308 --- Q199602290005
Scientific Notebook #139
Supporting the Regional
Hydrogeologic Processes of

CNWRA
CONTROLLED
COPY 139

Contents | Page

Scientific notebook used to record some of the work performed by Donna Balin, consultant to the CNWRA, on behalf of the Research Project on Regional Hydrogeologic Processes of the Death Valley Region.

Gordon Wittmeyer
2/21/96

March 15, 1995

Work to be completed for:
Gordon Wittmeyer, Ph.D.
Senior Research Scientist
Center for Nuclear Waste Regulatory Analyses
Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78238-5166
Tel: 522-5082
Fax: 522-5155
E-mail: gwitt@dopey.cnwra.swri.edu

Gordon is constructing a 3-D hydrostratigraphic model — computational flow modeling.
Needs regional stratigraphic cross-sections for the entire region around Yucca Mountain. Wants to focus on the Paleozoic carbonate aquifer.

Area of about 80,000-100,000 sq. km.
Basin and Range province.

NE part of area of interest — e.g., Sheep Range — structures trend sort of north-northeastwards.
SW part of area of interest — Walker Lane Belt (e.g., Spring Range) — structures shift to a northwesterly orientation.
Clastics in western part of the region — carbonates to east.
Miogeosynclinal trough.

Showed me a stratigraphic column for the area:
All of the Paleozoic limestones are lumped together for the purposes of this study and form part of a regional aquifer system (the one that we're interested in). They are shown as Devonian to Cambrian on the column. Sequence is about 10,000 feet thick (I think he meant the Paleozoic carbonate section — check for sure)
The overlying Eleana Formation (Mississippian) is argillaceous and forms an aquitard.
The Pennsylvanian/Permian Tippipah Limestone is part of a more localized aquifer system (not of interest to this study).
Note: But Eleana Fm. not present farther east (near S. Sheep Range as I look at cross-section) => so maybe composite with lower carbonate aquifer there?
Tertiary volcanics unconformably overlie this sequence.

Don't go west of center of Death Valley (Owens Valley way far west).
Don't go east of Sheep Range and Pahranagat Range.
(Misc: Ash Meadows is a discharge area.)

Want to look also at the style of faulting.

DF Balin
3/15/95

<u>Data</u>: Have surface geology (Paleozoic carbonates are lumped)
Water wells
Emplacement holes for weapons (can be 13,000 feet deep) — e.g., Frenchman Flat, Yucca Flat — penetrates into Paleozoic carbonates.
Geological county maps (Cathy).
May be possible to get driller's logs for USGS water wells — consultant who has worked for SW Research named George Rice tried to obtain information on cuttings but only was sent information related to drilling procedures when he requested a driller's log. (Presumably a log of this type exists — is it called a mud log when it's a water well?)

Looked at water well information on computer (U.S.G.S. — Note: only U.S.G.S. or others?)
Codes:
Latitude, Longitude, + 2 digits
0
550 (Note: indicates that the depth goes from 0 to 550 feet depth — this data in feet)
Then lithological code: 100 = Cenozoic
200 = Mesozoic
300 = Paleozoic
400 = Precambrian
USGS lithological code: e.g., 300 LMDM (means Paleozoic limestone and dolomite)
Then sometimes more lithologic description.

Other codes: DDBG (Dunderberg Shale; a stratigraphic unit)
Code given as year/month/day

Showed me computer-generated geological models in the GIS room.
Using Earth Vision geological modeling program.

D. F. Balin
3/15/95

****
Concerned with DV-03 boundary (defined by Bedinger, 1989) => continuous hydrologic unit.
Have topographically closed basins draining into regional carbonate aquifer.

RASA — Regional Aquifer System Analysis
Gordon wants to avoid estimating fluxes across boundaries.

Ash Meadows => discharge of 17,000 acre feet

Have lines showing where private companies drew cross-sections but don't have access to the cross sections themselves => the private companies are IT and GeoTrans.
Still, it would be good to know why they chose to make cross-sections along the lines shown on the map => Have a better look at the geology here.

Bare Mountain => structurally complex (Alan Morris has done a lot of work in this area).

Also have AV-1 seismic line (Amargosa Valley) => fairly long, about 20 km.
Steve Young — structural geologist => He might know why this line was shot =>
E-mail for Steve Young: MVE1USA@AOL.COM
Alan Morris also may know about this line.
<u>Find out whether any cross-sections have been developed based on this line.</u>
Maybe also some short lines at Yucca Flat but don't go deep enough.

Looking at map on wall of GIS room:
Pahute Mesa => highest points on mesa are about 7300 feet
Spring Range — up to almost 12,000 feet => highest range in area.

Discharge at Ash Meadows.
Also discharge at Furnace Creek and Navares Springs area in Death Valley.

Yucca Flat => about 4000 feet => high Mojave Desert
Changes in vegetation:
Mesa => get juniper, pinon pine
Amargosa Desert => creosote
Phreatophyte growth along springs.

Pahranagat Valley — lots of springs, lakes => probably outside area of interest.

Discharge => Furnace Creek, Nevares Springs (Death Valley) => 5000 acre feet/year
Oasis Valley => 4000 acre feet/year

Flux from Pahranagat area => about 3000 acre feet/year

Tikaboo Valley — used to be called Desert Valley
Looking at map from Winograd & Thordarson report showing composition of waters:
Calcium magnesium bicarbonate => from carbonate aquifer.
Sodium potassium => from volcanics.
Ash Meadows — the major discharge point for the Paleozoics => get mixed water composition.
Discharge areas in blue.
Plate 1

D. F. Balin
3/15/95

Volcanic aquifer system coming in from further NE.
Carbonate aquifer system also coming in from NE but further south => get mixing in Ash Meadows.

Two subbasins:
Ash Meadows
Oasis Valley-Nevares Springs-Furnace Valley (second one correct? => I'll check report).

Devil's Hole => solution feature in Ash Meadows.
Death Valley was submerged by Lake Manley in the Pleistocene.

15 digit well ID (examples only):
Depths:

U (upper)	L (lower)	4-character lith code	NV local lith code	Unit, Formation
0'	200'	ALVM	110 ALVM	Red Clay
200'	1200'	TUFF	110 VLCC	Furnace Creek Beds
1200'	1430'	TUFF	120 VLCC	Topopah Spring
1430'	1800'	LMSN	350 BNZK	Bonanza King
1800'			400 STRL (Stirling)	Quartzite

Will use locations of wells with strat columns
Maps with surface geology
County maps
7-and-a-half minute geology maps
Geology map of Nevada
NTS (Nevada Test Site) — maybe more data
GWSI => Ground Water Site Inventory
Larry McKague => element manager here => maybe can get more info from boreholes at the site.

D.F. Balin
3/15/95

Pena Blanca, Chihuahua (Mexico) => analogue to Yucca Mountain site => uranium ore body in tuff, similar hydrogeological regime, arid climate, etc.

Hydrogeological Map of Regional Aquifer System:
Sheep Range => lumped all into lower carbonate aquifer
Area of steep hydrologic gradient => run cross-sections perpendicular to the gradient.
Try to find out reason for steep gradient here.
Same system across the gradient? => Chemistry implies yes but not always the case.

Bedinger et al (paper):
Studies of geology and hydrology in the Basin and Range Province, southwestern United States, for isolation of high-level radioactive waste — characterization of the Death Valley region, Nevada and California. USGS Prof. Paper 1370-F, 1989.

March 18, 1995

Donna F. Balin
3/18/95

****

Met Gerry Stirewalt — structural geologist and liason with NRC — is in Washington, D.C. office.
He is working on the structural interpretation of Yucca Mountain — geological framework model.
Met with Gerry (on Wednesday, March 15) along with Craig Fenrich (works the Earth Vision software), George Rice (gathered data on which the model was based), and Steve McDuffy (NRC representative).
Showed me Earth Vision models for the repository site.
Repository: 14% porosity.
Size of the repository site: 5-8 km^2

Three main faults transect the repository site in a north-south orientation:
Solitario Canyon Fault (westernmost of the three faults)
Ghost Dance Fault (middle fault — passes directly through the repository itself)
Bow Ridge Fault (easternmost of the three faults)

All three faults are downthrown towards the west.
Solitario Canyon Fault has a much larger amount of displacement than the others — a fault scarp is topographically developed along this fault but not along the others.
The Ghost Dance Fault (about 50 meters? of displacement across the fault) may terminate in the repository or it may connect with other faults (e.g., the Abandoned Wash Fault located to the south of the repository)

Alan Morris is working the area from Forty-Mile Wash to the western margin of the repository.

Planar fault model or a listric model — merging into a flat-lying fault sequence (maybe two or three of these surfaces below Yucca Mountain — depth to first surface may be about 3 km — or maybe down to 5.5 km which would certainly affect the Paleozoic rocks).

There is only one borehole within the repository boundary that penetrates the carbonate sequence under the Tertiary volcanics:
UE25P-1

Can see surface exposures where Tertiary faulted against Paleozoics => Old Bullfrog Mine in Bullfrog Hills (where Beatty is out west — south end of Black Mountains) => Here shows contact of crystalline basement => above get carbonate stringers and volcanics.
Chaos:
Low-angle faults — blocks above are intensely fractured (still in their stratigraphic positions though).
May have important effects for regional hydrology.

On Friday, March 17, Gerry Stirewalt showed me a 2-D cross-section of the Yucca Mountain repository site showing the flat-lying detachment surface at 7 km below sea level (elevation of land surface shown at approximately 1 km, so total depth below surface at about 8 km).
Question: So is this a different surface than the one he mentioned previously where the depth may only be at 3 km or 5.5 km? What would be the configuration of the faults if they were different faults? => Answer: May have merging of detachment surfaces to west.

All of the faults shown on the cross-section are dipping towards the west and are downthrown to the west => form a single detachment surface at about -7 km.
Bare Mountain (located farther to the west) is faulted with an eastward dip on the fault plane and is downfaulted towards the east.

References for this area:
Scott and Bonk
Frizzell and Schulters
Maldonado map in the Bullfrog Hills

Other questions:
1) If there was a rise in the water table that threatened the repository, couldn't there be relief pumping wells to lower the water level => like the Catfish Farm?
2) Which geologic horizon is the repository to be located in? Answer: lower part of Topopah Spring Member of the Paintbrush Tuff (Miocene) => part of Piapi Canyon Group (shown as part of welded-tuff aquifer in Winograd and Thordarson)

D.F. Balin 3/18/95

March 18, 1995:
Spoke with Dave Ferrill about Zeke Snow's work.
Snow/Wernicke → their model differs from other models.
Snow has proposed a structural model for this area → says that the carbonate aquifer may not underlie this whole region → blocks.
Has stretched out the structure → reconstruction for 36 m.y.
Carbonate aquifer may have facies change to north → shale? (Depositional systems?)
Dave has a library of Snow's, Wernicke's, etc. papers.

D.F. Balin

March 21, 1995

D.F. Balin 3/21/95

What was the structural history of the area?
A) Winograd and Thordarson
Large positive area (Sevier Arch) probably existed in much of southeastern Nevada and western Utah from late J to early Late K => therefore, J and K strata were probably never deposited within most of the study area.
Precambrian and Pz miogeosynclinal rocks => were first significantly deformed during late Mz and perhaps early Tertiary time => marked by uplift and erosion and subsequent folding, thrusting, and strike-slip faulting (made region mountainous).
Beginning with the Miocene volcanism and continuing through the Quaternary, large-scale normal block-faulting has disrupted the Tertiary volcanic and sed strata, as well as the previously deformed Precambrian and Pz rocks => caused the Basin and Range structure reflected by topography in the region today.
(Some evidence of strike-slip faulting during Tertiary time, some time after deposition of the early Miocene tuff => possibly may reflect periodic rejuvenation of strike-slip faults formed during the late Mz orogeny).
In late Tertiary and Quaternary => resulting valleys largely filled with detritus, aggregating several hundred to a few thousand feet.
Normal faulting is currently active => indicated by fault scarps cutting alluvial fans and by absence of extensive unfaulted pediments.

In contrast to the miogeosynclinal rocks => postdepositional distribution of Tertiary rocks has been controlled mainly by fairly simple block faulting and erosion.
NW part of area => a faulted and eroded volcanic plateau (Pahute and Ranier Mesas are remnants). In the remainder of the area => ridges of pre-Tertiary rocks interrupt the continuity of the once extensive ash-flow sheets.

Thrust faults (most spectacular of the tectonic features of the area) => displaced the pre-Tertiary rocks laterally a few thousand feet to several miles. Locally, imbricate thrusting repeatedly stacked the miogeosynclinal strata upon one another. Some major thrust faults (though folded, crossfaulted, and eroded) can be followed in outcrop or reconstructed for miles (Plate 1).
(NOTE: So maybe could get lower carb aquifer units underlying some areas where lower clastic aquitard outcrops if lower clastic aquitard overthrust over the lower carbonate aquifer.)
Discrepancies about the nature of the thrust faults => some believe that the major thrust faults (which commonly have dips of 35°-50°) flatten with depth and follow less competent strata (specifically the shales of the Carrara Fm — cites Burchfiel, 1965; Secor, 1962) => this would be thrusting of the decollement type where sed rocks slide over the crystalline basement.
Others reject the decollement hypothesis (cites Vincelette, 1964: Fleck, 1970) => they presented evidence that the relatively steep dip of the major thrust faults remains unchanged with depth.

Strike-slip faults and shear zones cut and offset the thrust faults in several places within the region => best documented is the Las Vegas Valley shear zone (expressed topographically by a valley that extends from Las Vegas almost to Mercury — distance of about 55 miles — amount of displacement estimated between 15-40 miles).

Other strike-slip zones (smaller than the Las Vegas shear zone) => in Death Valley, the Spring Mtns, the Amargosa Desert, the NTS — some of these faults may be structurally related to the Las Vegas Valley shear zone.

Normal faults — the most common tectonic features of the area (numbering within the thousands within the study area) => displacement generally < 500', but is 1000s of feet on some.

DF Balin 3/21/95

April 5, 1995

Hydrogeological studies done to date will be analyzed to determine:

1) lateral extent of the region modeled;
2) the type of data used to construct the model;
3) geologic and hydrologic description of the stratigraphy used;
4) type and location of the basin boundaries and the data used to determine them;
5) methods used to account for the hydraulic effects of faults and stratigraphic contacts within the basin;
6) methods used to determine recharge and discharge locations;
7) methods used to infer hydraulic connections between topographically-closed sub-basins;
8) geochemical tracer and hydrochemical facies data.

1) Lateral extent: Area of about 80,000-100,000 sq. km. Approximate DV-03 boundary as defined by Bedinger 1989 => continuous hydrologic unit. Have topographically closed basins draining into regional carbonate aquifer. Extends eastwards as far as the Pahranagat Range and Sheep Range. West as far as Death Valley (discharge point for the regional carbonate aquifer, so haven't extended our study area any further westwards even though Bedinger shows further).
2) Type of data:
   Have surface geology (Paleozoic carbonates are lumped)
   Water wells
   Emplacement holes for weapons (can be 13,000 feet deep) — e.g., Frenchman Flat, Yucca Flat — penetrates into Paleozoic carbonates.
   Geological county maps.
   May be possible to get driller's logs for USGS water wells
   Also have AV-1 seismic line (Amargosa Valley) => fairly long, about 20 km.

Need to focus on:

Nature of the structural/stratigraphic control that creates the steep ground water gradient north of Yucca Mountain.

Location and nature of faults that may control the regional flow regime (e.g., sealed faults vs. faults that may enhance fracturing providing conduits for flow, juxtaposition of lower carbonate aquifer against impermeable units, etc.)

Barriers to flow (e.g., removal of carbonates by erosion or by faulting into blocks; non-permeable carbonate or non-carbonate rocks, etc.)

Role of fractures in controlling saturated flow in the regionally extensive Paleozoic carbonate aquifer (would also apply to the local tuffaceous aquifers).

Lateral and vertical extent of the regional flow system (inc. thickness changes in the lower carbonate aquifer).

Type and magnitude of the boundary conditions at the base and perimeter of the regional flow domain.

Limited borehole data, especially for the Paleozoic carbonate aquifer system.

Construct alternative conceptual models of the regional flow regime.

DF Balin 4/5/95

Question is will the water table intersect the repository. What are ground water flow paths now? What are the geological conditions that affect the present ground water flow paths?
Geologically, how will the ground water flow paths be affected by geologic conditions that may exist in the future? This also involves rate of change of geologic features that may affect flow conditions, e.g., effects of active faulting, resultant fracturing, changes in porosity, etc.

How far into the future are we considering? When will the levels of radioactivity in these materials be safe?
What level is safe?

Define what we know about the present ground water flow paths:

Regional ground water flow is associated with the lower carbonate aquifer.
1) References:
A) Dettinger (1989):
Flow paths => requires an understanding of where the carbonate rocks are present, and where they are continuous enough to form local and regional aquifers.
Carbonate-rock province (limestone and dolomite) => 50,000 mi^2 (about 130,000 km^2) area of southern and eastern Nevada => also extends beneath western Utah and into southeast Idaho and eastern California.
Large springs associated with these rocks — many with discharges >1000 gallons per minute.
=> Suggests that the carbonate-rock province of Nevada contains aquifer systems of regional scale and significance.

East-central Nevada => the source of most regional ground-water flow throughout the carbonate-rock province.
Regional flow systems originating in east-central Nevada discharge both to the south into southern Nevada and to the northeast into Utah (Fig. 8 of this paper; Harrill et al, 1988).

Southern Nevada => the thick carbonate-rock layers are continuous enough to transmit ground water at regional scales only beneath a north-south "corridor" 60-90 miles wide (97-145 km)that extends southward from east-central Nevada to and beyond the Spring Mountains.
Two major regional flow systems within this corridor => 1) Ash Meadows-Death Valley system, 2) White River-Muddy River Springs system.

These flow systems link the ground water beneath dozens of valleys and over distances >200 miles (= 323 km).
(The White River-Muddy River Springs system lies outside our area of interest -- trends east of the Sheep Range => So the Ash Meadows-Death Valley system is the one of interest in our study.)

DF Balin 4/5/95

Outside of this corridor => the carbonate rocks are present mainly in isolated blocks that form aquifers of limited extent, recharged mainly by local precipitation.
East and west of the central corridor are blocks of carbonate rocks (west of Yucca Mountain and underlying the Mormon Mountains) that are thick but largely isolated from carbonate-rock aquifers in other areas by noncarbonate rocks of low transmissivity (Wernicke et al., 1985, Fig.15; Blank, 1988; Carr, 1988; Hamilton, 1988, p.57,61,79; Scott, 1988; Wernicke and Axen, 1988b, Fig.2) => these blocks become much thinner north and south of the A-A' cross-section (shown in paper on p.14, 15) and do not receive regional inflow.
NOTE: What specific evidence for the above statements? What is the specific evidence for this corridor? How has it been defined? => See Guth (1988)(reference given in Dettinger 1989). Also try Winograd and Thordarson (1975), Bedinger, and check Cordilleran volume.

But even in this corridor — the thickness of the carbonate rocks was reduced from c. 40,000 feet (about 12,000 m) to between 3,000 and 19,000 feet (about 900 and 5800 m) due to deformation (averaging about 12,000 feet = c.3600 m).
NOTE: How do they derive the 40,000 feet of original thickness?

In southern Nevada, the aquifers are thick enough and continuous enough to collect and transmit regional ground-water flow only within this north-south corridor centered under Pahranagat Valley, the Sheep Range and Spotted Range areas, and Spring Mountains.

Area underlain by thick and relatively continous carbonate rocks within the central corridor in area of interest: the Pintwater-Spotted Range area (cites Guth, 1988). (Also mentions Coyote Spring Valley area (Guth, 1988; Wernicke and Axen, 1988a, p.1749) but I think outside area of interest -- east of Tikaboo Valley and northern Sheep Range).
NOTE: Exactly how thick here? How determined? Any well data?

Further south: Central corridor underlies the Spring Mountains-Pahrump Valley area at this latitude (cites Wright et al., 1981)
Single continuous corridor of thick carbonate rocks (surrounded by noncarbonate rocks) and a few small and isolated blocks of carbonate rock (e.g., the western edge of Death Valley).
At this latitude => water in the corridor derived mainly from recharge from snowmelt in the Spring Mountains => moves radially away from the high-altitude areas of the Spring Mountains to discharge near Tecopa, in Pahrump Valley, at Indian Springs, and (in the past) at Las Vegas Springs (cites Hershey et al., 1987)
NOTE: So is there any connection between the flow path that runs east of the Sheep Range and ground water in the area of the Spring Mountains?
What happens to the flow south of Pahrump Valley? Looks like mostly a flow barrier caused by outcropping of the lower clastic aquitard => so where does it go? What are the water-table elevations in this area? Does Winograd & Thordarson or Bedinger have information on these questions?

DF Balin 4/5/95

Most recharge to the aquifers of southern Nevada (both carbonate and basin-fill) originates in the high mountain ranges => springtime snowmelt releases large quantities of water (water that falls on valley floors provides only very minor recharge).
NOTE: How do we know this?

<u>Ground water flow in the lower carbonate aquifer is mainly through fracture-generated porosity.</u>

1) References for fracture porosity vs. primary porosity:

A) Dettinger 1989:

Detailed field observations of the carbonate rocks and younger sediments centered on the Sheep Range [cites Guth (1986); also Guth et al. (1988)] => mapping indicated small fractures through which small volumes of water can flow probably are common throughout the region => resulted from region-wide geologic forces that fractured the rocks =>

Concluded that along certain recently-active, steeply-dipping faults (such as those that form the steep margins of mountain ranges) => rocks were fractured under conditions that allowed them to develop and maintain much larger voids spaces through which large volumes of water can flow => these fault zones may constitute the principal paths through which most ground water flows.

In contrast => rocks that were fractured and fragmented along older, flat-dipping fault zones subsequently resolidified into rock masses that can now impede ground-water flow.

NOTE: I'm not sure why this would happen => Couldn't the older faults have been preferentially enlarged due to longer period of dissolution? Maybe the main key here is the inclination of the faults => flat-lying prone to compressional forces due to weight of overburden thereby sealing the faults? Also older ones maybe more prone to being sealed rather than undergoing dissolution.

Some zones in the central corridor are highly transmissive => may act as large-scale drains collecting water from adjacent, less transmissive rock that underlies most of the study area => would ultimately conduct much of the flow that discharges at regional springs.

Wells drilled during the Air Force's MX Missile-Siting program during 1980-81 (NOTE: outside area of interest but still informative as to the transmissivity of the carbonate-rock aquifers):

Extremely-high transmissivity aquifers at the MX wells in Coyote Spring Valley => Geophysical logging in the wells indicated porosities averaging 5.5 percent (total primary and secondary porosities).

Secondary porosity locally may constitute almost half of that total (estimated from the logs in zones where many fractures are present).

B) Winograd and Thordarson (1975):

Intracrystalline porosity of the carbonate rocks is extremely low (vugs as much as 0.4 inch in diameter were observed in some hand specimens, but no interconnected vuggy porosity was noted).

DF Balin 4/5/95

Character of lower carbonate aquifer based on cores, drilling records, geophysical logs:

Intercrystalline porosity and permeablility of cores from formations composing the lower carbonate aquifer are extremely low, as shown below:

	Range	Median	Mean
Total porosity (16 samples)	0.4-12.4	5.5	5.4
Effective porosity (25 samples)	0.0-9.0	1.1	2.3
Permeability (13 samples)	0.00002-0.1	.00008	.01

(Effective porosity = connected porosity; total porosity = sum of unconnected and connected porosity).

Drilling records do not indicate the penetration of any major caverns in the lower carbonate aquifer.

There is no evidence for stratigraphically-controlled regional solution of the carbonate rocks or for significant solution below the major Tertiary-pre-Tertiary unconformity => no evidence that sinkholes or karst topography developed on the carbonate rocks below the Tertiary-pre-Tertiary unconformity. Transmissibility of the carbonate aquifer beneath the Tertiary-pre-Tertiary unconformity is not above average.

In contrast to the many unconnected caverns of minor dimension seen in outcrop ot the NTS, Devils Hole and Gypsum Cave represent two major solution features developed within the carbonate aquifers.

Devils Hole => a water-filled, funnel-shaped cavern at Ash Meadows, about 23 miles southwest of Mercury => at the south end of a ridge composed of the Bonanza King Formation (appears to be structurally-controlled by a nearly vertical fault, which strikes about N40°E).

Gypsum Cave (a world-famous archeological site) — about 13 miles east-northeast of Las Vegas.
Formed in carbonate rocks of Permian age. Deposits of selenite crystals are abundant in one of its rooms (hence the name).

The carbonate rocks are highly fractured and locally are brecciated.

Strike and frequency of the faults and joints — vary considerably from area to area (Even within an area of a few square miles, the strike of the high-angle faults may differ from fault block to fault block).

Fracturing and brecciation is most intense where the carbonate rocks compose segments (klippen) of the upper plate of low-angle thrust faults (e.g., unnamed hills bordering Pahrump Valley on the NW).

Fine-grained carbonate rocks have greatest joint density of any studied (cites Barosh).

Also have landslide plates of carbonate rocks => may have above-average porosity and fracture transmissibility.

Drill stem and pumping tests yielded information that water-bearing fractures are sparse, but are open to depths of at least 1500 ft. beneath the top of the aquifer and up to 4200 ft. below land surface (no apparent decrease in fracture yield to this depth).

DF Balin 4/5/95

(NOTE: Does this mean that they are not open below 4200 ft., or just that they are open at least to that depth?)
Core examination suggests that the effective fracture porosity of the lower carbonate aquifer is probably a fraction of 1 percent.
Evidence that fault zones, rather than solution-widened joints, are locally the principal water-bearing fractures in the lower carbonate aquifer — suggested by pump tests of a couple of different wells.

2) References for amount of flow through the lower carbonate aquifer (quantity of water):
A) Dettinger 1989
Part of total ground-water income (recharge plus inflow) flows directly into the carbonate-rock aquifers and discharges at 1) regional springs, 2) by flowing out of the study area through carbonate rocks that extend into California, or 3) by leaking into basin-fill aquifers.
Large springs associated with the carbonate-rock aquifer — many with discharges >1000 gallons per minute.
About 130,000 acre-feet of water recharges to and discharges from aquifers of all types (carbonate and noncarbonate) in the central corridor each year. NOTE: Hard to picture this => any way to make an analogy?
Of that, about 77,000 acre-feet discharges each year directly from the carbonate-rock aquifers => nearly all this discharge occurs in Ash Meadows and at Muddy River Springs in Nevada and in Death Valley and vicinity in California.
Water that discharges today has spent thousands of years flowing through the aquifers.
Quantity of water in transit through the aquifers at present may be on the order of 800 million acre-feet.

Capacity of the carbonate-rock aquifers to transmit water ranges from low to very high, depending on location.
Wells drilled during the Air Force's MX Missile-Siting program during 1980-81 (NOTE AGAIN: outside area of interest but still informative as to the transmissivity of the carbonate-rock aquifers):
Transmissivity of MX wells in Coyote Spring Valley is extremely high (c. 200,000 ft^2 per day and high productivity [3400 gallons per minute pumped with only 12 feet of water-level decline (Ertec Western, Inc., 1981, p.51) => but most other wells drilled in carbonate rocks are much less productive.
Average aquifer properties => (e.g., Army Well 1 near Mercury) get 455 gallons per minute can be pumped for long periods of time with 85 feet of water-level decline (drawdown) in the well — transmissivity at this well estimated between 5000-11,000 ft^2 per day (cites Winograd and Thordarson, 1975, Table 3, well 67-68).

D.F. Balin 4/5/95

B) Winograd and Thordarson (1975):
Individual springs associated with valley-level carbonate rocks in study area yield as much as 2800 gpm.
The coefficient of transmissibility of the aquifer ranges from about 1000 to 900,000 gallons per day (gpd) per foot.

Ground water is also associated locally with alluvial fill and some volcanic rocks (predominantly welded tuffs) => connection between aquifers of different rock types.

1) References:
A) Winograd and Thordarson (1975)
Lower carbonate and valley-fill aquifers have the widest areal distribution => are the principal aquifers in the region.
Las Vegas Valley => only the valley-fill aquifers are presently tapped for water supply because of the great depth to the underlying carbonate rocks.
In parts of the NTS (where valley fill is unsaturated or absent) => lower carbonate aquifer provides the sole source of ground water.
Amargosa Desert — some irrigation wells tap both valley-fill and lower carbonate aquifers.

Structural relief on many of the hydrogeologic units => commonly ranges from 2,000 to 6,000 ft. within a few miles, and as much as 500 feet within 1000 feet.
Therefore, a fully-saturated unit at depths of several 1000 ft. below the structurally deepest part of an intermontane valley may be only partially saturated near the margins of that valley.
May cap a mesa rising 2,000 ft. above valley floor (unsaturated) or may be absent due to erosion.

Depth to water table => also markedly influences the saturated thickness of most of the Cenozoic aquifers and aquitards beneath valley floors.
Valleys with relatively shallow water tables (<500 ft.) => all the hydrogeologic units except the uppermost few 100 ft. of the valley-fill aquifer are usually saturated.
But in valleys with relatively deep water tables (500 to 2000 ft.), both the vertical disposition of rocks and depth to water table influence saturated extent => Commonly here Cenozoic units are unsaturated beneath valley margins and some units may be unsaturated even beneath structurally deepest part of valleys.

D.F. Balin 4/5/95

B) Dettinger (1989)

Sand-and-gravel aquifers that partly fill the basins of Nevada ("basin-fill aquifers") => are the sources of most of the ground water now used in the state.

Along its path from recharge to discharge, water may flow through basin-fill aquifers, carbonate-rock aquifers, or both. Also through Tertiary volcanic aquifers.

Water flows between aquifers to connect the ground-water systems in some places [e.g., Pahrump Valley (cites Harrill, 1986, p.27) and at Ash Meadows (cites Dudley and Larson, 1976, p.48)].

At Ash Meadows => direct connections between pumping from basin-fill aquifers and water-level declines in the carbonate rocks has been demonstrated => Withdrawals from irrigation wells near Devils Hole drew down water levels by more than a foot in the carbonate-rock aquifers between 1969-72 (Fig. 7 of this paper; Bateman et al., 1974; Dudley and Larson, 1976) => Water levels recovered slowly over a period of about 15 years after pumping ceased.

But around Muddy River Springs (outside area of interest) => varying levels of development of ground water from basin-fill aquifers over the last 20 years have resulted in minimal changes in water levels of the carbonate-rock aquifers.

=> So have to be assessed on a site-by-site basis.

D.F. Balin
4/5/95

April 24, 1995

****

Notes from earlier conversation with Larry McKague:

Said that at least in one locality, the lower clastic aquitard produces a lot of water => so where fractured, may not be much of an aquitard.

In contrast, the Eleana Formation (upper clastic aquitard) has a lot of shale => reacts more plastically to deformation so more likely to remain an aquitard.

Mentioned an area to SE of Funeral Mountains where there is evidence of water table being much higher previously => have a lot of tufa infilling fractures in one of the volcanic units (which one?) indicating that the water table was about 1000' (feet?) higher than present.

Info from earlier conversation with Brit Hill:

I was curious how feeders to craters (volcanic necks) might form barriers to ground water flow.

The volcanic centers shown on Frizzell and Shulters (1990) "Geo Map of the NTS" are the only volcanic centers in the area.

There are some basalt flows produced by dikes in the Skull Mountain area but these would not be of regional hydrologic significance.

Also with regard to the Greenwater Range => have about 25-30 vents producing volcanics of the Greenwater Range (centered along the range).

Greenwater => cinder cones

Overlain by 8-6 m.y. basalts.

Also in Greenwater Range area => have granites in c. 20 m.y. range => would also be flow barriers.

Note: <u>Area of steep hydraulic gradient</u> => <u>corresponds roughly with SE boundary of volcanic centers north of Yucca Mountain and NW of Shoshone Mountain</u> (Timber Mountain caldera) => <u>any relationship</u>?

D.F. Balin
4/24/95

April 25, 1995

There is a high gradient area west of Yucca Flat (east of the Eleana Range), passing NW of Syncline Ridge, NW of Shoshone Mountain, north of Yucca Mountain, extending possibly as far as the north side of Bare Mountain.

1) What evidence defines this gradient? Where are our control points?
A) Fridrich paper:
4 drill holes constrain the steep gradient zone under Yucca Mountain:
Define top of high gradient:
USW G-2
UE25-WT No. 6
(Both have water-table elevations of about 1030 m above sea level: 1029 m and 1035 m, respectively)
Define lower end of steep gradient:
USW G-1 (water table elevation of 775 m above sea level)
UE25-WT No. 16 (water table elevation of 738.2 m above sea level)
=> So approximately 300 m decline in water table elevation over 2 km distance (300 m/2000 m = 0.15 gradient)
Moderate gradient north of this feature: 0.015 (So one-tenth of steep gradient)
Very small gradient south of this feature: 0.0001 (So about one-thousandth of steep gradient)

See also:
B) See Winograd and Thordarson list
C) Information on ER12-1
See 1991 report given to me by Larry McKague: "Preliminary geology and drill hole data report...." by Drellack et al. (Raytheon Services Nevada) Note: He doesn't think there has been a subsequent report.
D) Well UE-25p #1 (adjacent to Yucca Mountain)
(Info sources: Fridrich paper; p.82 from USGS Open-File Report 88-468: "Water levels in periodically measured wells in the Yucca Mountain area, Nevada, 1981-87). Others?
E) Cow Camp Road Well BH-2
See Desert Research Institute report: "Carbonate aquifer study: Black Hills Drilling Cow Camp Road Well BH-2" (May 1990)
F) Well DR-1
See Desert Research Institute report: "Carbonate aquifer study: Desert Range Drilling Well DR-1" (May 1990)
G) Additional well data (water wells, emplacement holes, oil wells)
Maps generated by Sid Jones showing well locations according to hydrologic basins.
H) Where is our source of information concerning new wells currently being drilled?
2) Are we able to identify the lithologic units that are associated with the water levels? (see same sources given above)
3) Perched ground water tables along with deeper confined flow?

D.F. Balin
4/25/95

There are two other regional-scale domains of large hydraulic gradient in this area:
One separates Death Valley from Amargosa Valley.
Another along northwest margin of the Spring Mountains.
1) These features are mentioned in Fridrich paper, but what are the control points? (not given by Fridrich)
2) How steep are the gradients?
A) From Fridrich paper (Fig. 2), I calculated a gradient of 0.04 for the gradient along the northwest margin of the Spring Mountains at steepest area (200 m change in water-table elevation over about a 5 km distance => 200 m/5000 m = 0.04)
From same figure, I calculated a gradient of 0.05 for the gradient along the northeast margin of Death Valley at the steepest area (600 m change in water-table elevation over a distance of about 12 km => 600 m/12000 m = 0.05)
=> So the high-gradient zone under Yucca Mountain is about 3 times as steep as these other zones of high gradient.

There is a central domain of very low gradient (0.0001) bounded by the steep gradient zone that underlies Yucca Mountain, a steep-gradient zone along the northwest margin of the Spring Mountains, and moderately low-gradient zone along what appears to be the western margin of the Desert Range.
1) References for this zone of very low gradient?
i) Fridrich paper: Fig. 2, p.137:
Fridrich gives a figure of 0.0001 for the gradient of the "central domain of very low hydraulic gradient".
Fig. 2 shows the central domain to be bounded on the east by a moderately low-gradient zone that appears to correspond with the western margin of the Desert Range => I calculated a gradient of about 0.0067 for this zone => 200 m/30 km => 200 m/30,000 m = 0.0067)
2) How well established is this zone and its boundaries? Any conflicting evidence?

Spring Mountains are a recharge area (outcrop of lower carbonate aquifer).
1) References?
A) Fridrich paper: No direct mention but Fig. 2 shows water-table elevation contours partially wrapping around the Spring Mountains.
B) Dettinger 1989
At this latitude => water in the corridor derived mainly from recharge from snowmelt in the Spring Mountains => moves radially away from the high-altitude areas of the Spring Mountains to discharge near Tecopa, in Pahrump Valley, at Indian Springs, and (in the past) at Las Vegas Springs (cites Hershey et al., 1987)

D.F. Balin
4/25/95

What geological features control the distribution of these flow paths?

Central domain of very low hydraulic gradient in area **not** associated with outcrops of clastic confining units (neither upper nor lower clastic aquitards outcrop in this area) but **is** associated regionally with area underlain by highly transmissive Paleozoic carbonate aquifer.

Fridrich paper, Fig. 2, p.137: Shows central domain in area not associated with outcrops of clastic confining units or with inferred distribution of clastic confining units in the subsurface at or near the water table (except some infringement of subsurface clastic distribution along northeastern margin => appears to correspond roughly with the northernmost Pintwater Range in the area where it intersects the northern Desert Range)

Abstract states association with Paleozoic carbonate aquifer.

Area of moderate gradient (north of the high-gradient zone underlying Yucca Mountain) is underlain by a thick section of Tertiary volcanic rocks.

Fridrich et al. (1994)

Areas of steep hydraulic gradient (one underlying Yucca Mountain, NW margin of Spring Mountains, and Death Valley/Amargosa Valley margin) have some association with outcrops of clastic confining units (either upper or lower clastic aquitards) or with inferred distribution of clastic confining units in the subsurface at or near the water table.

Fridrich paper, Fig. 2, p.137: Shows these domains associated with outcrops of clastic confining units or with inferred distribution of clastic confining units in the subsurface at or near the water table (except some infringement of subsurface clastic distribution along northeastern margin => appears to correspond roughly with the northernmost Pintwater Range in the area where it intersects the northern Desert Range)

D.F. Balin
4/25/95

June 19, 1995

What do we know about the stratigraphy of the lower carbonate aquifer?

1) Stratigraphic sequence

A) Winograd and Thordarson: See comments included in Jim Cole's stratigraphic units. Age of units included in the lower carbonate aquifer (p. C11 of their publication) ranges from Middle Cambrian to Upper Devonian => concurs with Cole, although Cole not as specific with upper, middle, or lower.

B) Jim Cole (unpublished info; "Characteristics of the pre-Tertiary rock units at the Nevada Test Site and vicinity; revision of 3 May, 1995) => See this paper for full info (brief summation below).

Jim Cole simply indicates the age by symbol => Where I have been more specific as to Upper, Middle, or Lower, this comes from Winograd and Thordarson.

Has irregular unconformity between the upper carbonate aquifer and the overlying Eleana Fm. (upper clastic aquitard)

Formations as listed (presuming from youngest to oldest here => NOTE: Are any of these coeval? What is their specific distribution?):

Guilmette Fm (Dev)-- 1400 ft (c. 425 m) (Says upper part at Shoshone Mtn and Mine Mtn shows karstic dissolution breccias beneath lowermost Eleana Fm.)

(= Devils Gate Limestone? => Upper Dev, basal may include Middle Dev -- of Winograd and Thordarson)

NOTE: But Center chart lists Guilmette Fm as Middle Dev, so maybe Guilmette and Devils Gate are distinct formations? See section on stratigraphy given on chart produced by Center below. Need other ref to straighten out or talk to Jim Cole.

NOTE: Tschanz & Pampeyan (1970, pp. 6, 8, 9) show Guilmette Fm of Lincoln County as Middle to Upper Devonian. Their Fig. 3 shows the Devils Gate Limestone of the Nevada Test Site correlating with the Guilmette Fm of the Pahranagat Range (nothing above Pogonip Group shown in Groom Range). So do appear to correlate here.

Simonson Dolomite (Dev): (Middle Dev indicated by Maldonado & Schmidt)

(= Nevada Formation? (Middle Dev)-- of Winograd and Thordarson;

NOTE: This does appear to be the correlation => Tschanz & Pampeyan (1970, pp. 8, 9) show the "Nevada Fm." at NTS correlating with the Simonson Dolomite of the Pahranagat Range.)

Upper unit -- 950 ft (c. 290 m)

Cherty argillaceous unit -- 200 ft (c. 60 m)

Sevy Dolomite (Dev/Sil)-- 750 to 900 ft (c. 230 to 275 m)

(included as part of "undifferentiated Devonian and Silurian"? -- of Winograd and Thordarson)

*** Minor unconformity ***

Laketown Dolomite (Sil)-- 530 to 820 ft (c. 160 to 250 m)

(included as part of "undifferentiated Devonian and Silurian"? -- of Winograd and Thordarson)

*** Minor unconformity ***

Ely Springs Dolomite (Upper Ord)-- 280 to 430 ft (c. 85 to 130 m)

*** Minor unconformity ***

D.F. Balin
6/19/95

Eureka Quartzite (Middle Ord) -- 320 to 400 ft (c. 100 m to 120 m) (note this is a minor clastic unit contained in the lower carbonate aquifer)
*** Minor unconformity ***
Pogonip Group (Lower to Middle Ord):
(NOTE: This group seems to be made up of members (not stratigraphically correct) => Checked Winograd and Thordarson, p. C11, and they have the Pogonip Group consisting (from top to base) of the Antelope Valley Limestone (1530 ft, c. 465 m), Ninemile Fm. (335 ft, c.100 m; note this is a minor clastic unit contained in the lower carbonate aquifer), and the Goodwin Limestone (>900 ft = >275 m) -- Eureka Quartzite overlies the Antelope Valley (but is not part of the Pogonip Group) -- W & T don't have any reference to the following members of Cole.
Aysees Peak Member -- 750 to 900 ft (c. 230 to 275 m)
Ranger Mountain Member -- 200 ft (c. 60 m)
Paiute Ridge Member -- 400-700 ft (c. 120 to 215 m)
Goodwin Limestone (Lower Ord)-- 900 ft (c. 275 m)
Nopah Fm (Upper Camb):
Smoky Member -- 670 ft (c. 205 m)
Halfpint Member -- 1060 ft (c.325 m)
Dunderberg Shale Member -- 150 ft (c. 45 m) (note this is a minor clastic unit
contained in the lower carbonate aquifer)
Bonanza King Fm (Middle Camb):
(= Highland Peak Limestone in the Groom Range and Pahranagat Range - ref is Tschanz & Pampeyan 1970)
Banded Mountain Member -- 2200 to 2600 ft (c. 670 to 790 m)
Papoose Lake Member -- 1400 to 2100 ft (c. 425 to 640 m)
Carrara Fm (Middle Camb):
Units D-E-G and Jangle Limestone Member -- 950 ft (c.290 m)
NOTE: I have not included Units A-B or C in the lower carbonate aquifer because the lower part of the Carrara Fm. is considered part of the lower clastic aquitard. From the description of these informal divisions of the Carrara Fm., these other units are mainly clastic. (Note: Tschanz & Pampeyan (1970, pp. 8, 9) show the part of the Carrara older than the Jangle Limestone Member (so the part included in the lower clastic aquitard) as equivalent to the Pioche Shale of the Groom Range and Mormon Mountains area. They also show the part of the Carrara that includes the Jangle Limestone Member and younger Carrara Fm rocks (so the part included in the lower carbonate aquifer) as equivalent to the Chisholm Shale and Lyndon Limestone of the Groom Range and Mormon Mountains area.)

Cumulative thickness (NOTE: Assuming these units are sequential and not lateral equivalents):
Minimum thickness: 13,110 ft (3996 m)
Maximum thickness: 15,330 ft (4673 m)

D.F. Balin
6/19/95

C) Center info: "Pre-Cenozoic stratigraphic and hydrogeologic units, Yucca Mountain region, Nevada":
NOTE: Says modified from Winograd aned Thordarson, 1975, but significant differences => some different units (bold print) altogether from Winograd and Thordarson, as well as different from Jim Cole => only a slightly different area geographically. See chart for maximum thicknesses and other info on ages and lithology.
From "youngest" to "oldest" (just how they're stacked in the column) =>
Monte Cristo Limestone (Mississippian; underlying Eleana and above the Devils Gate Limestone)
NOTE: Winograd & Thordarson and Cole did not have any units in the lower carbonate aquifer with a Mississippian age. The Monte Cristo Lmst is the time-equivalent of the Eleana Fm., and Winograd & Thordarson (p. C9) state that it and "part of Bird Spring Fm of the Spring Mtns, are tentatively considered representative of time-equivalent (carbonate) rocks in the Spotted Range and Indian Springs Valley". So Eleana Fm. has shaled out eastwards and been replaced by these carbonate units (=> See section on the upper clastic aquitard for more info).
Still not sure of distribution of Monte Cristo Limestone => Tschanz & Pampeyan 1970 p. 8,9, show the Monte Cristo Limestone underlying the Bird Spring Formation in the Mormon Mountains area. They show it correlating with an "Unnamed Limestone" underlying the Chainman Shale in South Meadow Valley Mountains and in the Pahranagat Range.
Devils Gate Limestone
Guilmette Formation
NOTE: They then have the Devils Gate Limestone above the Guilmette Fm (so are they different formations or is the Guilmette the new name of the Devils Gate Limestone as I thought previously?)
Sultan Limestone (NOTE: Shown in strat chart on p.41 of Tschanz & Pampeyan 1970 -- shown as name used in northern and southern Clark County by Longwell et al. 1965. Correlates with the Simonson Dolomite (= c. Nevada Fm), Guilmette Fm. (= c. Devils Gate Limestone), and lower part of the Pilot Shale -- so very inclusive formation! Overlain by the Monte Cristo Limestone.)
Nevada Formation
"Undifferentiated Devonian and Silurian: Simonson, Sevy, **Hidden Valley**, **Spotted Range**, Laketown, **Lone Mountain** and others"
NOTE: I thought that the Simonson Dolomite might be the new name for the Nevada Formation but they have given both. Need to sort this out. Also need to get this "undifferentiated" stratigraphy straightened out => where are these other units distributed and where are they sequentially?
NOTE: Tschanz & Pampeyan sort out a lot of this in their strat columns and text -- p.41 shows the "Nevada Fm" as formerly used at NTS correlates with the Simonson Dolomite and the uppermost part of the Sevy Dolomite, although their chart on p.8 shows it wholly correlative with the Simonson Dolomite only). Also from Cole's symbols, the Simonson Dolomite is Devonian, the Sevy

D.F. Balin
6/19/95

Dolomite is "DSs" so Devonian/Silurian, and the Laketown Dolomite is Silurian.

The Lone Mountain Dolomite appears to be a rather restricted name. In Tschanz & Pampeyan (p.31), says that the "Lone Mountain Dolomite in Clark County, as mapped by C.R. Longwell 30 years ago, includes the Sevy Dolomite of Early Devonian Age as we mapped it (Cole gives it as Dev/Sil), but excludes the lower part of Laketown Dolomite. The Lone Mountain Dolomite in the region surrounding Eureka, Nevada (cites Nolan et al. 1956, p.39) is only partly equivalent to the Laketown Dolomite; an exact correlation cannot be made." So it appears to correlate roughly with the Sevy Dolomite and part of the Laketown Dolomite. Strat chart on p. 41 of Tschanz & Pampeyan shows a correlation with the Laketown Dolomite and not the Sevy, so a little ambiguous.

The Hidden Valley Dolomite is a name used in strat sections shown for the Quartz Spring area and the Darwin quadrangle, both of California (ref Tchanz & Pampeyan 1970, p. 31, 41). It correlates with both the Sevy Dolomite and Laketown Dolomite.

Ely Springs Dolomite

Eureka Quartzite

Pogonip Group (no additional subdivisions; they haven't listed the Goodwin Limestone so I suppose they are including it in the Pogonip Group like Winograd and Thordarson)

Nopah Formation

Highland Peak Formation (NOTE: Highland Peak Limestone in the Groom Range and Pahranagat Range = the Bonanza King Fm. (ref is Tschanz & Pampeyan 1970). So this is out of order and should be shown as the stratigraphic equivalent of the Bonanza King.

Emigrant Formation (NOTE: I see a reference for the Emigrant Springs Limestone in Tschanz & Pampeyan (1970, p.21) although it is included as part of the Cambrian section above the Highland Peak Formation (described in the Egan Range of northern Lincoln County). Says the Emigrant Springs Limestone is overlain by the Dunderberg Shale -- now a member of the Nopah Fm. -- so if the Highland Peak Fm is put into its correct strat position as equivalent of the Bonanza King Fm., then the position of the "Emigrant Fm" (sic) would seem correct.)

Bonanza King Formation

Upper Carrara Formation

D.A. Balin
6/19/95

2) Thickness of lower carbonate aquifer:

A) Dettinger (1989):

Carbonate rocks of southern Nevada => cumulatively as much as 40,000 feet (about 12,000 meters) thick on the continental shelf off the ancestral west coast of North America between about 570-280 million years ago (west coast of the continent during that time was in present-day Utah).

NOTE: 280 m.y. is into the Lower Permian => so must be including the Tippipah Limestone (localized aquifer) and Eleana Formation (aquitard => not a carbonate; only locally significant though => carbs deposited to east). Also lowermost Cambrian, so some noncarbonates there also => So I doubt the Paleozoic carbonate aquifer sediments are this thick. These dates seem off.

The carbonate rocks were deposited on even older, noncarbonate sediments and crystalline basement rocks.

Within carbonate-rock corridor, the thickness of the carbonate rocks was reduced from c.40,000 feet (about 12,000 m) to between 3000 and 19,000 feet (about 900 and 5800 meters) due to deformation (averaging about 12,000 feet = c.3600 m).

NOTE: How do they derive the 40,000 feet of original thickness?

B) Nevada Test Site and vicinity:

a) Jim Cole (unpublished info; "Characteristics of the pre-Tertiary rock units at the Nevada Test Site and vicinity: revision of 3 May, 1995):

Cumulative thickness (NOTE: Assuming these units are sequential and not lateral equivalents):

Minimum thickness: 13,110 ft (3996 m)

Maximum thickness: 15,330 ft (4673 m)

(Note: For more detail re: thickness of individual formations, see section above)

b) Winograd and Thordarson:

=> Aggregate about 15,000' in thickness (but as a result of erosion of the miogeosynclinal rocks, is rarely present in any one location). Comprises carbonate rocks of Middle Cambrian through Devonian age (ie., all the formations from the upper half of the Carrara Fm through the Devils Gate Limestone)

Saturated thickness of the lower carbonate aquifer: from a few 100 ft. to several thousand feet => usually several thousand feet of aquifer in zone of saturation throughout study area (completely unsaturated or eroded only in vicinity of outcrops or buried structural highs of pre-Middle Cambrian clastic strata).

D.A. Balin
6/19/95

3) Where is the lower carbonate aquifer missing on account of erosion?

4) Where is the lower carbonate aquifer isolated into blocks? (so not part of regional aquifer)
A) Dettinger 1989
Outside of "corridor" => the carbonate rocks are present mainly in isolated blocks that form aquifers of limited extent, recharged mainly by local precipitation.
East and west of the central corridor are blocks of carbonate rocks (west of Yucca Mountain and underlying the Mormon Mountains) that are thick but largely isolated from carbonate-rock aquifers in other areas by noncarbonate rocks of low transmissivity (Wernicke et al., 1985, Fig.15; Blank, 1988; Carr, 1988; Hamilton, 1988, p.57,61,79; Scott, 1988; Wernicke and Axen, 1988b, Fig.2) => these blocks become much thinner north and south of the A-A' cross-section (shown in paper on p.14, 15) and do not receive regional inflow.
B) Snow refs

5) What facies changes are evident to the north, east, south, and west?
A) Dettinger 1989
a) Natural transition exists between: i) areas in southeasternmost Nevada where carbonate rocks commonly intermingle with other rocks containing thick or numerous layers of salts (evaporite minerals such as gypsum and halite).
Eastward transition to the evaporite-bearing rocks => these are younger than most of the carbonate rocks and older than the volcanic rocks and basin-fill aquifers (Longwell et al., 1965, p.38; Tschanz and Pampeyan, 1970, p. 60-63).
NOTE: So not really a contemporaneous facies change.
Complex geologic history has placed these younger rocks in complicated and unpredictable juxtuposition with the carbonate rocks.
ii) areas elsewhere in southern Nevada where these other rocks are nearly absent
b) Carbonate rocks under Las Vegas Valley believed to thin abruptly to the east toward Lake Mead (cites Smith et al., 1987, p.38).

D. L. Balin
6/19/95

August 7, 1995

What do we know about the stratigraphy of the rest of the geologic sequence?
1) Lower clastic aquitard
A) Sequence and thickness:
a) Winograd and Thordarson:
NTS area: 10,000' thick (although not present everywhere due to faulting, folding, erosion) => Precambrian to Middle Cambrian strata -- mainly quartzite and siltstone.
Older to younger: Johnnie Fm., Stirling Quartzite, Wood Canyon Fm., Zabriskie Quartzite, and lower half of Carrara Fm.
Before the first deformation of the region (late Mz orogeny), the Precambrian and Lower Cambrian clastic rocks were buried to depths of at least 15,000' in the eastern half of the area and about 27,000' in the western half =>
Today these rocks exposed in several areas => form bulk of northwest one-third of the Spring Mountains, a significant part of the Groom and Desert Ranges, and the bulk of the Funeral Mountains => distribution is a function of geologic structure and depth of erosion => exercises significant control over the regional movement of ground water.

B) Hydrologic characteristics:
a) Winograd and Thordarson:
Plate 1 => shows outcrop pattern and inferred distribution in zone of saturation.
Some similarities to lower carbonate aquifer => negligible interstitial porosity, highly fractured and locally brecciated => secondary porosity occurs along joints in the quartzitic rocks and more rarely in sandstone, shale, and siltstone (all secondary porosity probably due to weathering).
Differs from carbonate rocks in two important ways: 1) Secondary porosity rarely develops along bedding planes (low solubility); 2) siltstone, shale, and sandstone exhibit tight folding, slaty cleavage and shearing, whereas carbonate rocks and quartzite tend to form broad folds due to differences in strength (plastic deformation vs. brittle).
Plastic deformation => fractures sealed by same process that formed them.
Wherever quartzites interbedded with argillaceous rocks (e.g., parts of the Stirling Quartzite and Wood Canyon Fm.), open fractures in the quartzites tend to be isolated or even sealed by plastic deformation of the weaker strata. (However, where the Zabriskie and Stirling contain few or no micaceous partings or argillaceous beds => interconnected secondary fracture porosity is possible => locally may be aquifers.)
Also, in subsurface, may become tightly sealed by selvage minerals or by quartz or calcite.
Gross fracture transmissibility of lower carbonate aquifer vs. lower clastic aquitard =>
Discharge from carbonate rocks at valley level or from valley fill immediately adjacent to carbonate rocks or outcrops => Contrast with no major springs from clastic rocks or valley fill adjacent to clastic rocks.

D. L. Balin
8/7/95

Individual springs associated with valley-level carbonate rocks in study area yield as much as 2800 gpm, whereas springs associated with clastic strata in vicinity of study area yield less than 25 gpm and are restricted to NW Spring Mountains.

Highest reported yield of a spring associated with clastic strata in vicinity of study area is 150 gpm at Resting Spring, Inyo Co., California (c. 10 miles south of area of Fig.1) => Interpreted as quartzite ridge barrier forcing water out of valley fill, rather than as source of water).

Apparent absence of high- or even moderate-yield springs in the clastic miogeosynclinal rocks in Nevada reflects absence of regionally-integrated fracture transmissibility =>

Due to: 1) low susceptibility to solution; 2) tendency to deform plastically; 3) tendency of micaceous partings and argillaceous laminae to seal fractures in the brittle quartzite rocks.

Therefore, regional movement of water through the clastic aquitard probably governed by the very low interstitial permeability rather than by fracture transmissibility.

2) Upper clastic aquitard (Eleana vs. Chainman)

A) Distinction between Eleana Fm. and Chainman Shale

a) Cashman and Trexler

b) Tschanz and Pampeyan 1970:

(p.48): Says Chainman Shale originally defined by Spencer (1917, p.26) in the Ely district. Says it is widely recognized in eastern Nevada -- thickest and best-exposed in the parts of Lincoln County north and west of Hwy. 93 -- where thick and distinct, was mapped separately from the Scotty Wash Quartzite => these units are too thin to distinguish in the Pahranagat Range and in the Meadow Valley and Delamar Mountains => Complete sections are exposed on Dutch John and Grassy Mounains in the Egan, Timpahute, and Pahranagat Ranges and in the Meadow Valley and Delamar Mountains => also exposed in the Fairview, Golden Gate and Spotted Ranges; in the Worthington Mountains; and on Chert Ridge.

Typically forms valleys so generally poorly-exposed. Most characteristic part is a fissile black carbonaceous shale which makes up the entire formation at its type locality near Ely => this "black shale facies" forms the bulk of the Chainman Shale over much of Linclon County.

Recognize 3 informal members:

lower: The siltstone facies is a fairly resistant calcareous siltstone or silty limestone that weathers brown but is commonly black on a fresh surface (about 140 feet thick on Grassy Mountain and about 200 feet thick in the Pahranagat Range.

middle: Black shale (is a varecolored shale in the Spotted Range.

upper: In East Pahranagat Range contains 7 layers of limestone (10-20 ft thick) and one thin quartzite layer, layers interbedded with an olive gray shale.

B) Lateral extent (including facies changes and thickness changes)

a) Cashman and Trexler

D.F. Balin 8/7/95

b) Winograd and Thordarson:

Eleana Fm. --Late Devonian to Late Mississippian

Devonian and Mississippian rocks of Yucca Flat area => argillite and quartzite (c. 8000')

W. Yucca Flat, Jackass Flats, and areas W and NW => composed mainly of clastics (quartzite, siltstone, argillite, conglomerate) up to 8000' (Note: => they lump everything into Eleana Fm (prior to distinction of Chainman Shale by Cashman & Trexler).

However, in the <u>Spotted Range and Indian Springs Valley</u> => <u>rocks of equivalent age are mainly carbonate</u> (aggregate about 1000' in thickness) => The predominantly carbonate Monte Cristo Lmst, and part of Bird Spring Fm of the Spring Mtns, are tentatively considered representative of time-equivalent rocks in the Spotted Range and Indian Springs Valley (<u>Note</u>: See also section on "upper carbonate aquifer" below).

States that "preliminary work by Poole et al. 1961 indicated that the southeastward transition from clastic to carbonate was probably gradational, but that postdepositional thrust or strike-slip faulting may have obscured the transition.

Plate 1 => shows outcrop pattern and probable subsurface distribution.

States Eleana Fm. only important under western Yucca Flat and northern Jackass Flats.

Elsewhere at NTS, Eleana Fm. has been removed by erosion, occurs 100s of meters above the regional water table, or is represented by equivalent rocks of carbonate lithology.

Similar characterisics as lower clastic aquitard.

Gross fracture transmissibility probably <500 gpd per foot (NOTE: This still is substantially higher than the lower clastic aquifer which is associated with springs yielding only c.25 gpd in NW Spring Mountains.) -- Similarly, regional ground water movement through the upper clastic aquitard probably controlled by interstitial permeability rather than fracture transmissibility.

c) Tschanz and Pampeyan 1970: (Note: Has a lot of additional info pp.48-49):

(p.48): Says a major facies change in the Chainman Shale occurs in the Meadow Valley Mountains where the thick black shale thins drastically in a few miles southeastward and interfingers with thin reddish-weathering shaly limestone and limestone conglomerate that resemble the basal (Indian Spring) member of Longwell & Dunbar (1936) of the Bird Spring Formation. An even more pronounced facies change occurs between the Spotted Range and the Nevada Test Site. Thrust faults or unconformities may be responsible for these apparent facies changes. A probable unconformity occurs at the top of the beds, which we correlate with the Chainman Shale in the Arrow Canyon Range and Meadow Valley Mountains, Clark County (cites Longwell et al., 1965).

(p.49): Thickness of the Chainman Shale in Lincoln County ranges from 200 to 1000 ft. In the Meadow Valley Mountains, the Chainman thins rapidly southward and eastward from 932 ft on the west side to about 200 ft on the

D.F. Balin 8/7/95

east side, the same in the Arrow Canyon Range, Clark County. It is between 900 and 1000 ft thick in the southern Egan Range and about 1000 ft thick on Grassy Mountain and in the Fairview and Spotted Ranges. The exposed section of the Chainman Shale and Scotty Wash Quartzite in the Pahranagat Range is about 800 ft, but the total thickness probably approaches 1000 ft. The equivalent rocks at the base of the Bird Spring Formation are about 100 ft thick in the Spring Mountains of Clark County (cites Rich, 1960).

(p.49): Age given as Late Mississippian (Chester).

Tentatively correlated with the upper part of the Eleana Formation in the Nevada Test Site and at least part of it is equivalent to the basal member of the Bird Spring Formation of Longwell & Dunbar (1936, p.1203) in Clark County.

d) Cole et al. 1989:

(Fig.3; strat column): caption states that "formation thicknesses are reasonably constant in the area (vicinity of Yucca Flat), except for extreme variablility within the Eleana Formation."

E) Other units:

a) Pilot Shale

i) Tschanz & Pampeyan (p.42): Says it is widely recognized throughout eastern Nevada. Includes all the slope-forming rocks between the cliff-forming limestone in the Guilmette Formation and the overlying unnamed Mississippian limestone above. Crops out widely in the northern and western parts of Lincoln County and in the Meadow Valley Mountains. Complete sections are exposed in the southern Egan, southern Schell Creek, Seaman, Golden Gate, Pahranagat, Timpahute, Desert, and Spotted Ranges; on Dutch John Mountain; and in the Worthington and Meadow Valley Mountains.

Says <u>in Lincoln County, the Pilot Shale contains comparatively little shale and is composed mainly of thin-bedded silty limestone</u>. => Note: <u>So generally in Lincoln County, it wouldn't be an effective aquitard. Could include this unit here as part of the carbonate aquifer</u>. (States however that a layer of dark gray carbonaceous shale that contains limestone concretions occurs in the upper part of the Pilot Shale in the Pahranagat Range => Also partial measured section shown on p.43 shows mostly shale, chert, quartzite, and siltstone => So sounds like an aquitard in the Pahranagat area. Strat column on p.8 shows that the overlying "Unnamed Limestone" of Mississippian age and the Chainman Shale which in turn overlies the unnamed limestone are both correlative with the Eleana Formation.)

(p.43) Thickness about 250 feet in the Pahranagat Range and about 350-450 ft in the East Pahranagat Range.

Says 4 Mississippian formations are shown on the geologic map of Lincoln County. The map units are: 1) unnamed Mississippian limestone; 2) Monte Cristo Limestone; 3) Chainman Shale; and 4) Scotty Wash Quartzite. (Where last 2 were too thin to show separately, they were combined on the map.)

D.F. Balin
8/7/95

3) Upper carbonate aquifer (Tippipah Limestone, Bird Spring Formation?)

A) Which formations included?

a) Winograd and Thordarson:

NTS area: Pennsylvanian and Permian => mainly limestone

Tippipah Limestone of Pennsylvanian and Permian age

B) How does the stratigraphic sequence vary from area to area?

C) Variations in thickness?

a) Winograd and Thordarson:

NTS area: Pennsylvanian and Permian (Tippipah Limestone) -- 3600 ft. thick, but eroded from most of study area.

Saturated only beneath western one-third of Yucca Flat at altitudes <3800 ft. => elsewhere in study area these rocks are absent beneath valleys or occur in ridges well above the regional water table.

Western Yucca Flat -- upper carbonate aquifer separated from lower carbonate aquifer by as much as 8000 ft. of upper clastic aquitard (Eleana Fm.) (NOTE: This may also include Chainman Shale since this formation wasn't distinguished when this paper was written).

D) Where does it merge with the lower carbonate aquifer? (would correspond with absence of upper clastic aquitard)

a) Winograd and Thordarson:

Indian Springs village in southern Indian Springs Valley => carbonate rocks equivalent in part to Tippipah Limestone occur within zone of saturation (Bird Spring Fm.) => tentatively considered part of lower carbonate aquifer here because strata equivalent to the Eleana Fm. are very thin here and mainly carbonate lithology.

Term "upper carbonate aquifer" restricted to Yucca Flat.

E) Hydraulic character

a) Winograd and Thordarson:

No hydraulic tests of this aquifer, but outcrop examination and exploration by shallow core holes indicate that its water-bearing character is probably similar to that described for the lower carbonate aquifer.

Upper carbonate aquifer (though of limited potential value as a source of water supply for part of western Yucca Flat) => <u>does not play a role in the regional movement of ground water beneath NTS because it is restricted to small areas</u>.

4) Volcanic sequence

A) Sawyer et al.

B) Winograd and Thordarson:

Tertiary rocks => largely Miocene and Pliocene, some Oligocene.

Cenozoic Fms. shown in Table 1 => representative only of Yucca Flat, Frenchman Flat, and Jackass Flats (Cenozoic volcanic formations vary widely) => not representative of the Pahute Mesa and Timber Mountain areas of the NTS.

Several general characteristics of the Cenozoic pyroclastic rocks, lava flows, and associated sediments are summarized as follows:

D.F. Balin
8/7/95

1) Areal extent, thickness, and physical properties of each of the Cenzoic volcanic formations vary widely (function of their modes of emplacement, prevailing wind directions, and the topographic relief at the time of their extrusion.
2) Tertiary rocks generally overlie Precambrian and Pz rocks with angular unconformity. There is no evidence of the development of karst terrane on the carbonate rocks beneath the unconformity.
3) The oldest Tertiary rocks were deposited on a paleotopographic surface of moderate relief developed on Precambrian and Pz strata. Erosion surface had a maximum relief of about 2000'. By partly filling the topographic lows, the oldest Tertiary rocks reduced the relief. By late Miocene, the relief was considerably reduced (evidenced by the widespread distribution of ash flows of the Paintbrush Tuff).
4) The Miocene and Oligocene rocks up through the basal Wahmonie Formation are of both pyroclastic and sedimentary origin => consist mainly of nonwelded ash-flow tuff, ash-fall tuff, tuff breccia, tuffaceous sandstone and siltstone, claystone, and freshwater limestone (lava and welded ash-flow tuff are of minor importance in the area considered).
The Pliocene and Miocene rocks above the Wahmonie Fm., in contrast, are mainly welded ash-flow tuffs (nonwelded ash-flow tuff, ash-fall tuff, and tuffaceous sandstone are relatively minor in these younger rocks).
5) Bulk of the Miocene and Oligocene sed rocks appears to be restricted to the Frenchman Flat, eastern Jackass Flats, Rock Valley, and Mercury Valley => these strata make up the Rocks of Pavits Spring and the Horse Spring Formation, also are present in the Salyer Formation.
(Miocene and Oligocene sed rocks are of minor occurrence in Yucca Flat and western Jackass Flats — although the entire section of Tertiary strata in the latter valley has yet to be explored by drilling.)
6) Miocene and Oligocene rhyolitic tuffaceous rocks up through the Wahmonie Fm. => generally massively altered to zeolite (clinoptilolite, mordenite, and analcime) or to clay minerals.
Above the Wahmonie Fm. => the Miocene and Pliocene rhyolitic tuffs are either glassy or have devitrified to cristobalite or feldspar (but are less commonly altered to zeolite or clay).

a) Aquifers:
(p. C10): Looks like everything younger than the Wahmonie Fm. is considered aquifer => (from base to top) have bedded-tuff aquifer, welded-tuff aquifer, lava-flow aquifer (lava-flow aquifer restricted to Jackass Flats area), and valley-fill aquifer.
Welded-tuff aquifer -- Includes Topopah Spring and Tiva Canyon Members of Paintbrush Tuff and Ranier Mesa and Ammonia Tanks Members of the Timber Mtn. Tuff
(NOTE: Check these terms and see if they agree with new terminology of Sawyer).
Only the Topopah Spring Member has been tapped by wells within the zone of saturation => As of December 1966, it was the sole aquifer used for water

D.F. Balin 8/7/95

supply in Jackass Flats. (Although occurs throughout NTS, potential source of water only in structurally deepest part of the intermontane basins where it occurs within zone of saturation.)
b) Aquitards:
i) Tuff aquitard -- Wahmonie Fm. and older -- separates Cenozoic from Paleozoic aquifers in Yucca Flat, Frenchman Flat, Jackass Flats, and other valleys.
One feature in common => matrices of zeolite or clay minerals.
As much as 2000 ft. thick in central Yucca Flat where it consists of the Indian Trail Fm. (Note: Check terminology with Sawyer)
>2,000 ft. thick in western Jackass Flats (rhyolite flows and tuffaceous beds of Calico Hills).
Frenchman Flat -- may aggregate >4,500 ft. thick (mainly Wahmonie Fm., Salyer Fm., and Rocks of Pavits Spring) (Note: Check terminology with Sawyer).
Rock Valley and Mercury Valley => aquitard consists of Rocks of Pavits Spring and the Horse Spring Fm. (Note: Check terminology with Sawyer).

ii) Lava-flow aquitard (younger than tuff aquitard) -- restricted to small area in central part of NTS.
Consist of dacitic lava flows of the Wahmonie Fm. => As much as 4,000 ft. aggregate thickness.
Occur mainly NW of Cane Spring Fault zone.
Perched water in these rocks.

5) Alluvial fill
A) Winograd and Thordarson:
Quaternary => generally < 2000' (valley fill and minor basalt flows)
Major aquifer used for water supply in Frenchman Flat, western Emigrant Valley, and Amargosa Desert => only locally saturated or unsaturated in Yucca Flat, western Jackass Flats, and Mercury Valley.
At least 1870 ft. thick under central Yucca Flat.
At least 1200 ft. under central Frenchman Flat.
It is 1040 ft. thick in central Jackass Flats and unsaturated.
=> Because of the great depth to water in these valleys (690 to 1915 ft.), the saturated thickness of the valley fill is but a fraction of the thickness cited.
B) Dettinger 1989:
Thickness of basin fill overlying carbonate rocks =>
<500 feet in Hidden Valley (east of southern part of Sheep Range)
c. 1000 feet in Coyote Spring Valley (east of Tikaboo Valley and northern Sheep Range)
c. 2000-3000 feet in northwestern Las Vegas Valley (south of the Sheep Range and east of the Spring Mountains)
>6000 feet in southern Tikaboo Valley

D.F. Balin 8/7/95

6) Granitic stocks (minor: form aquitards)
A) Winograd and Thordarson:
Granitic stocks (only rocks of Mz age in the "study area") -- north-central and northwestern Yucca Flat:
Climax stock
Gold Meadows stock
The only Mesozoic strata => SE one-third of the Spring Mountains and in ridges E and NE of Las Vegas — not known to underlie the NTS or its immediate surrounding area.
p. C-12: says Sevier Arch over much of SE Nevada and W. Utah from late J to early late K => Therefore, J and K strata probably never deposited.

D.F. Balin 8/7/95

August 22, 1995

What are the main structural features in the area of interest?
1) Where are the major faults?
A) caldera bounding faults
a) Frizzell and Shulters map of the NTS => How well-defined are the locations of the bounding faults?
b) Winograd & Thordarson (Plate 1): Show only the caldera bounding fault for Timber Mountain caldera in Plate 1 => doesn't show it extending as far to the northeast as Frizzell & Shulters.
c) Evidence for fault?
B) Belted Range thrust
a) Caskey and Schweickert
b) IT Report
c) Cole et al.1994 (Fig.3) => shows it continuous with the Miekeljohn (sp?) Peak thrust at Bare Mountain. (NOTE: Should be other Cole references also)
d) Snow 1992:
Shows the Belted Range thrust (which he still calls the CP thrust) as continuous with the Meikeljohn thrust (sp) and the Meikeljohn duplex zone at Bare Mountain and with the Grapevine thrust system in the Grapevine Mountains.
NOTE: I don't know whether Jim Cole agrees with this interpretation. He mentioned that Snow projected structures incorrectly into the NTS based on map interpretations now known to be incorrect.
e) Snow & Wernicke 1989:
Related to Belted Range thrust: States that Cornwall & Kleinhampl (1961) mapped the Meikeljohn thrust at Bare Mountain which was later correlated with the Grapevine thrust (cites Burchfiel et al. 1970, Reynolds 1974).
(p.1359): Says the Grapevine thrust has been correlated (cites Burchfiel et al. 1970) with isolated remnants of a large thrust fault ("CP thrust of Barnes & Poole, 1968 => now known as the Belted Range thrust) exposed farther north at the Nevada Test Site.
f) Winograd & Thordarson (Plate 1): Show it as the "CP thrust fault" (old terminology) -- They show it intersecting the caldera bounding fault along Timber Mountain caldera's SE margin. Have a parallel thrust fault closer to the Eleana Range marked as the "Mine Mountain thrust fault" => See Cole for new interpretation. Trace of Belted Range thrust as shown by W & T is just slightly different from Cole et al.1994.
C1) CP thrust
a) Caskey and Schweickert
b) IT Report
c) updated figure of Cole et al. 1994 => shows CP thrust fault hand-drawn into position; slight adjustment needed where CP fault shown to intersect the "Yucca Fault" (really the Carpetbag fault; Cole mismarked this trace as the Yucca fault) => He shows the CP thrust transecting the Carpetbag fault, but the Carpetbag is a later structural feature. The law of cross-cutting relationships would dictate that the trace of the Carpetbag fault would transect the CP thrust.
C2) Mine Mountain fault
a) Winograd & Thordarson (Plate 1): Show it as the "CP thrust fault" (old terminology) -- They show it intersecting the caldera bounding fault along

D.F. Balin 8/22/95

Timber Mountain caldera's SE margin. Have a parallel thrust fault closer to the Eleana Range marked as the "Mine Mountain thrust fault" => Here the Mine Mountain thrust fault (marked #3).

NOTE: Jim Cole in personal communication said that the Mine Mountain fault does not exist, but in the hand-corrected figure he sent to me at the same time, he shows an eastward-vergent thrust fault in the same position as that shown by W&T as the Mine Mountain fault! So if he thinks it doesn't exist, then why does he show it in this figure (unless there is some confusion with the terminology; this fault not really in the vicinity of Mine Mountain)?

b) Snow & Wernicke 1989:

(p.1359): Says the Tippinip fault forms a prominent high-angle boundary between contrasting structural domains (cites Heinrichs 1968). Says also that a correlation to the "west vergent structure" is suggested by proximity to the Mine Mountain thrust, on strike and adjacent to the south, and by the presence of older rocks east of the Tippinip thrust.

(NOTE: From this discussion, I'm not sure that Snow & Wernicke use the term "Mine Mountain thrust" for the same fault trace as Winograd & Thordarson (Plate 1).

c) Other references?

D) Yucca fault

a) Frizzell and Shulters map -- shows offset down to the east (so does X-section C-C')

b) Cole, Wahl, and Hudson (1989), Fig.2

E1) Carpetbag fault

a) Frizzell and Shulters map

b) Cole, Wahl, and Hudson (1989), Fig.2

E2) Tippinip thrust fault => NOTE: This may not exist.

a) Winograd & Thordarson (Plate 1) -- show this immediately west of the Yucca fault (in approximate position with the Carpetbag fault) => a misinterpretation?

b) Snow & Wernicke 1989:

(p.1359): Says it forms a prominent high-angle boundary between contrasting structural domains (cites Heinrichs 1968). Says also that a correlation to the "west vergent structure" is suggested by proximity to the Mine Mountain thrust, on strike and adjacent to the south, and by the presence of older rocks east of the Tippinip thrust.

F) Las Vegas Valley shear zone (dextral strike-slip fault; extends from Las Vegas Range to Spotted Range)

a) Geological Investigations of an Active Margin paper (Cole)

b) Snow 1992

c) Winograd & Thordarson (Plate 1)

d) Barnes et al. 1982 -- fault zone corresponds pretty closely with trace shown by Winograd & Thordarson, but W&T trace probably more reliable as it passes through springs at Corn Creek and Indian Springs.

d) Caskey and Schweickert (fig. 3)-- suggest connection between Las Vegas Valley shear zone and the Specter Range thrust (nobody else does that I've seen)

DFBalin
8/22/95

G1) Rock Valley fault

Left-lateral strike-slip fault; trends NE-SW and is located SE of Yucca Mountain. More specifically, it separates the Striped Hills from the Skeleton Hills to the south (transects Hwy 95), then runs north of the Specter Range, separating it from Skull Mountain to the north. Ends at Frenchman Flat.

a) Geological Investigations of an Active Margin paper (Cole et al. 1994)

Cole shows this as a left-lateral strike-slip fault, but also shows it as a normal fault downthrown to the northwest at its northeastern projected extent in Frenchman Flat.

b) Snow 1992

c) Barnes et al. 1982

Trace of fault and sinistral strike-slip concurs with that of Cole et al. 1994, but Barnes doesn't project it quite as far northeast as Cole (stops before reaching Frenchman Flat) and nowhere does he show it as a normal fault along its length); map also suggests that the fault only has surface expression to the SE of Skull Mountain around Hampel Hill and is inferred over the rest of its length.

G2) Cane Spring fault

Left-lateral strike-slip fault; trends NE-SW across the NW part of Frenchman Flat. Extends from within Skull Mountain northeastwards across Frenchman Flat and along the NW side of the Massachusetts Mountains (French Peak) in the Halfpint Range.

a) Barnes et al. 1982: Information given above from this source; map also suggests that the fault only has surface expression in the Skull Mountains and is inferred over the rest of its length.

H) Spotted Range thrust

a) Geological Investigations of an Active Margin paper (Cole)

b) Snow 1992

Snow shows the Spotted Range thrust as continuous with the Specter Range thrust

(northwest Spring Mountains) and with the Schwaub Peak thrust (Funeral Mountains). NOTE: I don't know whether Jim Cole agrees with this interpretation. He mentioned that Snow projected structures incorrectly into the NTS based on map interpretations now known to be incorrect.

I used Snow's trace except that I didn't extend it any further northward than the southern limit of the Papoose Range (because of info shown in Tschanz & Pampeyan, Plate 3 => tectonic map of Lincoln County, Nevada => shows possible truncation of the Spotted Range thrust here by the ENE-trending Arrowhead Mine fault that extends into the Pahranagat Range.)

The surface exposures of the thrust as shown by Snow seems to match up well with Cole's info and Caskey & Schweickert except for the northernmost area at Chert Ridge.

c) Caskey and Schweickert 1992 (Fig. 3): NOTE: seems to be a discrepancy between Snow 1992 and Caskey & Schweickert => C & S show the position of the Spotted Range syncline immediately west of the Spotted Range thrust, but further north its position would seem to conflict with the northward position of the Spotted Range thrust (trace shown by Snow; thrust first and syncline

DFBalin
8/22/95

later?) => Syncline not named by Snow, but shows an overturned syncline east of the Spotted Range thrust in the southern Spotted Range area. Snow depicts the syncline dying out northwards, but Caskey & Schweickert show it extending significantly northwards, as does Winograd & Thordarson. Snow shows the Spotted Range syncline as overturned, but W&T show it as a simple syncline. Trace of Spotted Range syncline shown on map is that of Winograd & Thordarson (extend it as far north as Emigrant Valley).

d) Updated figure of Cole et al.1994 that Jim Cole sent to me => shows southern part of Spotted Range thrust (mostly appears as series of thrust klippes).

e) Cole, Wahl, and Hudson (1989) (Fig.1) => Used this trace of Spotted Range thrust to digitize (but didn't extend west of Mercury Ridge).

f) Tschanz & Pampeyan (1980)
Plate 3 (tectonic map of Lincoln County, Nevada) => Shows "Spotted Range thrust and fold belt" extending as far north as Chert Ridge (immediately southeast of the Papoose Range) => possible truncation by the ENE-trending Arrowhead Mine fault that extends into the Pahranagat Range.

g) Evidence for fault:
i) Frizzell & Shulters show Bonanza King thrust over Nopah Fm. and Pogonip Group in the northern part of the Specter Range (conforms with trace of Spotted Range as shown by the previous references). East of Mercury, Frizzell & Shulters shows Bonanza King thrust over undivided Mississippian carbonate rocks and Devils Gate Limestone (Upper Devonian) in position of thrust klippe shown by Cole in updated figure.

I) Pintwater thrust

a) Snow 1992 => this trace preferred but don't extend past the northernmost limit of the Pintwater Range (Tschanz & Pampeyan, Plate 3 -- tectonic map of Lincoln County, Nevada -- suggests that this thrust is truncated by the Arrowhead Mine fault).

b) Caskey and Schweickert 1992 (Fig. 3).
NOTE: Disagreement in position between C &S and Snow 1992 => Snow shows outcrop trace farther north than C & S. Also Snow shows the thrust as very extensive but C&S show only a rather short trace along the western edge of the Pintwater range. Really need to define this better.

c) Winograd & Thordarson -- Don't show the Pintwater thrust but do show trace of the Pintwater anticline => the thrust as shown by Snow would transect the trace of the Pintwater anticline as shown by W&T and by Caskey & Schweickert.
Maybe better to depict the Pintwater anticline and take the more conservative view of the Pintwater thrust (ie. Caskey & Schweickert) because both W&T and C&S depict the Pintwater anticline similarly.

d) Tschanz & Pampeyan -- compare Plate 3 (tectonic map of Lincoln County, Nevada) and their geologic map of Lincoln County, Nevada => geo map shows that the Pintwater thrust places Silurian Laketown Dolomite or Devonian Sevy Dolomite over the Ordovician Pogonip Group along the northern part of the fault. The trace of this unnamed fault corresponds best with the trace shown by Snow (1992)

J) Northern Death Valley-Furnace Creek fault zone

DFBahin
8/22/95

a) Snow 1992: southeast-trending, dextral strike-slip fault along southwest side of the Funeral and Grapevine Mountains

b) Snow & Wernicke (1989): Shows trace in their Figure 1.

K1) Clery thrust

a) Snow 1992 (southeast Funeral Mountains): See notes regarding Kwichup Spring thrust in "M1" below.

b) Snow & Wernicke 1989 (compare Figs. 1, 2, 5):
(p.1355) says this is one of three major north-northeast-trending Mesozoic structures that is present in the Funeral Mountains (others mentioned are the Schwaub Peak thrust and the Winters Peak anticline).
From structurally lowest to highest: Clery thrust => Schwaub Peak thrust => Winters Peak anticline.

K2) Schwaub Peak thrust

a) Snow & Wernicke 1989:
(p.1355) says this is one of three major north-northeast-trending Mesozoic structures that is present in the Funeral Mountains (others mentioned are the Clery thrust and the Winters Peak anticline).
From structurally lowest to highest: Clery thrust => Schwaub Peak thrust => Winters Peak anticline.

b) Wernicke et al. 1989 => Fault in fig. on pp.T138:6-T138:7 differs from fault shown by Snow & Wernicke 1989!

K3) Keene Wonder fault (dextral strike-slip fault, trending NW-SE, in the Funeral Mountains)

a) Snow & Wernicke 1989:
Offsets the Winters Peak anticline in the Funeral Mountains

K4) Grapevine thrust system (Grapevine Mountains)

a) Snow & Wernicke 1989:
(p.1356): Titus Canyon anticline folds a segment of the Grapevine thrust system.
Grapevine thrust system emplaces Cambrian-Precambrian Z strata above Mississippian strata. It has been correlated with the Last Chance thrust (exposed west of the northern Death Valley-Furnace Creek fault zone), on the basis of its structural position and stratigraphic throw of about 5,300 meters (cites Reynolds 1974, Stewart et al. 1966).
(p.1359): States that Cornwall & Kleinhampl (1961) mapped the Meikeljohn thrust at Bare Mountain which was later correlated with the Grapevine thrust (cites Burchfiel et al. 1970, Reynolds 1974).
(p.1359): Says the Grapevine thrust has been correlated (cites Burchfiel et al. 1970) with isolated remnants of a large thrust fault ("CP thrust of Barnes & Poole, 1968 => now known as the Belted Range thrust) exposed farther north at the Nevada Test Site.

b) Caskey & Schweickert:
Trace of Grapevine thrust as shown in Fig.3 differs in configuration from that shown by Snow & Wernicke (1989, Fig.1), however trace shown by C&S is same as that shown by Snow 1992 => will use C&S trace.

L) Wheeler Pass thrust system (Spring Mountains)

DFBahin
8/22/95

a) Caskey and Schweickert 1992 (Fig. 3): Figure implies correspondence of the Wheeler Pass thrust (WPT) with the Gass Peak thrust to the northeast (Sheep Range/Las Vegas Range area) => offset along the Las Vegas Valley shear zone.
b) Snow 1992 (Figure doesn't extend as far as the Gass Peak thrust, so can't compare with Caskey & Schweickert) => Snow shows the Wheeler Pass thrust system (WPTS) extending west to unnamed hills at NW end of Pahrump Valley (north of Stewart Valley Road) => The fault in this area is called the Mongomery thrust (MT) by Caskey & Schweickert (See "Y" below) => Both Snow, and Caskey & Schweickert suggest an intervening strike-slip fault (Snow shows a dextral strike-slip fault but lets it die out southwards without showing its intersection with the Wheeler Pass thrust system).
c) Snow & Wernicke 1989:
(p.1356): Implies that the Wheeler Pass thrust has a stratigraphic throw of about 5 km.
NOTE: Their Fig.1 on p.1352 shows the Wheeler Pass thrust system in the Spring Mountains extending westwards, but the segment corresponding with the Montgomery thrust shown by C&S has a different configuration => So until I figure which is correct, I will not have Rick Klar digitize the segment any farther west than the Spring Mountains.
d) Barnes et al. 1982: trace of fault corresonds with that of Caskey and Schweickert.
e) Winograd & Thordarson (Plate1): trace corresponds with Caskey and Schweickert.
f) Cole et al. 1994 (Fig.1) -- show unnamed trace (corresponding with the Wheeler Pass thrust) -- I used their projection of the fault towards the Las Vegas Valley shear zone.

M1) Kwichup Spring thrust (Spring Mountains -- northwest of Wheeler Pass thrust system)
a) Snow 1992: Figure implies offset along the Las Vegas Valley shear zone=> Kwichup Spring thrust implied to correspond with the Pintwater thrust to the northeast across the shear zone.
Same figure implies correspondence of the Kwichup Spring thrust with the Clery thrust (southeast Funeral Mountains) located to the SW, but also offset right-laterally along an unnamed strike-slip fault.
NOTE: I don't know whether Jim Cole would agree with this interpretation. He mentioned that Snow projected structures incorrectly into the NTS based on map interpretations now known to be incorrect.
b) Caskey and Schweickert 1992: <u>No thrust</u> shown by them but they do show some of the same structures as Snow 1992 in the same area.
c) Cole, Wahl, and Hudson 1992: <u>No structure</u> of any type shown on their generalized geo map in Fig. 1.

M2) Lee Canyon thrust (Spring Mountains -- southeast of Wheeler Pass thrust system)
a) Barnes et al. 1982

M3) Deer Creek thrust (Spring Mountains -- southeast of Wheeler Pass thrust system, and SE of Lee Canyon thrust)
a) Barnes et al. 1982

DFBalin
8/22/95

<u>NOTE</u>: This page glued in out-of-order. It should follow page 43. DFB.

W) Butte fault
a) Caskey and Schweickert (1992), Fig. 3: Show it along the east margin of the Belted Range. (and they show an association with an overturned syncline as it is traced northwards)

X) Bare Mountain-Bullfrog Hills-Boundary Canyon detachment fault
a) Caskey and Schweickert (1992), Fig. 3: Shows all of these linked up.
b) Check Wernicke guidebook => know there's a reference to the Boundary Canyon detachment fault (also personal communication with Zeke Snow).
c) Snow & Wernicke 1989:
Boundary Canyon fault is a major detachment fault that separates the Funeral Mountains from the Grapevine Mountains. Grapevine Mountains lie structurally above the Boundary Canyon fault.
(p.1359): Separation on the Boundary Canyon fault at least about 30 km (constrained by correlation of the Titus Canyon anticline in the Grapevine Mountains with the Winters Peak anticline in the Funeral Mountains) -- As much as 90 degrees of counterclockwise rotation of the southern Grapevine Mountains during Tertiary extension.
d) Wernicke et al. 1989:
Used figure on pp. T138:6 to T138:7 to digitize.

DFBalin
8/22/95

M4) Keystone thrust (Spring Mountains -- southeast of Wheeler Pass thrust system, and SE of Deer Creek thrust):
a) Barnes et al. 1982
b) Snow & Wernicke 1989 (Fig.1): Shows trace of Keystone thrust in the SE Spring Mountains.
c) Wernicke et al. 1989 (fig on pp.T138.6-T138:7
N) Dog Bone Lake fault NOTE: I haven't seen this fault represented anywhere else.
a) Guth in Wernicke Guidebook (Fig. 4-1) -- runs along western margin of Desert Range; looks like a normal fault downthrown to the west.
O) Gass Peak thrust (Location checks out fine between all of the following references)
a) Guth in Wernicke Guidebook (Fig. 4-1) -- runs north-south between Sheep Range and Desert Range.
b) Caskey and Schweickert (Fig.3)
c) Barnes et al. (1982)
d) Cole, Wahl, and Hudson (1989) (Fig. 1)
e) Winograd & Thordarson (1975) (Plate 1) -- Note: Used this one to digitize.
P1) Alamo Road fault and Prospector fault NOTE: I haven't seen this fault represented anywhere else.
a) Guth in Wernicke Guidebook (Fig. 4-1) -- Desert Range area.
P2) Pahranagat Valley fault system = Menard Lake Fault of Tschanz & Pampeyan (1980)
a) Barnes et al. 1982:
Left-lateral strike-slip fault; NE-SW trending; Extends from northern part of "East Desert Range", across Desert Valley, and then between the Sheep Range (to the S) and the "East Pahranagat Range" (to the N).
Q) Wildhorse Pass fault
a) Guth in Wernicke Guidebook (Fig. 4-1) -- Sheep Range
R) Sheep Basin fault
a) Guth in Wernicke Guidebook (Fig. 4-1) -- west margin of central Sheep Range
S) Mormon Pass fault
a) Guth in Wernicke Guidebook (Fig. 4-1) -- west of Gass Peak thrust (in eastern Sheep Range)
T) Meiklejohn Peak thrust (Bare Mountain)
a) Caskey and Schweickert 1992 -- They show a strike-slip offset of this fault between Bare Mountain and Belted Range thrust further east (part of Stewart Valley-Stateline fault zone => dextral strike-slip)
b) Cole
c) Snow 1992 --Figure 12 shows fault labeled the "Meikeljohn duplex zone" that coincides with the Meiklejohn Peak thrust of Caskey and Schweickert.
d) Snow & Wernicke 1989:
(p.1359): States that Cornwall & Kleinhampl (1961) mapped the Meikeljohn thrust at Bare Mountain which was later correlated with the Grapevine thrust (cites Burchfiel et al. 1970, Reynolds 1974).
e) Barnes et al. 1982 -- show trace of a fault coincident with the Meiklejohn Peak thrust (single northernmost thrust that they show at Bare Mountain)
U1) Panama thrust (Bare Mountain)

DLBalin 8/22/95

a) Caskey and Schweickert 1992 -- show 2 traces of this fault at Bare Mtn => one immediately south of the Meiklejohn Peak thrust and the other further S at Bare Mtn.
b) Cole
c) Barnes et al. 1982 -- show trace of unmarked fault consistent with the "Panama thrust" of Caskey and Schweickert, and similar to (but not exactly) the trace shown by Snow 1992-- Also thrust fault immediately south of the Meiklejohn Peak thrust corresponds with part of the Panama thrust as shown by Caskey & Schweickert => NOTE: Snow 1992 only shows the Panama thrust along the southern part of Bare Mountain and doesn't show a second northern trace.
d) Snow 1992 (Fig.12) -- see comments above. The trace shown by C&S and Barnes are consistent with each other but are a little different than Snow's. The others are more accurate in terms of the geo map of Bare Mtn (Monsen et al. 1992).
e) Snow & Wernicke 1989:
States that Cornwall & Kleinhampl (1961) mapped the extensionally-disrupted remains of a large west-vergent fold, later shown to include the west-directed Panama thrust (cites Carr & Monson, 1988).
(p.1359): Restoration of movement on the northern Death Valley-Furnace Crrek fault zone and the Boundary Canyon fault places the west-vergent structure in the Cottonwood, Funeral, and Grapevine Mountains on strike with the Panama thrust, thereby suggesting a correlation.
f) Monsen et al. 1992 (Geo map of Bare Mtn) -- see comment above => Check this ref for additional evidence regarding the fault.
U2) Stewart Valley-Stateline fault zone
Dextral strike-slip fault; trending NW-SE along Stewart Valley (road I took)
a) Caskey and Schweickert 1992 -- they project it east of the Funeral Mountains and east of Bare Mtn.
b) Winograd and Thordarson -- more conservative (only in Stewart Valley) Note: Used this one to digitize.
V) Montgomery thrust (in unnamed hills NW of Pahrump Valley, N of Stewart Valley Road)
a) Caskey and Schweickert 1992 (Fig. 3): Shown as MT on map
b) Snow 1992 shows this same fault as part of the Wheeler Pass thrust system (He doesn't show name of Montgomery thrust) => Both Snow, and Caskey & Schweickert suggest an intervening strike-slip fault (Snow shows a dextral strike-slip fault but lets it die out southwards without showing its intersection with the Wheeler Pass thrust system).
c) Winograd and Thordarson -- positioning just slightly different (all of the above references are approximately the same.)
NOTE: Snow & Wernicke 1989, Fig.1 on p.1352, shows the Wheeler Pass thrust system in the Spring Mountains extending westwards, but the segment corresponding with the Montgomery thrust shown by C&S has a different configuration => So until I figure which is correct, I will not have Rick Klar digitize the fault any farther west than the Spring Mountains (so the Montgomery thrust not digitized yet).

DLBalin 8/22/95

2) Where are the other major structures in the area of interest?
NOTE: Winograd and Thordarson note that several large anticlines and synclines (orientation of axes shown on Plate 1; Note: appears to be a general north-south trend) => formed before the beginning of extensive sedimentation and volcanism in the Miocene — probably formed during period of the late Mz deformation (parallel other features of that episode).

A) Structural domains of Mark Hudson
a) See field trip report and paper sent to me by Jim Cole => French Peak accomodation zone (shown in Geological Investigations of an Active Margin paper)
b) Evidence for domains?
B) Striped Hills anticline
a) Caskey and Schweickert 1992 (Fig. 3):
NOTE: They have it swinging east-northeast and then north => Compared figure with Frizzell and Shulters map and the northernmost extent corresponds roughly with the northern part of the Halfpint Range (east of Yucca Flat; close to the Rhyolite Hills) => Cole mentioned that the Halfpint anticline does not exist (instead is boundary between structural domains) => so this may be an incorrect correlation.
b) Evidence for structure?
C) Pintwater anticline
a) Caskey and Schweickert 1992 (Fig.3):
NOTE: Trace of the Pintwater anticline as shown by them crosses the trace of the Pintwater thrust as shown Snow 1992 (Snow doesn't show the trace of the anticline and C&S don't show the trace of the Pintwater thrust) => thrust first and anticline later? Another apparent discrepancy: Snow 1992 shows a small left-lateral strike-slip fault in the exact same area (near Mercury) that C & S show the trace of the Pintwater anticline (with no strike-slip shown).
b) Barnes et al. 1982: map shows trace of Pintwater anticline that generally concurs with that of Caskey & Schweickert except for along its southern extent => trace shown differently in areas adjacent to the Las Vegas Valley shear zone (Barnes has it running further north). Also Caskey and Schweickert project the anticline much further north (into Lincoln County to where the Pintwater Range intersects the Desert Range) whereas Barnes stops in the southern part of the Pintwater Range.
c) Winograd & Thordarson -- trace most similar to that of Barnes et al. 1982
Also complicated structural zone south of Las Vegas Valley shear zone shown differently by Barnes vs. Caskey & Schweickert (Barnes shows as area of thrust faults; C&S show as overturned anticlines and synclines) => This area located in the northwesternmost Spring Mountains, S of Hwy 95 near Point of Rocks.
D) Indian Springs syncline
a) Winograd and Thordarson -- show syncline extending southwards from Indian Springs Valley into the Spring Mountains, but I haven't seen this represented in any other references.
E) Winters Peak anticline
a) Snow & Wernicke 1989:

D.F. Balin
8/22/95

(p.1355) says this is one of three major north-northeast-trending Mesozoic structures that is present in the Funeral Mountains (others mentioned are the Clery thrust and the Schwaub Peak thrust).
From structurally lowest to highest: Clery thrust => Schwaub Peak thrust => Winters Peak anticline.
It is offset by the Keene Wonder fault (dextral strike-slip) in the Funeral Mountains.
F) Titus Canyon anticline (Grapevine Mountains)
a) Snow & Wernicke 1989:
(p.1356): Together with the Corkscrew Peak syncline forms a large west-vergent fold pair in the Grapevine Mountains. I think he indicates that the Grapevine Mountains may be divided into three structural domains along strike according to the geometry of the Titus Canyon anticline and superimposed normal faults.
(p.1358): Age of Titus Canyon anticline is, at least in part, Tertiary.
Along the structure, there is spacial coincidence between large-amplitude recumbent folding and low-angle normal faulting, and between smaller amplitude folding with steeply-inclined axial surfaces and steep normal faulting => suggest a genetic relationship between Tertiary normal faulting and west-vergent folding (cites Reynolds 1969 and 1974).
G) Corkscrew Peak syncline
a) Snow & Wernicke 1989:
(p.1356): Together with the Titus Canyon anticline forms a large west-vergent fold pair in the Grapevine Mountains.

D.F. Balin
8/22/95

October 9, 1995

References.

Barnes, H., Ekren, E.B., Rodgers, C.L., and Hedland, D.C., 1982. Geologic and tectonic maps of the Mercury quadrangle, Nye and Clark Counties, Nevada. U.S. Geological Survey Miscellaneous Investigations Series, Map I-1197, 1:24,000

Barnes, H., and Poole, F.G., 1968. Regional thrust-fault system in Nevada Test Site and vicinity. In: Nevada Test Site (E.G. Eckel, ed.), Geological Society of America Memoir 110, 233-238.

Cashman, P.H., and Trexler, J.H., Jr., 1994. The case for two, coeval, Mississippian sections at the Nevada Test Site. In: Geological Investigations of an Active Margin (S.F. McGill and T.M. Ross, eds.), Geological Society of America Cordilleran Section Guidebook, 27th Annual Meeting, San Bernardino, California, March 21-23, 1994, 76-81.

Caskey, S.J., and Schweikert, R.A., 1992. Mesozoic deformation on the Nevada Test Site and vicinity: implications for the structural framework of the Cordilleran fold and thrust belt and Tertiary extension north of Las Vegas. Tectonics 11 (6), 1314-1331.

Cole, J.C., Trexler, J.H., Cashman, P.H., and Hudson, M.R., 1994. Structural and stratigraphic relations of Mississippian rocks at the Nevada Test Site. In: Geological Investigations of an Active Margin (S.F. McGill and T.M. Ross, eds.), Geological Society of America Cordilleran Section Guidebook, 27th Annual Meeting, San Bernardino, California, March 21-23, 1994, 66-75.

Cole, J.C., Wahl, R.R., and Hudson, M.R., 1989. Structural relations within the Paleozoic basement of the Mine Mountain block; implications for interpretation of gravity data in Yucca Flat, Nevada Test Site. 5th Symposium on Containment of Underground Nuclear Explosions, September 19-21, 1989, Mission Research Corp., Santa Barbara, California, 431-456.

Dettinger, M.D., 1989. Distribution of Carbonate-Rock Aquifers in Southern Nevada and the Potential for their Development: Summary of Findings, 1985-88. Program for the Study and Testing of Carbonate-Rock Aquifers in Eastern and Southern Nevada, Summary Report No. 1, 37p.

Drellack, S.L., Jr., Protho, L.B., Thompson, P.H., McCall, R.L., 1991. Preliminary geology and drill hole data report for groundwater characterization well ER12-1 Nevada Test Site, Nye County, Nevada. Prepared for U.S. Department of Energy/Field Office, Nevada. Available from National Technical Information Service, Springfield, Virginia, 77p.

Fridrich, C.J., Dudley, W.W., Jr., and Stuckless, J.S., 1994. Hydrogeologic analysis of the saturated-zone ground-water system under Yucca Mountain, Nevada. Journal of Hydrology 154, 133-168.

Frizzell, V.A., Jr., and Shulters, J., 1990. Geologic map of the Nevada Test Site, southern Nevada. U.S. Geological Survey Miscellaneous Investigations Series, Map I-2046, 1:24,000.

Harrill, J.R., Gates, J.S., and Thomas, J.M., 1988. Major ground-water flow systems in the Great Basin region of Nevada, Utah, and adjacent states. U.S. Geological Survey Hydrologic Investigations Atlas HA-694-C, 1:1,000,000.

Maldonado, F., and Schmidt, D.L., 1990. Geologic map of the southern Sheep Range, Fossil Ridge, and Castle Rock area, Clark County, Nevada. U.S. Geological Survey Miscellaneous Investigations Series, Map I-2086, 1:24,000.

D. Balin
10/9/95

Monsen, S.A., Carr, M.D., Reheis, M.C., Orkild, P.P., 1992. Geologic map of Bare Mountain, Nye County, Nevada. U.S. Geological Survey Miscellaneous Investigations Series, Map I-2201, 1:24,000.

Plume, R.W., and Carlton, S.M., 1988. Hydrogeology of the Great Basin region of Nevada, Utah, and adjacent states. U.S. Geological Survey Hydrologic Investigations Atlas HA-694-A, 1:1,000,000.

Robinson, G.D., 1985. Structure of pre-Cenozoic rocks in the vicinity of Yucca Mountain, Nye County, Nevada -- a potential nuclear-waste disposal site. U.S. Geological Society Bulletin 1647, 22p.

Snow, J.K., 1992. Large-magnitude Permian shortening and continental-margin tectonics in the southern Cordillera. Geological Society of America Bulletin 104, 80-105.

Snow, J.K., and Wernicke, B., 1989. Uniqueness of geological correlations: An example from the Death Valley extended terrain. Geological Society of America Bulletin 101, 1351-1362.

Tschanz, C.M., and Pampeyan, E.H., 1970. Geology and mineral deposits of Lincoln County, Nevada. Nevada Bureau of Mines and Geology Bulletin 73, 188 p.

Wernicke, B.P., Snow, J.K., Axen, G.J., Burchfiel, B.C., Hodges, K.V., Walker, J.D., and Guth, P.L., 1989. Extensional tectonics in the Basin and Range province between the southern Sierra Nevada and the Colorado Plateau. 28th International Geological Congress Field Trip Guidebook T138, 80p.

Winograd, I.J., and Thordarson, W., 1975. Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site. U.S. Geological Survey Professional Paper 712-C, 126p.

D. Balin
10/9/95

This research project was officially closed as of Jan 17, 1996. This notebook reflects work conducted by Donna Balin, a consultant to the CNWRA, on the geologic structure affecting groundwater movement in the Death Valley Region.

Gordon Wittmeyer
Principal Investigator
2/21/96