in and near the pipes, except for effects of decementation and minor iron and manganese staining, suggests that the solutions were not greatly out of equilibrium with the host rocks. Downward percolating surface or ground waters are, however, unlikely to account for the structures, not only because of their inferred great vertical extent, but also because the thick Mancos Shale, which formerly covered the area is a seal for gravity-controlled waters.

Solutions that dissolved buried limestone and salt and carbonate cement in the pipes may have been related to the igneous intrusions of the La Sal Mountains. The igneous bodies, chiefly diorite porphry, are central stocks from which radiate large laccoliths. Most of the laccoliths presumably spread in the incompetent salt sequence of the Paradox Member of the Hermosa (Hunt, 1958, p. 316) Connate water within the Paleozoic rocks probably was heated and set in motion by the underlying and cross-cutting igneous intrusions. The solutions possibly migrated downdip from the uplifted beds around the mountains and were discharged from upturned Paleozoic beds along the salt-cored anticlines of Spanish Valley and Pack Creek Canyon, as diagrammed in figure 16.

Thus, we conceive the formation of the breccia pipes along Spanish Valley to be the result of collapse of rock caused by solution of deeply buried salt and limestone and dissolving of carbonate in overlying rocks by rising heated waters, which perhaps emerged from the pipes as warm springs.

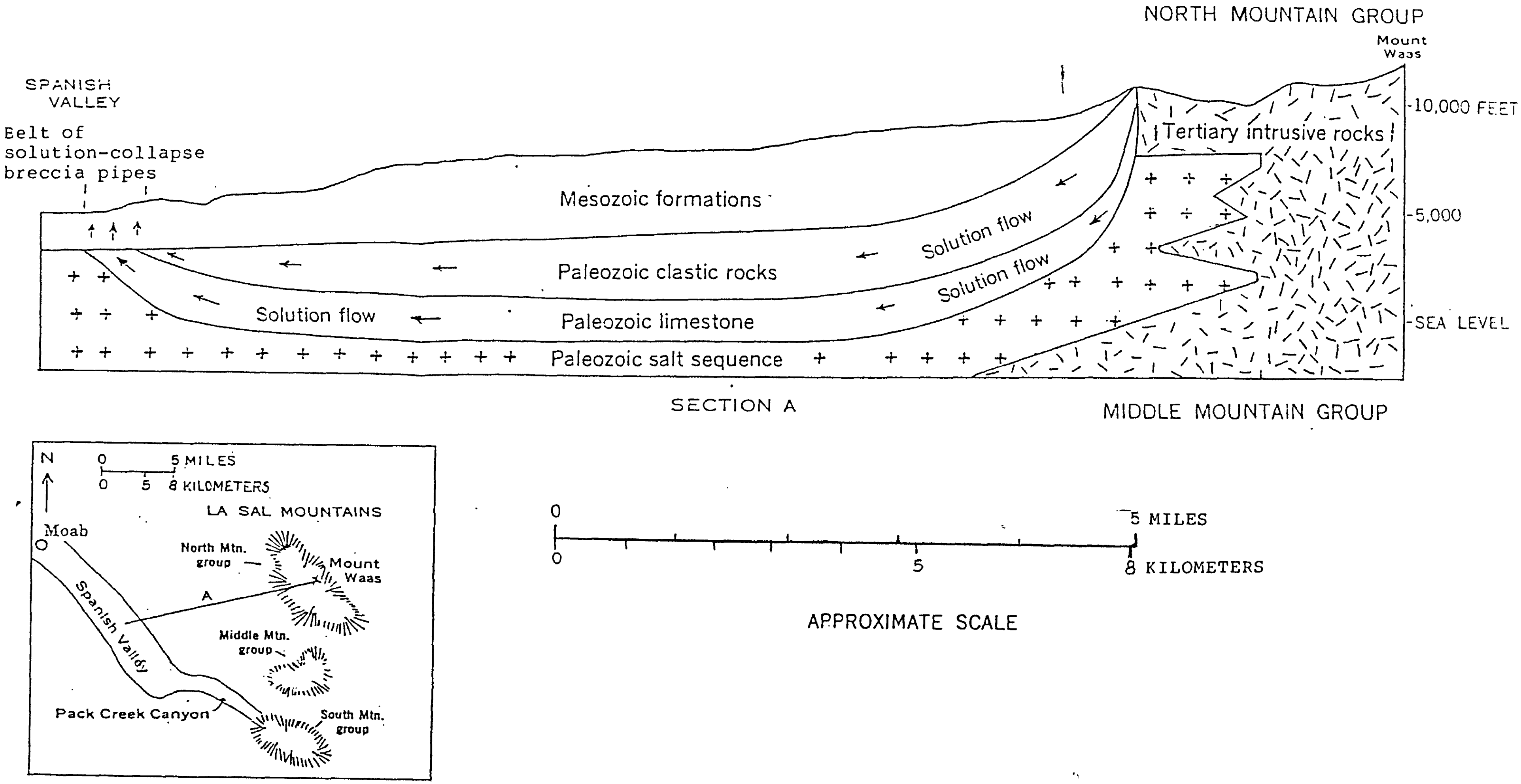


Figure 16. Diagrammatic cross section between Spanish Valley and Mount Waas in the north mountain group of the La Sal Mountains, showing hypothetical movement of warmed solutions from the mountain area to the belt of solution-collapse breccia pipes near Spanish Valley, Utah.

Comparison with similar structures

Breccia pipes, similar to those of Spanish Valley, crop out in several restricted areas on the Colorado Plateau (Sugiara and Kitcho, 1981).

The pipes nearest Spanish Valley are in Lockhart Basin, about 20 km to the southwest, where thirty-two small collapse structures have been identified. The outcrops are in Permian and Upper Triassic strata. The structures range from about 10 to 150 m in diameter, contain a breccia of younger rock that has dropped 30 m or more, and are inferred to extend downward about 600 m into salt and limestone of the Hermosa Formation (Huntoon and Richter, 1979; Sugiara and Kitcho, 1981, p. 36; Huntoon, 1988, p. 88-89).

In central Utah the San Rafael Swell contains eleven collapse-breccia structures in Triassic rocks (Sugiura and Kitcho, 1981, p. 38). The structures are roughly oval in plan, range from about 10 to 760 m across, are enclosed in a bowl of in-dipping strata, and contain breccia that has been dropped as much as 240 m (Hawley and others, 1965, 1968, p. 31-34). Breccia and country rock near the pipe are bleached; carbonate has been removed and dolomite and chromium clays added. Sandstone dikes are common in the breccia and surrounding rock. The structures apparently formed by collapse into cavities resulting from solution of underlying Permian and Triassic carbonates.

The Colorado Plateau of northwestern Arizona contains thousands of solution-collapse breccia pipes (Wenrich and Huntoon, 1989). A typical pipe is about 90 m across and extends upwards hundreds of meters. The pipes are rooted in cavernous Mississippian limestone and by upward stoping have breached Paleozoic and Mesozoic strata. Most pipes do not reach the surface but are commonly evidenced by collapse basins of inward-dipping beds. Rock around the breccia pipes is locally altered by bleaching, limonite staining, and minor silicification (Wenrich, 1985, p. 1726).

Breccia pipes in the in the southeastern part of the Colorado Plateau in northwestern New Mexico are in Upper Jurassic rocks. They range from a few centimeters to 60 m in diameter and from less than a meter to 90 m in height (Hilpert and Moench, 1960, p. 441). The pipes are circular in plan and are bounded by one or more ring faults. Breccia and downwarped beds within the pipe is the same material as the host rock a short distance above. The pipes flare upward and are covered by undisturbed beds. They appear to pass downward into undisturbed beds. Schlee (1963) suggested that the pipes were formed in the necks of former springs by foundering of partly consolidated sandstone into water-saturated mud, the foundering locally aided by solution of underlying gypsum. Hunter and others (1992) interpret the breccia pipes of northwestern New Mexico as solution-collapse structures resulting from the dissolution of underlying Jurassic gypsum-anhydrite beds originally present in the area.

Possible economic significance

The Spanish Valley structures are similar to breccia pipes that are host structures of mineral deposits elsewhere on the Colorado Plateau -- in northwestern Arizona, central Utah, and northwestern New Mexico. All the mineralized pipes are in or near areas that also contain tabular uranium deposits in sandstone, apparently localized by depositional features.

The breccia pipes of Spanish Valley are not known to be mineralized and show few signs of rock alteration. They lie outside areas considered on the basis of sedimentary features favorable for large uranium-vanadium deposits in the Chinle and the Morrison Formations (Butler and Fischer, 1978, figs. 4 and 6; Campbell and others, 1982, pls. 1A, 1B). The known ore deposits of nearby areas are not localized by structures of Tertiary age, but are apparently controlled by facies of the host sediments. The similarity of the breccia pipes of Spanish Valley to mineralized breccia structures elsewhere on the Colorado Plateau and their proximity to known uranium-vanadium and copper deposits suggests, however, that they may contain undiscovered mineralized rock.

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