Stratigraphic Studies of the Boise (Idaho) Aquifer System Using Borehole Geophysical Logs With Emphasis on Facies Identification of Sand Aquifers

Report to the Treasure Valley Hydrologic Study
Idaho Department of Water Resources

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Introduction

The cold-water aquifer system beneath the City of Boise is composed of sandy sediments interbedded with claystone and mudstone that were deposited near the shores of lakes which filled the western Snake River Plain during the late Miocene and Pliocene epochs (10 to 1.7 million years ago) (Figures 1and 2). The sand layers are the deposits of stream channels, beach sands winnowed by wave action, deltas built out into the lake, and possibly density-flows across the lake bottom from collapse of parts of the delta shelf. These depositional environments do not produce broadly distributed sand layers. Instead the sand layers are typically restricted in their horizontal and vertical continuity by interbedded mudstone or lateral termination into mudstone. The difficulty here lies with correlation of sand layers and determination of their shapes. Important is to predict whether sand layers found in wells have some sort of hydraulic connection, and which are not interconnected. By analogy to modern sedimentary environments and subsurface studies by others, our goal is to obtain at least a partial understanding of the three-dimensional geometrical shapes of sand aquifers.

Structural downwarping coupled with normal faulting along the margins of the plain further complicates deciphering the stratigraphic section. For example, a 4-degree dip of strata (370 feet per mile), results in strata identified in one well, being 370 feet deeper in a well one mile away in the down dip direction (Figure 2). Stratigraphic offset along down-to-basin normal faults (up to 800 feet of vertical throw on some faults) pose additional complexity, because in the older strata, faulting was contemporaneous with deposition.

For this report, we have compiled available geophysical logs (natural gamma, single-point resistance, or normal-resistivity logs at a scale of 1 inch equals 200 feet for the wells shown in Figure 3. Most of the logs are owned by United Water Idaho, Inc. and we have been permitted to use other data by the City of Boise, Micron Technology, and the Idaho Department of Transportation. On many of the United Water Idaho (UWID) wells, drill cuttings were examined by geologists, and the grain size of sands are known. On other wells, the driller's descriptions are the only record of lithology, and the grain-size of sands is not consistently reported. We explain our attempts to correlate geologic strata and identify depositional facies for the line of wells from Claremont Subdivision (end of 8th Street in the foothills) to the Cassia Street well, and for the line of wells from " Hill 3431" above Stewart Gulch in the foothills to the McMillan well of west Boise. Correlation from the Micron Technology plant area to Cassia Street are still preliminary, and not included. Correlation from Idaho Street well to the Bethyl Street well and west to the St. Lukes well (at east Meridian) is currently being evaluated using seismic reflection data acquired by the Boise State University CGISS group this summer of 2000.

Methods

Facies interpretations of geophysical logs are discussed in Rider (1996), Berg (1986); and Galloway and Hobday (1996); however, examples from lacustrine basins are few. Most of the examples from Rider's interpretations (shown in Figure 4) are from marine environments; however, his examples of a channel-point bar, delta-border progradation, transgressive shelf, and prograding shelf are probably applicable to the lacustrine setting. The study of the Pliocene lacustrine Ridge Basin in California by Link and Osborne (1978) is helpful, because they interpret logs of a mouth bar complex overlying a delta

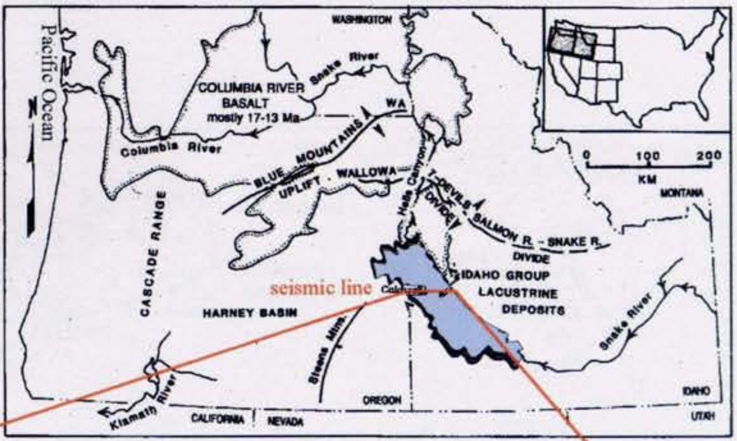


Figure 1. Location of Neogene Lake Idaho deposits in the northwest United States (from Wood, 1994)

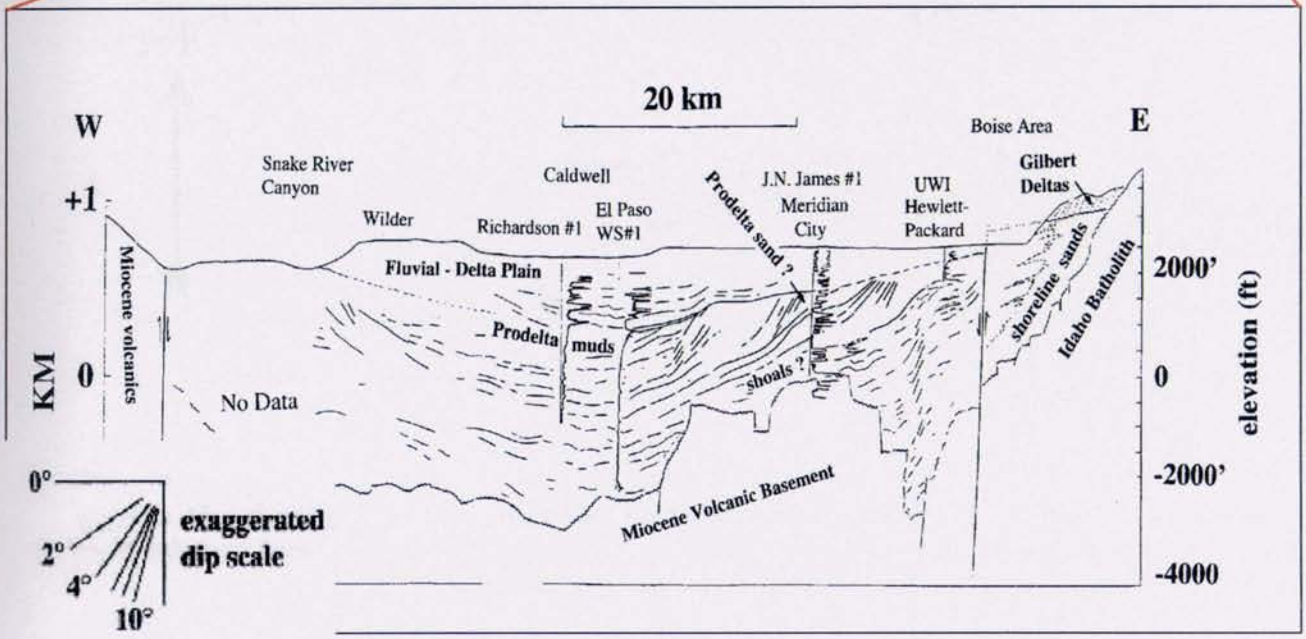


Figure 2. Interpreted cross-section from seismic lines across the western Snake River Plain, showing the geometry of strata that reflect seismic waves within lake and stream deposits and the resistivity response of borehole geophysical logs of deep wells. Drawn from petroleum industry seismic reflections lines which were focused on the deeper strata and did not image the strata shallower than 700 ft depth (i.e., the main cold-water aquifer section).

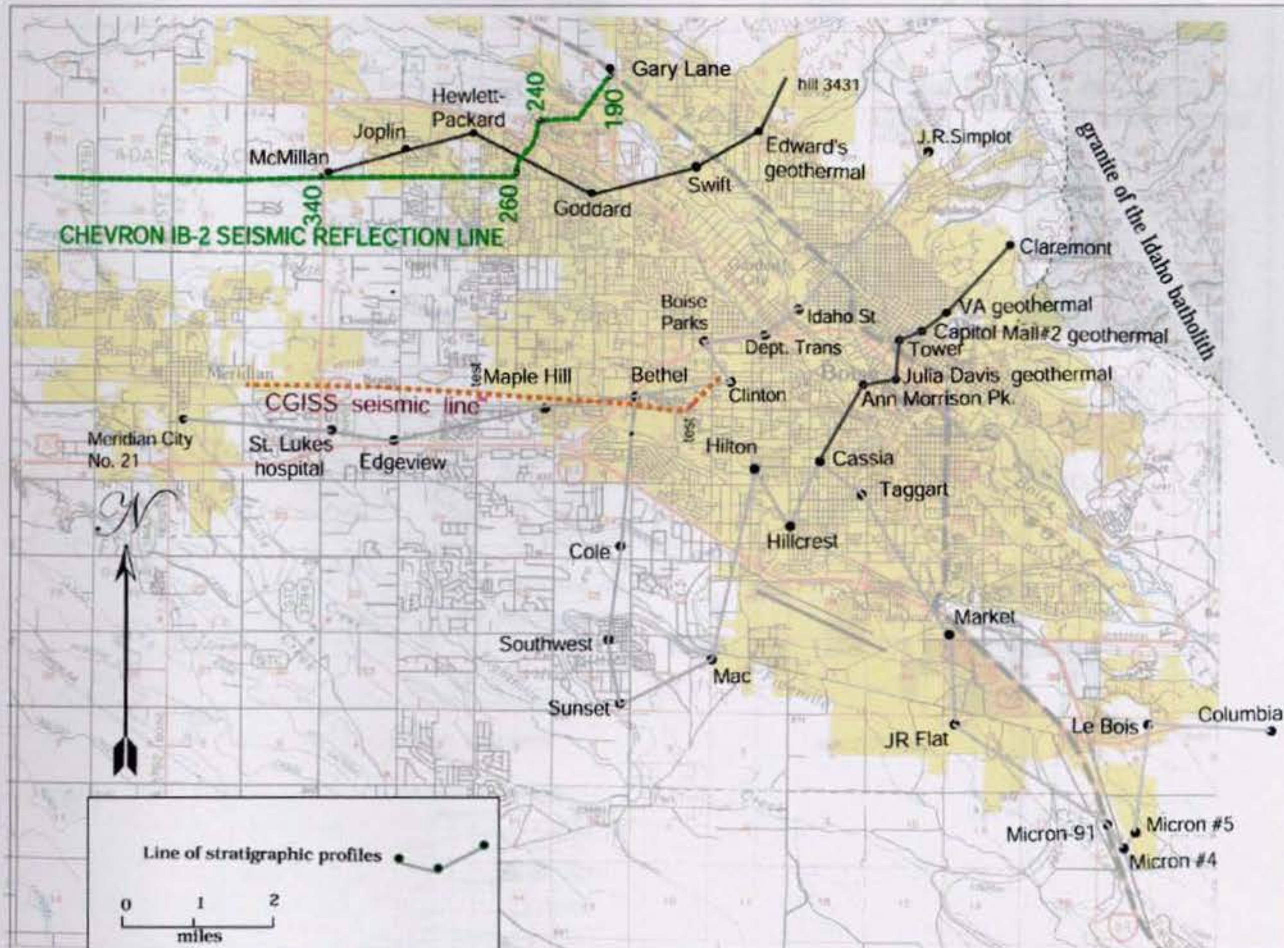


Figure 3. Map showing deep wells in the Boise area and locations of seismic lines. Profiles of Figures 9 and 10 are highlighted lines.

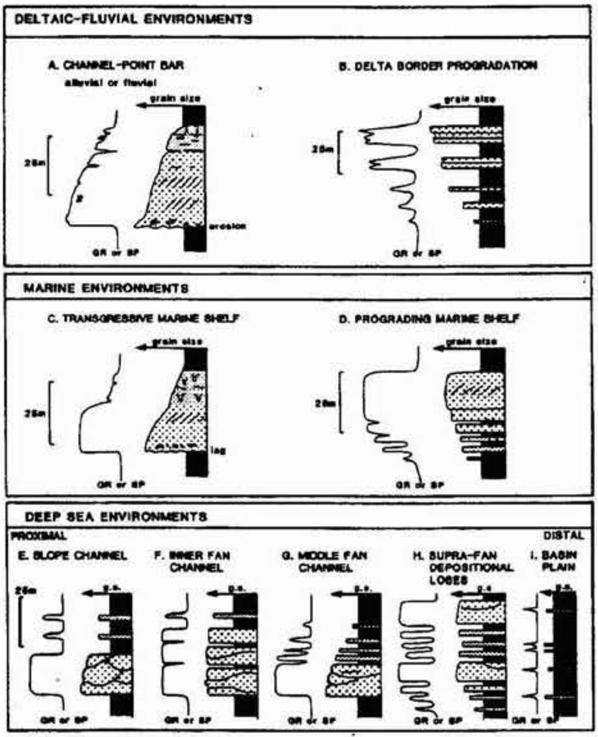


Figure 4. Idealized well log shapes (gamma or SP, or mirror image of resistivity) for sedimentary facies (From Rider, 1996).

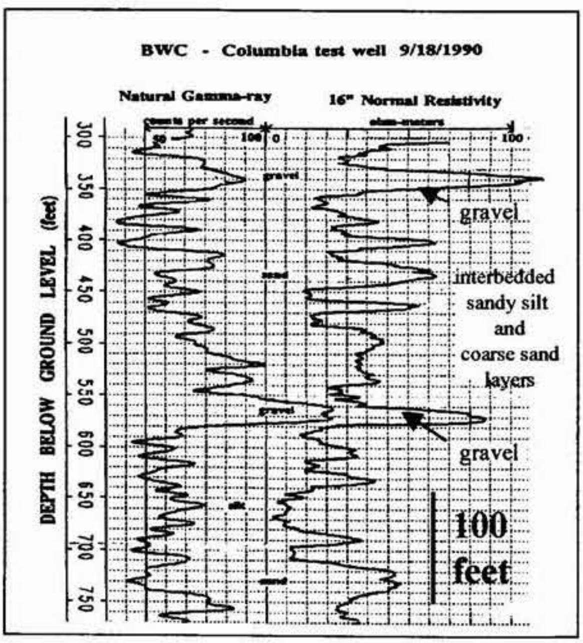


Figure 5. Geophysical log character of the mixed alluvial-fan - braided-stream facies beneath southeast Boise. Gravel layers are typically 20 feet thick and have higher radioactivity (high counts/sec on the natural gamma log) on account of a large percentage of cobbles of high-potassium porphyritic felsite. Gravels show a tendency to be more silty upwards (fining of matrix upward), and have abrupt bases typical of channels. Sands are typically 20 feet thick with abrubt bases and fining upward. Silty beds show a "spiky" character on the natural gamma log. (From Squires and others, 1992).

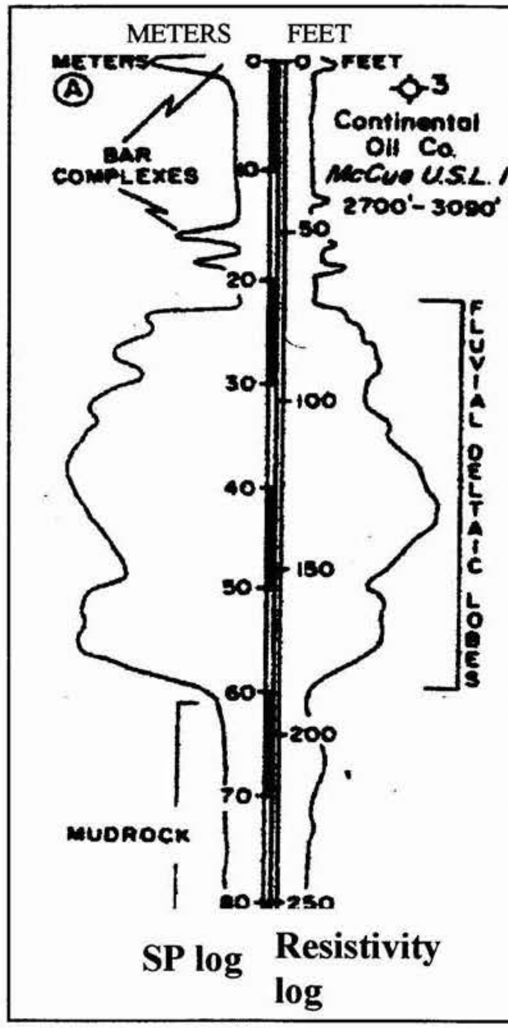


Figure 6. SP and resistivity log of lacustrine prodelta mudrock overlain by delta sand lobes, overlain by a mouth-bar complex: Ridge-Basin, California (from Link and Osborne, 1978).

1)**Funnel-shaped logs, over 20 to 100 m vertical extent**, overlain by abruptly more resistive sands, and correlative over 10's of km. These are interpreted as prodelta coarsening upward mud sequences overlain by channel sands.

2)**Funnel-shaped logs, of 5 to 20 m vertical extent**, and repeated in the section. Several to 10 or more units are repeated over intervals of 30 to 100 m. Units are rarely correlative over a few km. Sands generally medium-grained. These are interpreted as stacked mouth bars of streams entering the lake, or as beach sands.

3) **Monotonous low resistivity, and irregular medium gamma** activity, over vertical extents of 30 to 400 or more meters, interpreted as muds deposited in the open lake environment.

4) **Thin bell shaped units, less than 3 m thick**, and enclosed by thick muds, are interpreted as fining upward density-flow sands, and generally made up of fine well-sorted sand.

5) **Bell-shaped logs, with abrupt bases, 7 to 40 m in vertical extent**. Sands are typically coarse, and some have gravel at base. These are interpreted as fluvial channels, and rarely correlative over a few km.

6) **Spikey logs, with resistive units 3 to 7 m,** and low resistance units typically 3 m in vertical extent. 7 m units with abrupt bases, and high gamma. These are interpreted as alluvial fan deposits, with high-gamma rhyolite gravel with abrupt bases, and alternating silt and muddy sand layers none of which can be individually correlated.

Figure 7. Useful electric and natural gamma-ray signatures of depositional facies in Lake Idaho sediments (from Wood and others, 2000)

lobe (Figure 6). Studies by Ainsworth and others (1999), Flint and others (1988, 1989) of Miocene lake sediments in Thailand illustrate the continuity of bars and other lacustrine sands. They found mouth-bar sands to be coarsening upward (funnel-shaped logs), fine-grained sands with a sheet geometry of variable thickness. Individual sheets of mouth-bar sands, vary in thickness from 0.5 to 5 meters,and could be traced for a distances up to 5 km. Their studies of a Thailand oil field was for wells about 1 km apart accompanied by a 3D-seismic survey, a set of data far more detailed than that usually available in water resource studies.

The shapes of logs we have found useful in interpreting facies in the sedimentary section beneath Boise are summarized in Figure 7. Squires and others (1992) identified the log character of mixed alluvial-fan-and-braided-stream facies in the southeast Boise area (Figure 5).

The great value of borehole-geophysical logs is their ability to detect sand and gravel aquifers, and distinguish aquifers from low permeability mudstone, siltstone, and clay. The best log is one that measures electrical resisitivity in an open, uncased hole full of water or drilling mud (the 16 or 64-inch normal log, or induction logs). This log shows high resistivity in a fresh-water-filled clean sand or gravel aquifer, but the response is greatly reduced by low-resistivity (high-conductance, > 400 μS) groundwater in the aquifer. The single-point resistance log gives a similar response to resistivity in the sand and mudstone section and is equally useful, though not quantitative. Electrical resistivity logs have low values in silt and clay bearing sediments, thereby distinguishing them from aquifer sands and gravels. Natural gamma logs are generally useful, but their similar response in silt-clay and gravels with cobbles of high potassium content make an ambiguous interpretation of gravel or clay, unless accompanied by a resistivity or resistance log.

Background Geology and Problems

In the past, aquifers were typically named for the geologic formations in which they occurred. However, the variety of depositional environments of the lake-stream systems and the changing environments with fluctuating lake levels tells us that the sand units are complex. In previous reports on the western plain (Whitehead, 1992), the aquifer systems are associated with a set of geologic formations originally defined by Malde and Powers (1962). The stratigraphic order and characteristic lithology of the formations is a useful framework, because the changing lithology in some cases can be attributed to basin-wide geologic events or progressions of similar depositional environments across parts of the basin. However, it is unlikely that these formation units reliably relate to hydraulic connectivity of aquifers. In the areas Malde and Powers had geologically mapped, they found a general sequence of granitic rocks overlain by rhyolite, overlain by basalt, overlain by lake and stream sediments. They recognized an early set of lake and stream deposits that had been tilted, faulted and beveled off by erosion which they called the Chalk Hills Formation. Their concept of the Banbury Basalt beneath the Chalk Hills Formation is misleading, because we now know that many local basalt fields erupted during the time lake and stream sediments were accumulating in the basin (Wood and Clemens, in press). The Poison Creek Formation was originally identified on the south side of the plain as sediments dominated by one or several layers of 1-to-7-meter-thick fluvial or coarse-grained delta sand at or near the base of the lake and stream section.

These sands are discontinuous, and the Poison Creek Formation is best regarded as just a local sand facies of the Chalk Hills Formation (Wood and Clemens, in press). The basis for the top of the Chalk Hills Formation is well established as an unconformity with slight angularity on the south side of the western plain. On the south side, it is overlain by beach gravel and in places shoreline carbonate oolitic sands. On the north side of the plain, we have searched for such a straight-forward contact of a widespread angular unconformity overlain by the oolites or gravel, but have it only in one locality in the Boise foothills (discussed later in this section), and are uncertain of its occurrence in the subsurface, as discussed later in this report.

In the Boise foothills and in the subsurface are several gravel and coarse-sand occurrences indicating stream deposition or beach gravel over lake-bed muds. This can result from streams flowing out over the exposed mud surface as the lake lowers. These layers can also result from beach sand facies being spread as waves work the shoreline of a rising lake. We are looking for criteria to identify both situations, but the relationships in outcrop and on the well logs are not yet obvious to us. The gravel and coarse sand layers occur at several horizons within the mudstones, but we are still uncertain of the correlation of many of these layers.

Carbonate oolitic sands lenses occur in a 400-ft thick section of shoreline sands in the foothills which Burnham and Wood (in press) have always considered a part of their definition of the Terteling Springs Formation. The oolite bearing section varies greatly in thickness, and appears to be absent in places. The oolites were deposited as shoreline sand beaches and bars, and therefore occur only as lenses within the sediments. The oolite lithology appears to be a unique lithology associated with lake level rise (Wood and Clemens, in press; Repenning and others, 1994, p. 54). In the subsurface beneath Boise, oolite sands have been documented in the UWID'S Cassia, Taggert, and Cole water wells (locations of these wells is shown on Figure 3) at a relatively shallow depth (<300 ft), and above elevation 2500 ft.

Oolite sand also occurs in the Veterans Administration (VA) Reinjection Well, at a depth of 450-ft deep at elevation 2,300 feet. We mention this here, because the oolite layer is only 90 feet above the basalt of Aldape Heights which Clemens and Wood (1993) have dated by K-Ar as 9.4 million years old. The oolite sand occurrence here is not well understood. Because oolite in the VA well is only 90 feet above the basalt, it may be that most of the Chalk Hills sediments were eroded from this locality near the edge of the foothills, and oolite of the Terteling Springs Formation transgressed over the basalt surface. It is unlikely that the oolite in the VA well is a carbonate facies within the older Chalk Hills Formation, because nowhere else in the basin has carbonate sediment been found in the Chalk Hills Formation. The oolite layer in the VA well has probably been faulted down at least two hundred feet deeper than occurrences in the 3 UWID wells of west central Boise, suggesting a graben structure near the edge of the foothills.

We believe the sediments containing lenses of shoreline oolites to be a transgressive sequence over an unconformity at the top of the Chalk Hills Formation. An angular unconformity is mapped at the base of the oolite in Stewart Gulch (NW ¼, sec. 22, T. 4 N., R. 2 E.), but elsewhere in the foothills the contact appears to be conformable.

Overlying the oolite-bearing section in the western Boise foothill outcrops, is the "Pierce Park Sand", a 150-to-250- foot-thick layer of coarse sand. This thick sand represents a large "Gilbert-type" delta system. Where the oolite section is absent, the

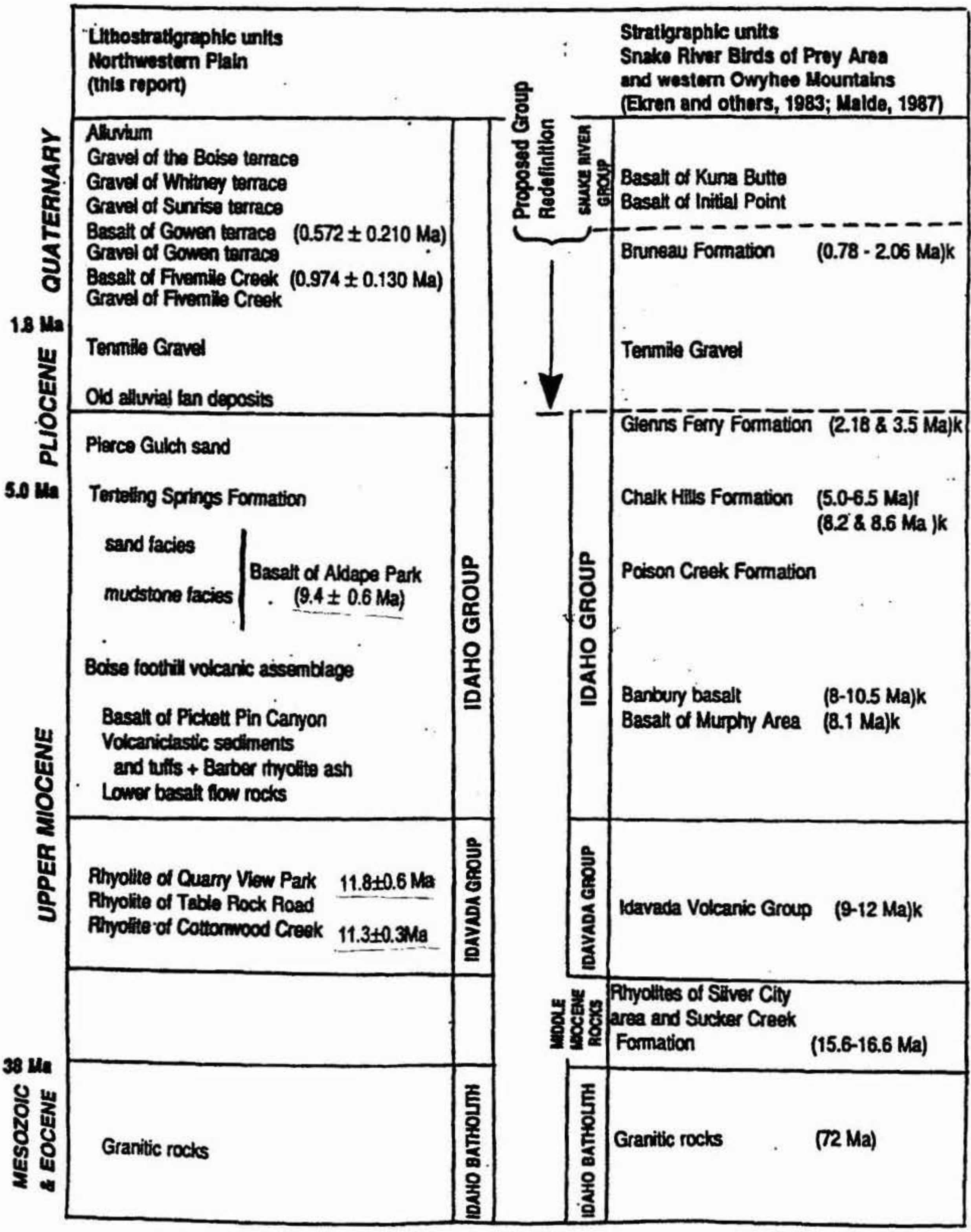


Figure 8. Stratigraphic names in the western Snake River Plain: Comparison of stratigraphic units of the Boise area (from Burnham and Wood, in press) to units mapped on the south side of the plain by other workers.

Pierce Park Sand conformably overlies mudstone. The reason the coarse sand directly overlies mudstone is because the delta prograded basinward over muds of the deep-lake deposits. The delta apparently formed as the level of Lake Idaho began lowering after it reached its spill point into Hells Canyon, probably in the early Pliocene (about 4 or 5 million years ago).

For the first time, in this study, we attempt to correlate the main features mapped in the Boise foothills with the subsurface sedimentary sequence in water wells beneath the city. We make an assumption that the oolite sequence is a singular occurrence in the stratigraphic record. We allow that gravel occurrences in the subsurface could be channel gravel, beach gravel, or river-terrace gravel, and that all gravel occurrences require a beach or a stream environment for deposition. The occurrence of an angular unconformity is not generally detectable in geophysical logs or the sequence of drill cuttings. Logs that detect dip (dip meter, resistivity borehole imager, or acoustic televiewer) have not been run in the Boise area water wells. To detect dip and angular unconformities, the configuration on high-resultion seismic reflection is also useful.

Discussion of the NE-W section from Claremont Subdivision Well to Cassia Street Well (Figure 9)

The dip of the deeper section between the Capitol Mall #2 well and the Julia Davis Well may be as much as 11° to the southwest as determined by a seismic reflection survey by Liberty (1998). The deeper sediments are a mudstone sequence more than 800 feet thick, shown on the borehole geophysical log of the Julia Davis well. Overlying the mudstone, between elevations 2,100 and 2,280 feet, is a sequence of stacked, coarse sand layers, each one 25 to 70 feet thick. Each of the upper 4 sand layers shows a coarsening-upward log signature. The log character of this sand sequence is similar to that shown in the Ridge Basin, California study by Link and Osborne (1978) as a delta-front bar complex (Figure 6). Similar beds occur near the bottom of the Ann Morrison Park well between elevation 2,000 and 2,200 foot elevation.

The overall funnel shape of the Cassia Street logs indicates a fine and medium sand delta above the silty mud at 2,100 foot elevation. These delta sands appear to correlate to sands in the Ann Morrison Park Well, but the funnel-shaped log signature is not as prominent in this well. That correlation implies an apparent dip of about 1.4° in the southwest direction between these two wells, which seems too low a dip, in view of deeper strata dipping in excess of 10 degrees in southwest direction. Another possibility is correlation of the Ann Morrison Park well sands to the deepest sands of the Cassia Street well.

Gravel occurs at the bottom of the Cassia Well at elevation 1,700 feet, but that part of the section was not geophysically logged. No other wells drilled gravel at that depth. The gravel indicates either a gravel beach deposit or a stream channel deposit. The gravel was deposited about 4 miles basinward from the basin margin indicating that the lake environment was not at this locality at the time of deposition: this locality was either a stream bed or a shoreline.

The major sand section of these wells is below an unconformity marked by an upper gravel, generally occurring in wells between elevation 2,400 and 2,550 feet (line colored pink on Figure 9). In the next paragraph we discuss evidence interpreting this unconformity as the top of the Chalk Hills Formation. The deeper sand section in these wells on the north side of the Boise River all appear to be good aquifers down to at least 1,600 elevation; however, temperatures approaching 85°F below that level may preclude development for cold-water supply.

The unconformity is marked by a prominent gravel bed about 30 feet thick in the Cassia Well at elevation 2, 550 feet. This gravel correlates with gravel in the Ann Morrison Park Well and with the Julia Davis well. This gravel horizon is shown with a pink line in Figure 9. Cavanagh (2000, p. 68-72) discovered from examination of well cuttings and Carbon-13 isotopic analysis of carbonate that a soil caliche had developed in this gravel layer. This discovery shows that the lake had receded from this area at one time, and a soil formed upon a river-terrace gravel, or perhaps an abandoned beach gravel. Above this gravel, in the Cassia well, a 30-ft thick carbonate oolite sand containing gastropod fossils occurs as a coarsening upward layer at a depth of 110 feet (elevation about 2,670 ft.) These features are taken as evidence that rising lake water transgressed over this gravel and and laid down the upper 200 to 300 feet of mostly near-shore lake sediment of these wells. It is uncertain whether the erosional unconformity is in the Capitol Mall#2 well. It may warrant re-examination of the cuttings to see if it can be identified. No obvious correlative gravel is reported from that well or the recently drilled Tower well, suggesting that this gravel horizon was not deposited to the northeast, or has since been eroded by the downcutting of the Boise River Valley.

Gravel of the active floodplain of the Boise River is about 60 feet thick in the downtown Boise area of these wells, and so is the terrace gravel that mantles the Whitney Bench. The bases of both river gravels are shown in Figure 9 by a yellow line.

Although we do not have a good geochronology of the lake deposits beneath Boise, the major geologic events can be tentatively correlated with the proposed, albeit hypothetical lake history proposed by Wood and Clemens (in press). In this correlation, none of the deposits shown in the section of Figure 9 would be correlated with the Glenns Ferry Formation. The very thick sediment section beneath the transgressive sequence would be regarded as the Chalk Hills Formation. The overlying sequence would be the Terteling Springs Formation. To the north of here (Swift Well to McMillan Well) is a delta sequence that appears to correlate with the Pierce Park sand. The Pierce Park sand is believed to be correlative in time with the declining lake level and the Glenns Ferry Formation.

Discussion of E-W section from Swift Well to the McMillan Well (Figure 10)

The two Swift-well sand aquifers appear to correlate with the Hewlett-Packard well, almost straight across; however, the Chevron Seismic data shows the lower sand in Swift to have an apparent west dip of about 2°, and to lie at least 300 feet below the bottom of the Hewlett Packard well (Figure 10). Well-log character of the deeper aquifer sand in the Swift Well has an abrubt base, typical of a channel sand, and the grain size is medium-fine sand. That lower aquifer appears to correlate with the bottom sand aquifer in the Goddard well. However, information on that bottom aquifer in the Goddard well is limited to the 1968 driller's description (see Squires and others, 1992, p. 94). It is problematic that no major sand units occur in the up-faulted foothills section to the northeast, either in outcrop or in wells, that might correlate with the lower Swift well

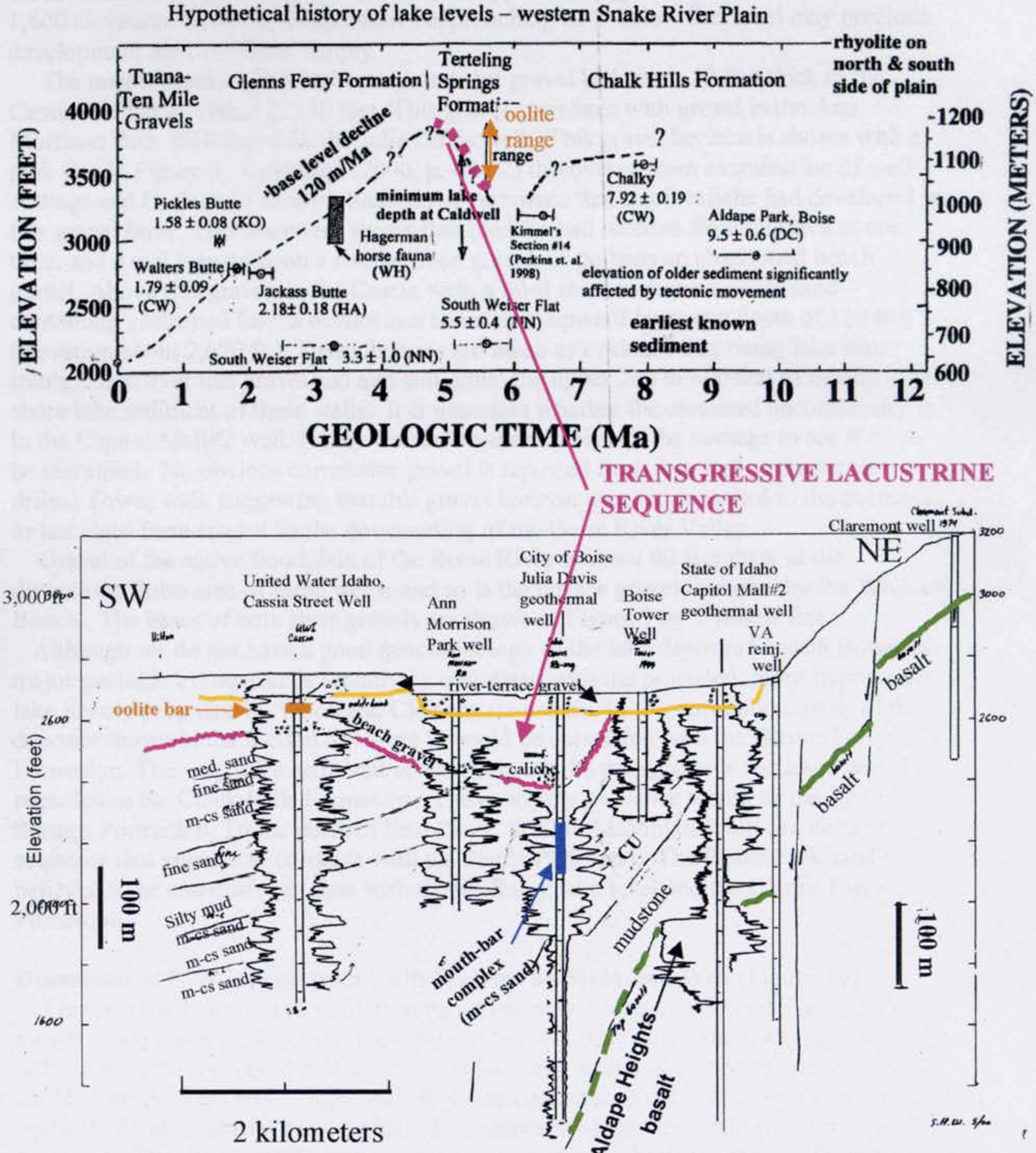
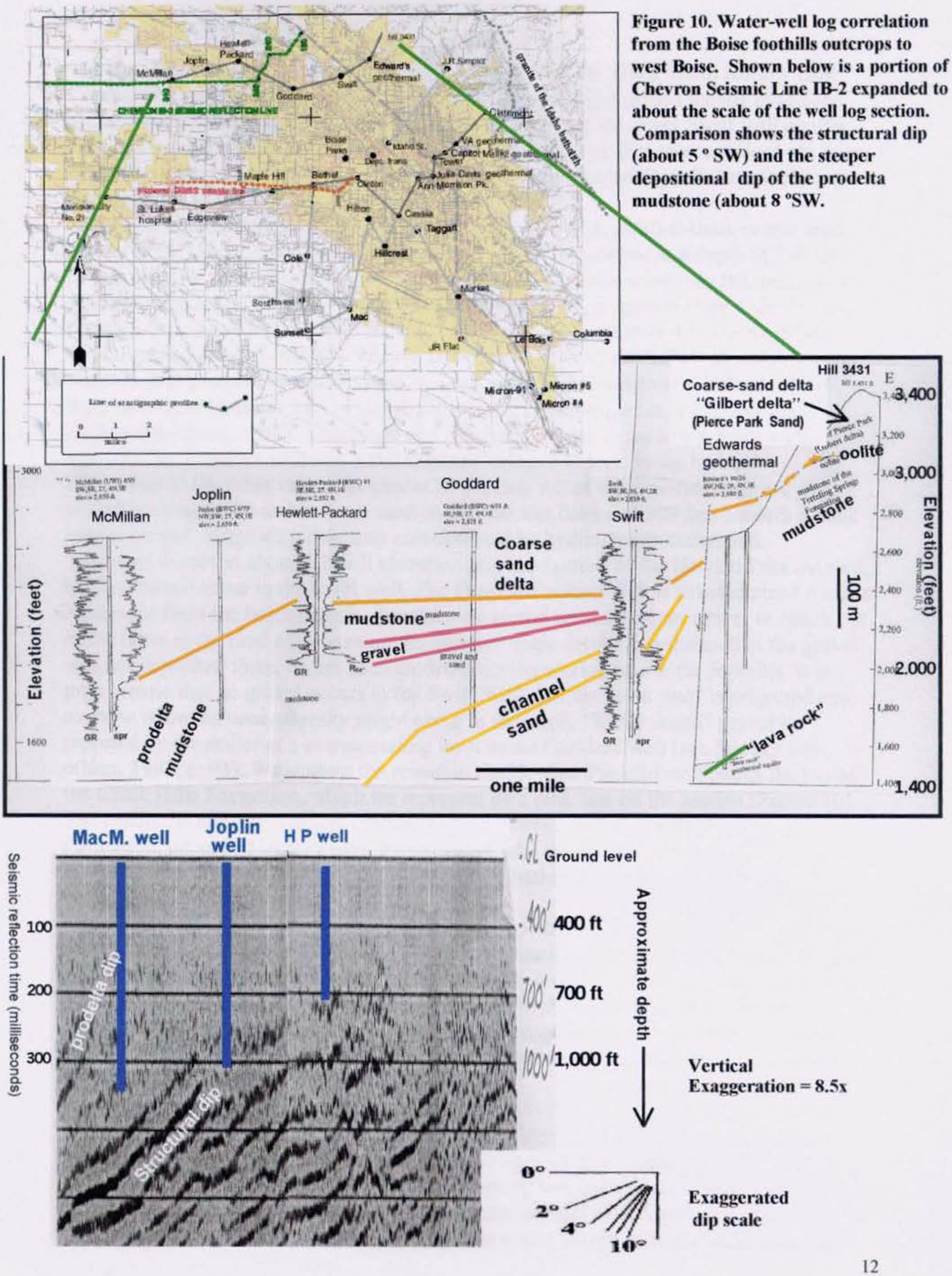


Figure 9. Correlation of strata in wells in a section from the Boise foothills (Claremont well, Boise Heights) to the Cassia Street Well. Basalt of Aldape Heights (9.5 Ma) shown in green. Mouth-bar complex of a sand delta deposited over mudstone shown in blue at the Julia Davis well. CU refers to coarsening upward sand layers, shown by small arrows. Dark pink line is an unconformity at about 2,400-ft elevation, indicated by Carbon-13 isotope analysis of caliche in the Julia Davis Well by Cavanagh (2000, p. 68-72). The unconformity surface is identified by occurrence of gravel in other wells, and is interpreted as the top of the Chalk Hills Formation. Sediment above the unconformity contains oolite, and is interpreted to be a part of the Terteling Springs Formation. Quaternary-aged terrace gravel shown in yellow. Hypothetical lake history corresponding to deposits is from Wood and Clemens (in press).

Figure 10. Water-well log correlation from the Boise foothills outcrops to west Boise. Shown below is a portion of Chevron Seismic Line IB-2 expanded to about the scale of the well log section. Comparison shows the structural dip (about 5 ° SW) and the steeper depositional dip of the prodelta mudstone (about 8 °SW.



aquifer. The nearby deep wells in the foothills (Hillside Jr. High, Quail Hollow Golf Course, and wells on the Terteling Stewart-Gulch properties) drilled mostly mudstone according to driller's logs. Possibly the section containing the lower Swift well aquifer sand has been eroded from the upthrown fault block, and for that reason it does not occur in the foothills. Alternatively the lower sand may be a channel deposit that simply was not deposited to the northeast.

One and one-half miles to the northwest of the Swift well, an 80-ft-thick coarse sand occurs in the UWID Gary Lane well below 350 feet of mudstone at a depth of 740 feet. In this well, the grain size is mostly 0.5 to 2 mm, and much coarser than the medium-fine sand reported for the lower Swift well aquifer. Otherwise, it appears to be a similar and possibly correlative sand. Three and one-half miles to the northwest of the Swift well is the Treasure Valley Hydrologic Project Monitoring Well #1 (TVHP#!) in which several medium-fine-grained sand beds occur beneath 300 feet of mudstone at a depth of 770 feet. Individual beds are 2 to 10 feet thick, and the sandy sequence is 120 feet thick (Dittus and others, 1997). Grain-size and depth are similar to the lower Swift well aquifer. The TVHP#1 well was not completed below 340 feet, so the hydraulic connection to the other two wells cannot be studied. All of these occurrences are probably along strike and indicate sand about 700 feet deep and 300 feet beneath a thick mudstone unit, suggesting they may correlate and be hydraulically connected.

Gravel occurs at about 2,100-ft elevation near the bottom of the Hewlett Packard well, but it does not occur in the Swift well. The Hewlett Packard well is situated about 6 miles basinward from the basin margin, therefore the gravel must represent a river or beach out in the basin at the time of deposition. Its absence in the foothills, requires that the gravel was not deposited there, or has been eroded from the section nearer the foothills. It is problematic that no gravel occurs in the Swift Well, but the "pink line" is projected east to show where an unconformity might occur in that well. "Red-colored" gravel is reported by the driller at a corresponding level in the Goddard well (see Squires and others, 1992, p. 94). We suspect the gravel in the Hewlett Packard well marks the top of the Chalk Hills Formation, which we represent by a pink line on the section (Figure 10). The mudstone above the gravel is tentatively correlated with the Terteling Springs Formation, deposited by the rising transgressive lake water. That mudstone, changes upward to the prodelta mud of a delta prograding basinward, discussed in the next paragraph.

In the foothills, and in all wells on the section depicted in Figure 10 is a clear signature of a delta prograding into the Basin. The delta signature on the logs the a funnel shape of side-by-side gamma and resistivity logs (Figure 4 B and D) seen in the Swift and Hewlett Packard wells above 2,350-ft elevation, and in the McMillan well above 1,900-ft elevation. The sand thickness and depth increase progressively to the west. The delta sand is coarse in the foothills, and the driller reported coarse sand in the depth interval 153 to 280 feet in the McMillan well.

Because this is the uppermost delta in the lacustrine sequence, we correlate it to the Pierce Park sand that crops out in the upper part of the foothills section west of Crane Creek. In the foothills, this unit is mostly foreset beds of coarse sand typical of the "Gilbert-type" of delta. Some foreset bed sets are 60 feet thick, and the sand unit as a whole is up to 250 feet thick in the foothills (Burnham and Wood, in press). This delta is then correlated by Wood and Clemens (in press) to the history of Lake Idaho. Since it is the uppermost major delta in the section its deposition over mudstone, is explained as a prograding sand delta in response to the slow lowering of lake levels after Lake Idaho spilled over into Hells Canyon. In the lake history context, this uppermost delta should correspond to the upper part of the Glenns Ferry Formation of Malde and Powers (1962) and Reppening and others (1994) which crops out south and southeast of the Boise area along the Snake River

We feel fairly certain that there is a "long term" hydraulic connection in the sands of the upper delta sequence (Figure 10); however, local lenses of mudstone in that section may prevent short-term detection of well-drawdown responses. It may take months to decades for large drawdowns to propagate through this seemingly continuous section of interbedded sand and thin muds.

Other older sand deltas surely occur in the lacustrine section. For example in Figure 9, the lower sands in the upper 800 feet in the Julia Davis well are mouth-bar sands of a delta sequence over mudstone. However because this section is steeply dipping, this delta is much older than the upper 800 foot section of the McMillan well (Figure 10). In our interpretation the delta sands in the Julia Davis well are part of the much older Chalk Hills Formation.

Comments on structure

We did not re-interpret the structure along the two cross-sections; however the framework published by Squires and others (1992, their Figure 11) generally concurs with observations in this study. They show the Eagle-west Boise fault with 800 feet of offset between the Swift well and Goddard well using data available to them at that time. The 800-ft offset they show is the offset of the volcanic basement. The fault does not necessarily offset of the upper section. The aquifer section below 2000-ft elevation (about 700 ft deep) may be offset, but the Eagle-west Boise fault does not appear to significantly offset the upper delta sequence.

Squires and others (1992) also show the "foothills fault zone", just northeast of the Swift well. In our Figure 10, the base of the upper delta is shown as offset by 300 feet with respect to the foothills outcrops, however this elevation shift could also be due to tilting without significant faulting. It is likely that a major fault or fault system occurs between the Swift well and the Edwards geothermal well and that this fault offsets the deeper section. Lava rock is reported by the driller at elevation 1,500 ft in the 1926 well (Idaho Supreme Court Records, *Silkey vs. Teigs,* 1931) showing that the "volcanic basement is relatively shallow here (Figure 10). None of these geothermal wells have been logged by borehole geophysics, and we do not know whether the geothermal aquifer in this area is basalt or rhyolite.

Conclusions

In this study we have identified gravel layers, oolite beds, thick mudstone sequences, and thick delta sequences that appear to correlate with regional concepts of fluvial and lacustrine deposition as outlined by Wood and Clemens (in press). We are still uncertain how many gravel layers are in the section; however, occurrence of gravel layers out in the basin, several miles basinward from the basin margin is an indication that the lake level lowered several times and streams flowed over exposed lake beds and delivered gravel away from the uplands. Some gravel may be beach gravel, and some may be channel or remnant terrace gravel; however, it had to be originally delivered to the site by a stream.

Our best evidence that a lake transgressed over the gravel is the occurrence of oolite sands in the shallow section of the Cassia, Taggert, and Cole wells (Figure 3 and 9). This section shown in Figure 9 also indicates that there may be topographic relief upon the tilted and eroded older section. This is also our best evidence that the sedimentary sequences shown in this profile (Figure 9) correlate to the Chalk Hills Formation and the overlying Terteling Springs Formation. We also conclude that the Pierce Park sand (correlative with the upper Glenns Ferry Formation) is absent from the section shown in Figure 9, but the Pierce Park Sand is the same sand as the upper delta sequence in the Swift, Hewlett-Packard, and McMillan wells shown in Figure 10.

Deeper sedimentary strata comprising the aquifer system have been tilted basinward (to the southwest, 2 to 11 degrees. The deeper strata are offset by faulting, but the amount of offset is known only where seismic data is available. The extent to which shallow parts of the aquifer system are faulted and tilted has not been determined, because the available petroleum-industry data was not focused on the shallow section (<600 feet) (see seismic section in Figure 10).

Eventually, the aquifer geometry can be determined accurately using high-resolution seismic reflection methods and continued diligence in obtaining borehole geophysical logs and cuttings examination of drilled water wells. We hope that this study provides a framework for future study.

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