ASSESSING THE POTENTIAL FOR DEEP-SEATED SALT DISSOLUTION AND SUBSIDENCE AT THE WASTE ISOLATION PILOT PLANT (WIPP)

Peter B. Davies

Department of Applied Earth Sciences
Stanford University
Stanford, California 94305

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1. INTRODUCTION

The following discussion of technical questions concerning deep-seated salt dissolution and the Waste Isolation Pilot Plant (WIPP) has been prepared for the Environmental Evaluation Group conference on "WIPP Site Suitability for Radioactive Waste Disposal" (May 12-13, 1983, Carlsbad, New Mexico). The discussion focuses on recently released WIPP studies of the geologic and hydrologic evidence for and against the occurrence of deep-seated salt dissolution within the Delaware Basin (as opposed to dissolution associated with the Capitan Reef around the margin of the basin) (Figures 1-1 and 1-2). This paper assumes that the reader has a working knowledge of the geology and hydrology of the Delaware Basin, as well as familiarity with the WIPP project.

The central question of concern is whether or not deep-seated salt dissolution and the associated development of breccia chimneys (breccia pipes) or other subsidence structures pose a significant threat to the long term integrity of the WIPP repository. This question can be broken down into the following geotechnical problems:

- Are the hydrogeologic conditions at WIPP capable of producing deep-seated salt dissolution?
- If deep-seated salt dissolution occurs, what type of subsidence would be produced, and how would this subsidence affect the hydrologic integrity of the repository?

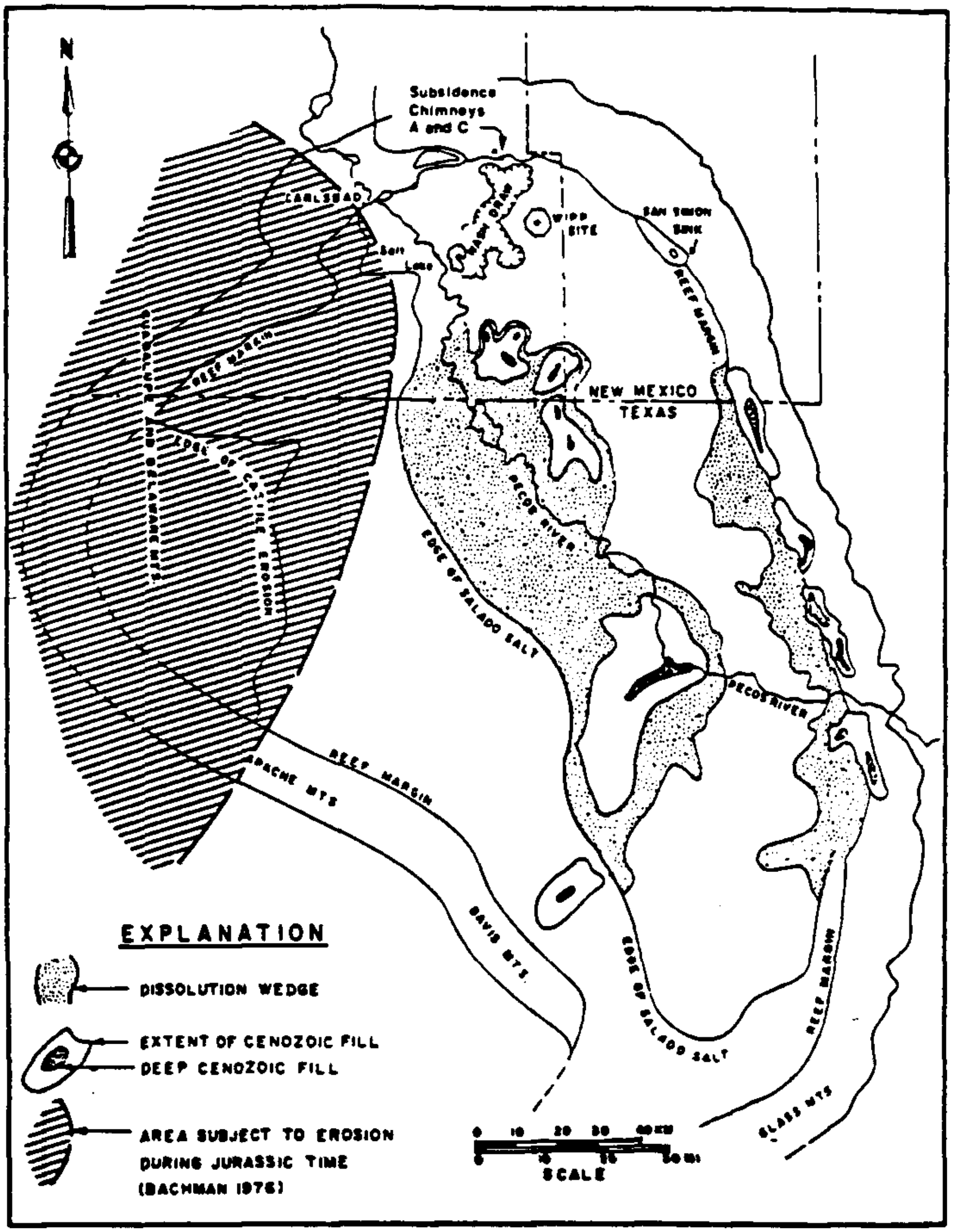


Figure 1-1. Map of the Delaware Basin showing the location of the WIPP site and of major dissolution-subsidence structures. (Adapted from Powers, et al., 1978).

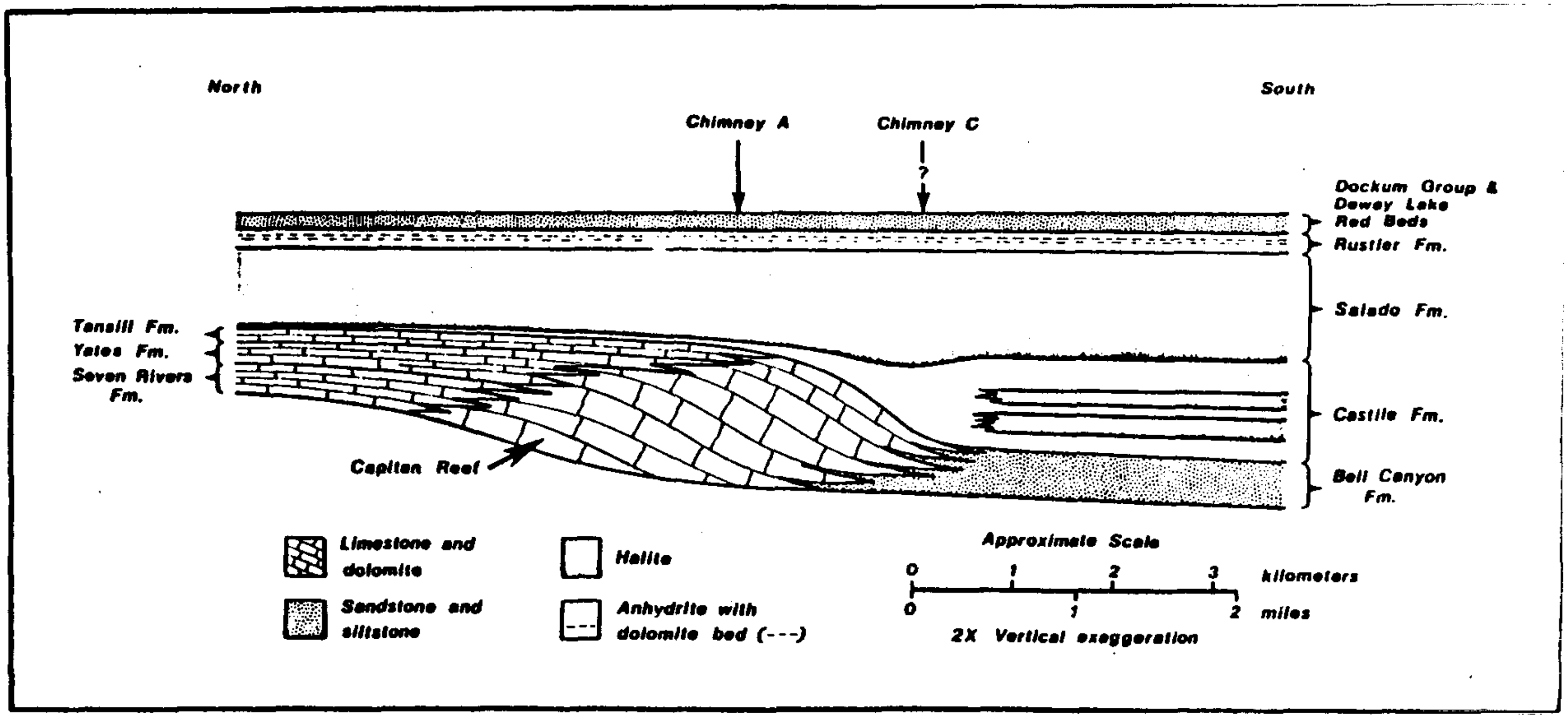


Figure 1-2. Schematic north-south cross section transecting the northern margin of the Delaware Basin. This cross section illustrates the stratigraphic relationships between the evaporites (Salado and Castile Formations) and the underlying Capitan Reef and Bell Canyon Formation. The approximate locations of subsidence chimneys "A" and "C" are shown, based on Hiss (1975) and Gail's (1974) interpretation of the thickness and distribution of the Capitan aquifer. This cross section has been adapted from the work of King (1948), Jones and Madsen (1968), and Meissner (1972). (From Davies, 1983).

Three WIPP studies have recently been completed that address the deep-seated salt dissolution issue. Those reports and their principal conclusions are briefly summarized in the following paragraphs.

Snyder and Gard (1982) carried out a detailed investigation of two dissolution-subsidence chimneys on the northern margin of the basin (Figures 1-1 and 1-2) and reviewed subsurface information from the WIPP site. They conclude that "no examples of breccia pipes that could lead to breaching of a repository at the WIPP site have been found to date and are not likely because the Capitan limestone is not present beneath the site" (p. 66).

Lambert (1983) reviewed the hydrogeology and geochemistry of the Bell Canyon Formation, and the characteristics of several salt dissolution models. He concludes that there is no interconnected flow within the Bell Canyon Formation and that there is no movement of fluids between the Bell Canyon and the adjacent Capitan aquifer (p. 30). From the geochemistry of Bell Canyon water samples, Lambert concludes that the Bell Canyon water is not involved in active salt dissolution as either a source or sink (p. 75-76). Lambert proposes a "stratabound" model for dissolution in which groundwater flows through fractured anhydrite beds, causing dissolution of the adjacent halite (p. 83-86). The primary difference between this model and a model proposed by Anderson (1981) is the discharge point for the solute rich fluids. Anderson (1981, p. 144) suggests that these fluids drain downward and are carried away by flow in the Bell Canyon Formation. Lambert suggests that these fluids move upward into "a chain of debris-filled depressions leading southward" and discharge at an unspecified location in the southern Delaware Basin.

Wood, et al. (1982) examine salt dissolution and transport mechanisms, and then evaluate the potential for future deep-seated salt dissolution in the Delaware Basin. Based on analytical and numerical computations, this report concludes that very slow dissolution, limited by the rate of molecular diffusion of dissolved NaCl through the lowest anhydrite of the Castile Formation, could produce the observed chloride concentrations in the Bell Canyon in the WIPP area (p. 80). Such dissolution could remove, at most, 10 centimeters of salt over 10,000 years in the WIPP area (p. 98). Since these results do not preclude more intense localized dissolution, "worst case" analyses were carried out assuming density-driven convective flow in a fracture and in a cylindrical porous zone. These computations yield, for a 10,000 year period, a cylindrical cavity with a 7 meter radius for the fracture case and a one meter high, 93 meter diameter cavity for the cylindrical porous zone case (Figure 1-3) (p. 98-99). The report concludes that neither of these cavities would adversely affect the WIPP repository (p. 101).

As noted by Snyder and Gard (1982), the Capitan aquifer does not extend below the WIPP site, and therefore, subsidence structures resulting from dissolution along the Capitan aquifer cannot adversely affect the site. However, the possibility of dissolution and subsidence associated with groundwater flow in the Bell Canyon Formation and/or within fractured Castile anhydrites is another issue. A key component of Anderson's (1980, 1981) salt dissolution models is the ability of the Bell Canyon Formation to transport dissolved salt. Lambert (1983) concludes that there is no interconnected flow within the Bell Canyon and therefore Anderson's models for deep seated dissolution cannot be applied to the WIPP area. Wood, et al. (1982) conclude that dissolution associated with Bell Canyon flow could occur, but this dissolution (even for the "worst case") is severely limited by the small transport capacity of the Bell Canyon. Because of the critical role of the Bell Canyon, the following reviews of Lambert (1983) and Wood, et al. (1982) will focus primarily on Bell Canyon hydrogeology.

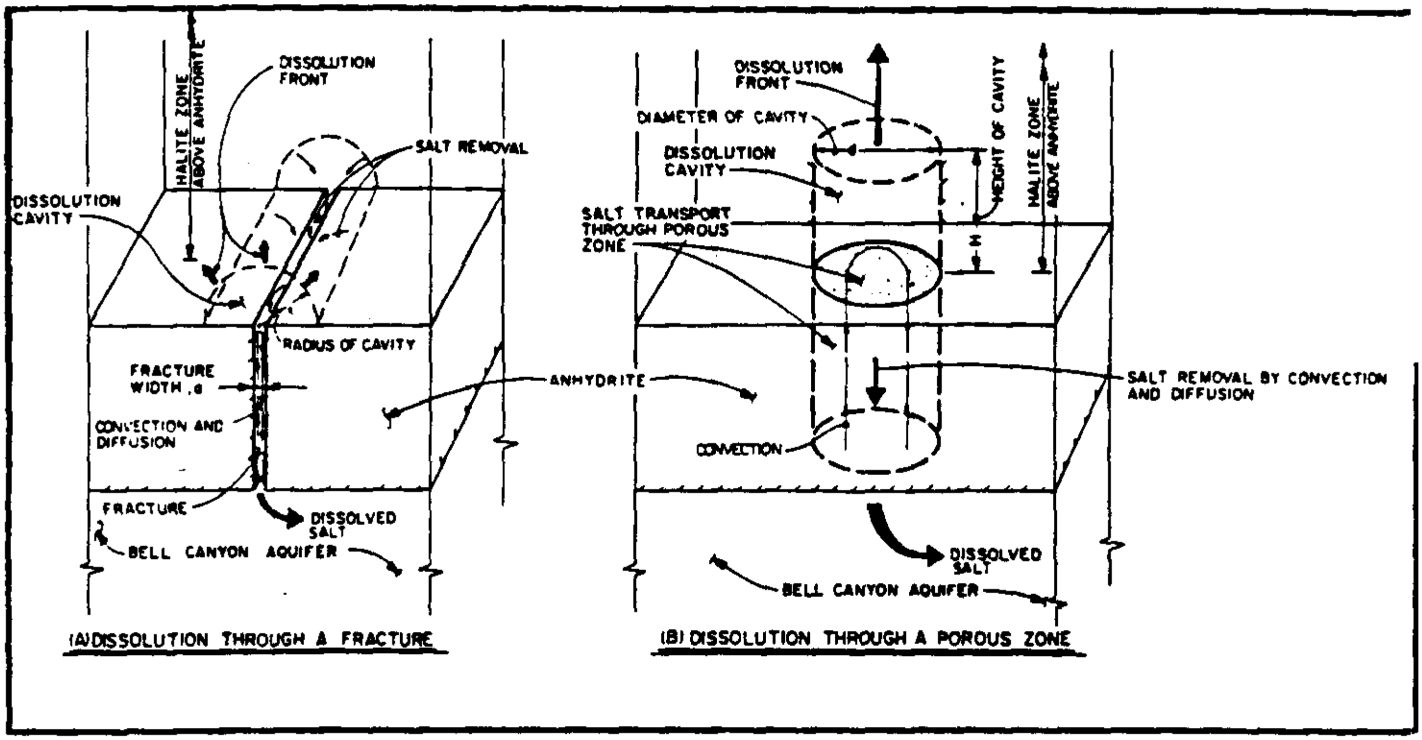


Figure 1-3. Illustration of localized salt dissolution as modeled by Wood, et al. (1982). (From Wood, et al., 1982).

2. BELL CANYON HYDROGEOLOGY - A REVIEW OF LAMBERT (1983)

Lambert (1983) proposes rather substantial changes to Hiss's (1975) interpretation of the hydrogeology of the Delaware Mountain Group (also called the "Basin Aquifer" by Hiss). Lambert's interpretation focuses on the Bell Canyon Formation, the uppermost formation in the Delaware Mountain Group. Two fundamental changes are proposed: (1) there is "essentially no connected flow within the Bell Canyon Formation" and (2) there is "virtually no involvement of the Bell Canyon in either recharge to or discharge from the Capitan" (p. 30).

The petroleum industry has developed extensive information about the Bell Canyon Formation, such as (1) the lithologic and depositional characteristics; (2) the hydraulic characteristics; and (3) the occurrence and movement of fluids. Fortunately, much of this information is available in the geological literature. An effective way to examine Lambert's reinterpretation of Bell Canyon hydrogeology is to examine each component of his interpretation for consistency with the information that has been developed by the petroleum industry.

2.1 Hydrogeologic Characteristics of the Bell Canyon Formation

Lambert's conception of the units within the Bell Canyon that are capable of transmitting water is as follows:

> The Bell Canyon contains permeable sandstone strata. Field and core testing has shown that these superposed saturated zones are ~15 ft thick, and are hydrologically isolated from one anoth... by sandstone

> of low vertical permeability. The two saturated zones nearest the base of the evaporites are ~500 ft below the Lamar.
>
> Lambert, 1983, p. 18

> During the renewed drilling of AEC 8 into the Bell Canyon Formation, geophysical logging revealed the vertical distribution of porosity in the sandstone units. Mercer and Orr (1979) did not comment on the Lamar member and the Ramsey sand (a locally important hydrocarbon "pay" zone) due to their low porosity. Two other sandstone beds (4832.5 to 4848.5 and 4809.5 to 4815.5 feet below Kelly bushing in AEC 8, known as the lower sand and upper sand, respectively) were the only potential water-yielding units encountered in the upper 700 feet of the Bell Canyon Formation . . .Thus, in the upper 700 feet of the Bell Canyon Formation, the total saturated thickness is <30 feet.
>
> Lambert, 1983, p. 25-26

This conception of the Bell Canyon is schematically illustrated in Figure 2-1. Note that Lambert implies that the hydrostratigraphy observed in AEC 8 is found over a large portion of the basin and that other than the two sandstone units, which are approximately 500 feet below the evaporites, the remainder of the upper 700 feet of the section is essentially impermeable and therefore transmits no groundwater.

This interpretation of the sedimentary facies and porosity/hydraulic conductivity (permeability) distribution in the Bell Canyon is not consistent with the information that has been developed by the petroleum industry. The Bell Canyon is a thick section of sandstone and siltstone (with some shale) that was deposited in a deep-water basin. The distribution of sand was controlled by numerous basinward-trending deep sea channels. These channels extend as far as 70 kilometers (44 miles) into the basin, and range from 0.5 to 8 km (0.3 to 5 miles) in width and from 1 to 35 meters (3 to 115 feet) in depth (Williamson, 1979, p. 39, 57). These sand-filled channels were incised into, and later

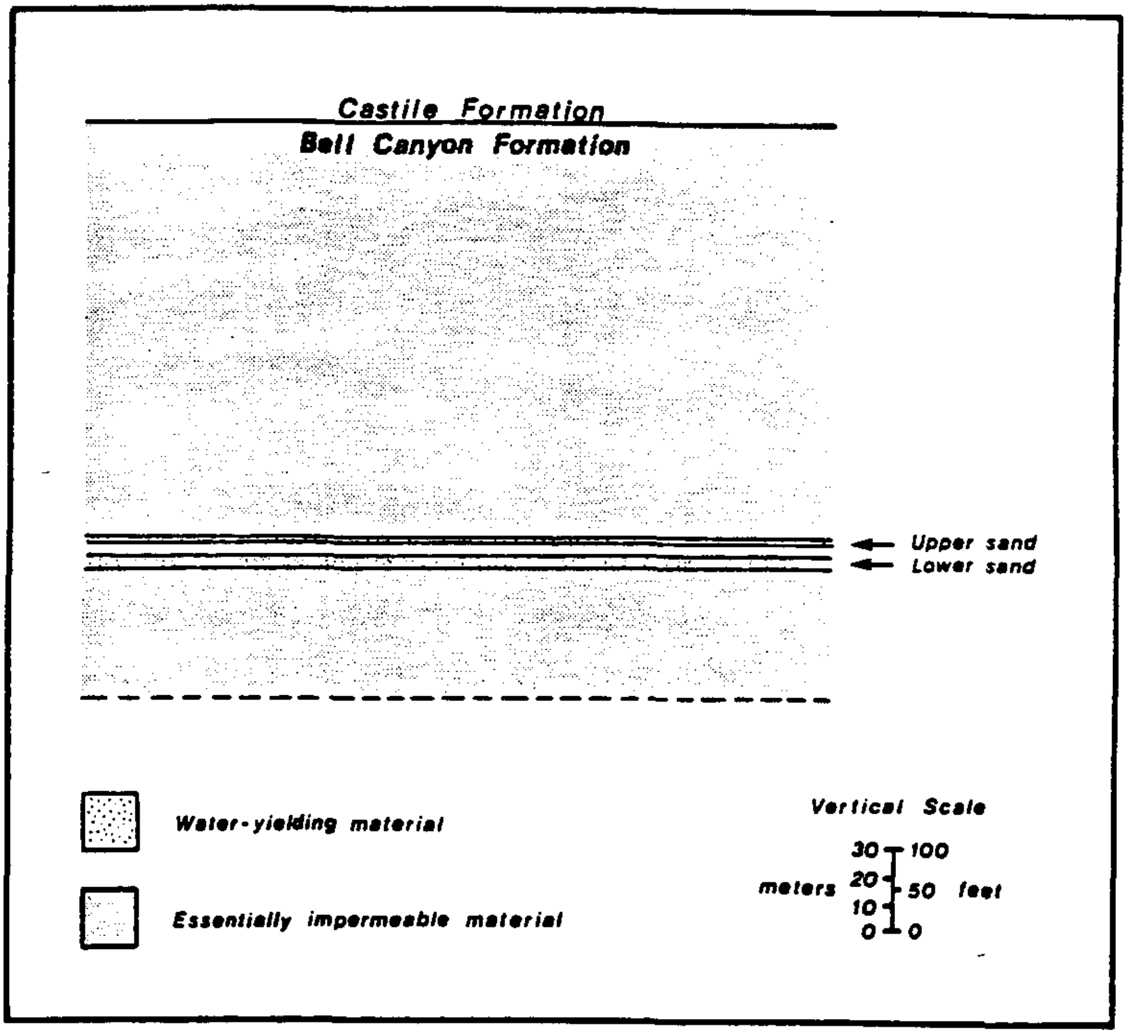


Figure 2-1. Schematic cross section illustrating Lambert's (1983) interpretation of Bell Canyon hydrostratigraphy. (This schematic section has been constructed following Lambert's (1983, p. 18, 25-26) description of Bell Canyon hydrostratigraphy. This section has the same vertical scale as the cross sections in Figure 2-3).

covered by, silt that was deposited from suspension, forming a complex sequence of elongate, overlapping (in many places) sandstone bodies with siltstone filling the inter-channel areas. Both turbidity currents (Jacka, et al., 1972, p. 172; Newell, et al., 1953, p. 54) and nonturbid, cold or saline density currents (Harms, 1974, p. 1782-1783; Williamson, 1979, p. 69-70) have been proposed as the mechanism for cutting and filling such channels. This complex sequence of channel sandstones and interchannel siltstones has been observed both in outcrop and in the subsurface. To the south and east of WIPP, extensive subsurface exploration has revealed the existence of several major channel sandstone trends in the upper Bell Canyon (Williamson, 1977, 1978, 1979) (Figures 2-2 and 2-3). Because deposition in the WIPP area occurred under similar conditions, major channel sandstones most likely exist in WIPP vicinity as well. The next important question is: What is the hydraulic conductivity of the sandstone and siltstone facies?

Lambert (1983) does not cite any specific values of hydraulic conductivity or porosity for either of his two "water-yielding strata" or the remainder of the section in the upper 700 feet of the Bell Canyon. However, he does make the following comment:

> Hiss (1975) compiled several laboratory determinations of permeability and porosity by oil companies. . .About 4900 feet of core was measured (4500 samples), mostly in horizons of the geologic section most promising for hydrocarbon production. . .Hiss reports an "average" permeability for the "Delaware Mountain Group" in the four county area (Eddy, Lea, Winkler, Ward) of 6.70 mD ($\sim$0.016 ft/d or 0.005 m/d [6×10^{-6} cm/sec] expressed as hydraulic conductivity). The "average" porosity was 15.65%.

Lambert, 1983, p. 26

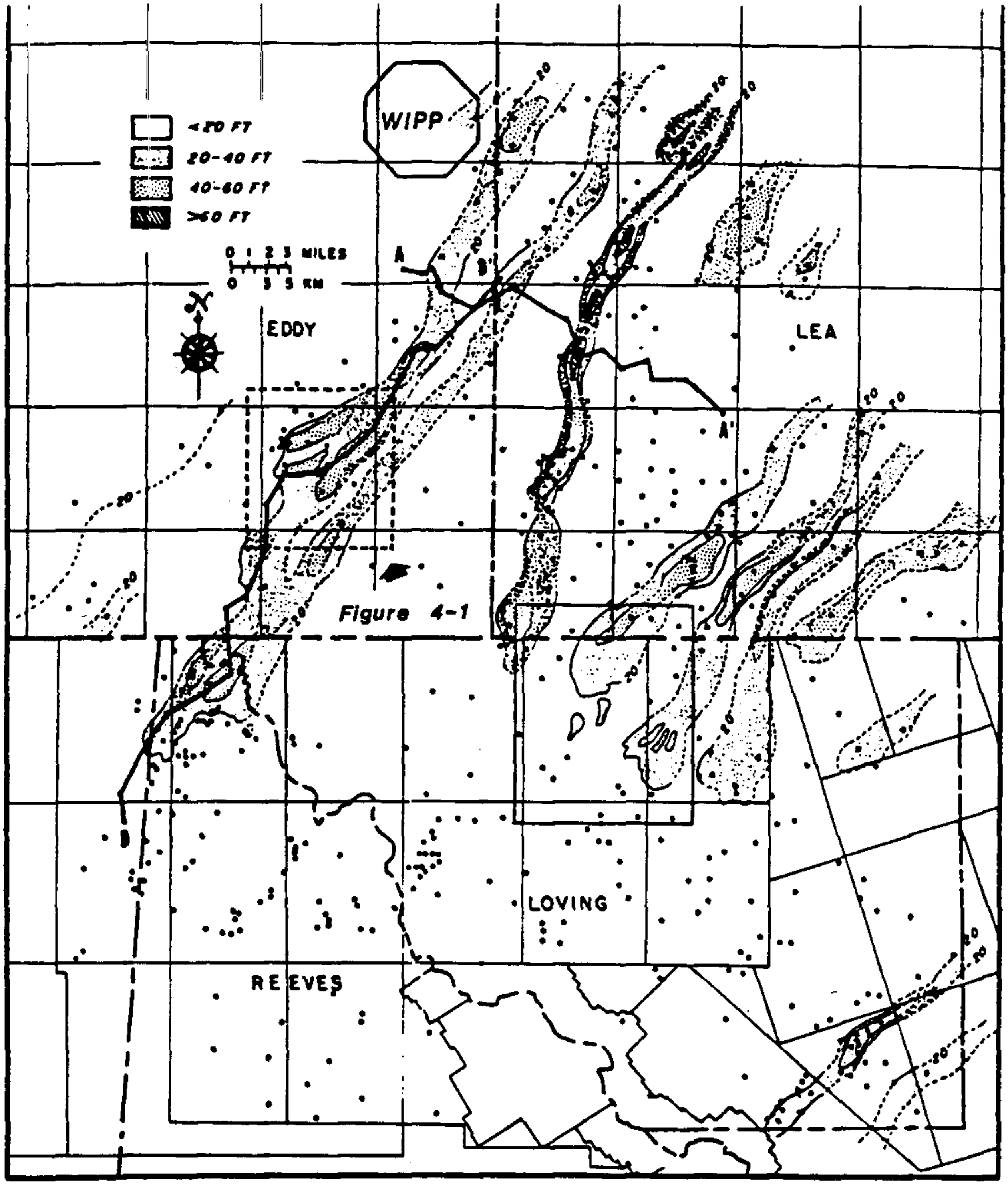


Figure 2-2. Regional sandstone isolith map of the uppermost Bell Canyon Formation (Ramsey Sandstone) showing the distribution of major channel sandstones. In the immediate vicinity of the WIPP site there is insufficient subsurface data to define the location of channel sandstones, however, regional trends suggest that channel sandstones may underlie at least part of the site. Note that this map does not show the distribution of pre-Ramsey channel sandstones. (Adapted from Williamson, 1979).

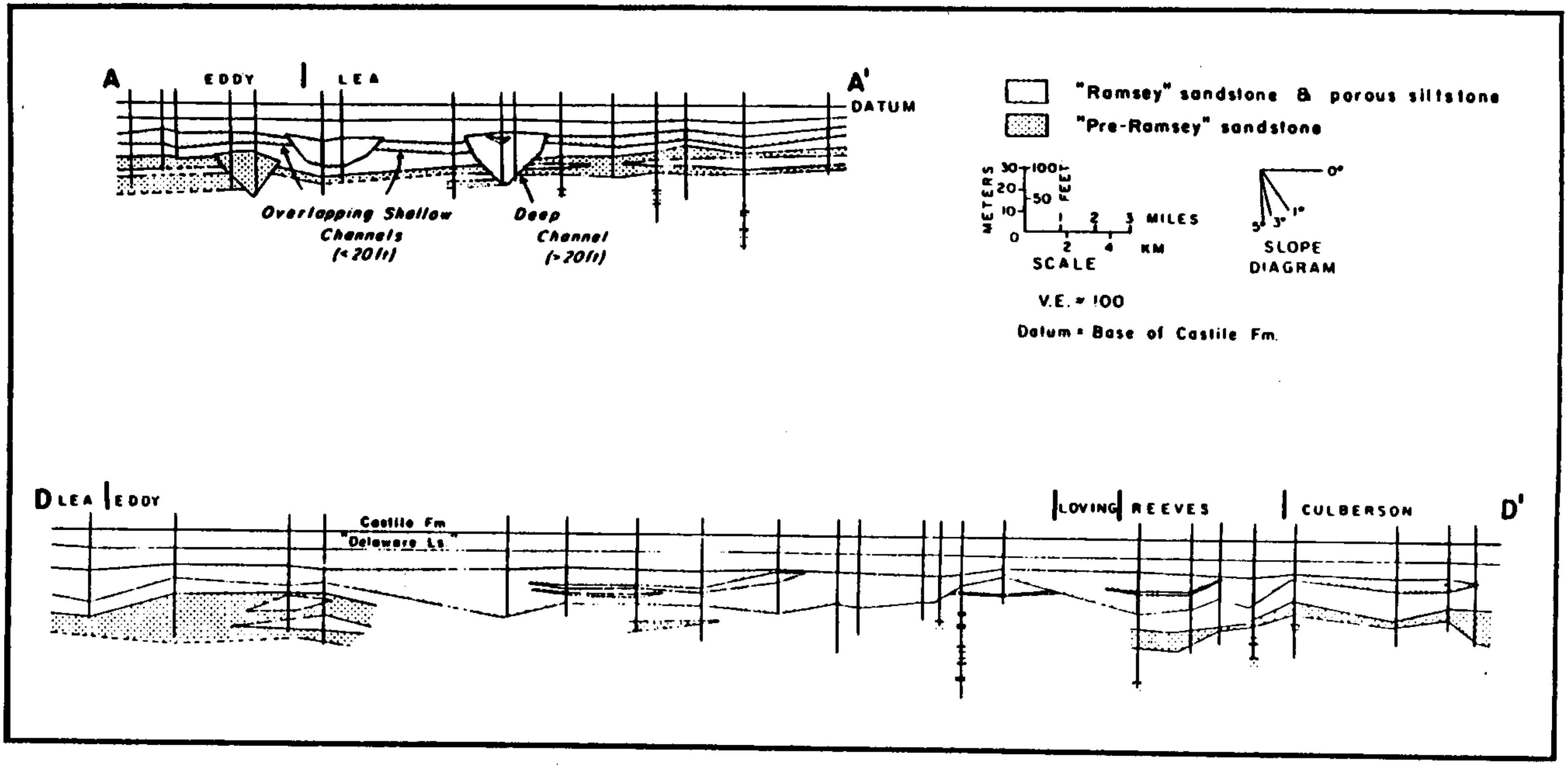


Figure 2-3. Regional stratigraphic cross sections of the upper Bell Canyon Formation. Areas separating sandstone are siltstone. The location of these cross sections is shown on Figure 2-2. (From Williamson, 1979).

Because the bulk of the core for these measurements presumably came from horizons targeted by the petroleum industry, Lambert concludes that "these values must be considered local maxima, and not representative of the entire Guadalupian sequence or the Bell Canyon Formation" (p. 26).

Permeability and porosity measurements by the petroleum industry have not been exclusively limited to reservoir sandstones. Data has been gathered on lower permeability sandstones and on the siltstone facies as well. In order to place Hiss's "average" values into perspective, permeability and porosity data have been compiled for the Bell Canyon, and is summarized in Figures 2-4 and 2-5. In Figure 2-4 and throughout the remainder of this report, permeability values are expressed in terms of equivalent hydraulic conductivity (assuming water at 20^{o}C). In Figure 2-4, note that Hiss's "average" hydraulic conductivity of 6 x 10^{-6}cm/sec is not a "maximum", as Lambert suggests. In fact maximum conductivities are one and a half orders of magnitude higher, at 2 x 10^{-4}cm/sec. Similarly in Figure 2-5, note that Hiss's "average" porosity of 15.65 percent is only half of the maximum reported porosity of 30 percent. This range of porosity and hydraulic conductivity values for the sandstone facies is not anomalously low for this rock type. In fact, these sandstone conductivities and porosities are well within the range commonly found in sandstones, 10^{-8}cm/sec to 10^{-3} cm/sec for conductivity and 5 to 30 percent for porosity (Freeze and Cherry, 1979, p. 29, 37; Brace, 1980, p. 242). As seen in Figures 2-4 and 2-5, the hydraulic conductivity and porosity of the siltstone facies are not that much lower than the sandstone. This fact has been noted in the petroleum literature.

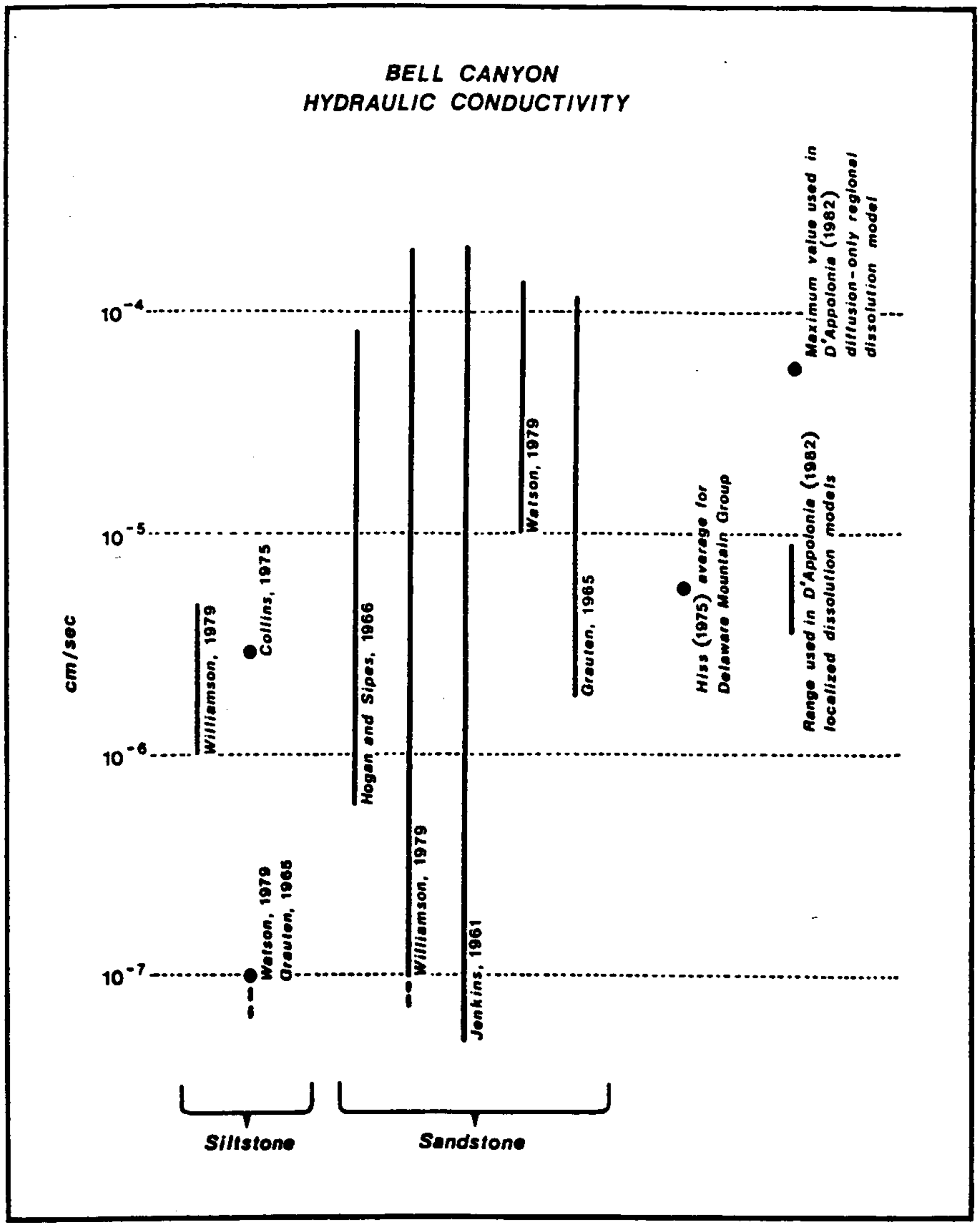


Figure 2-4. Compilation of Bell Canyon hydraulic conductivity (permeability) data.

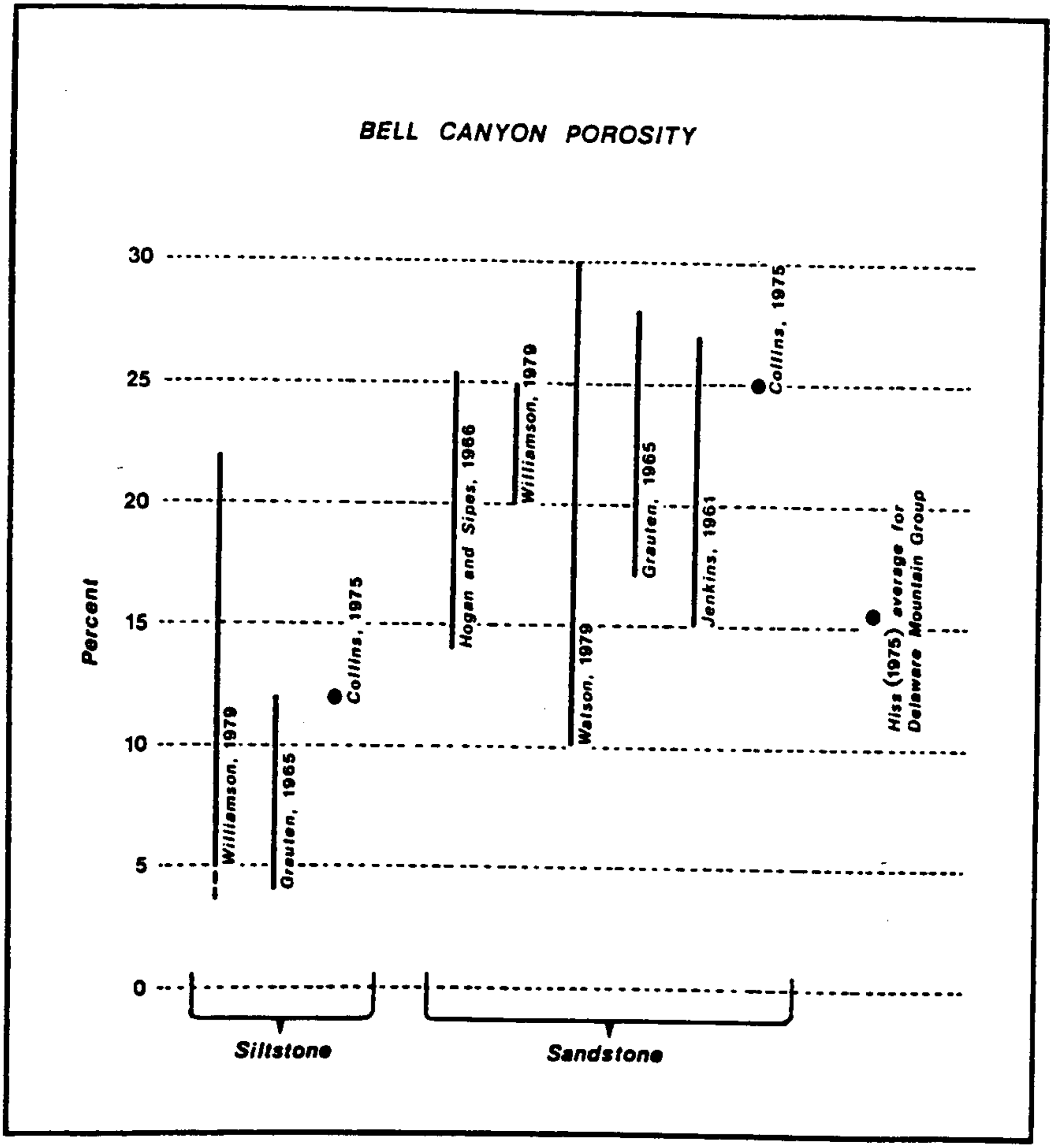


Figure 2-5. Compilation of Bell Canyon porosity data.

Stratigraphic traps are formed in areas where linear sand fingers show an updip decrease in permeability and porosity. The change in permeability and porosity between the permeability barrier and the reservoir rocks, however, is not great. The Saber field, for example, has an average porosity of 25% and permeability of 70 md, and the barrier rock an average porosity of 12% and permeability of 3 md. Since in some areas this barrier rock would be considered a possible reservoir, something in addition to these changes in porosity and permeability is necessary to prevent the movement of oil into the barriers.

Collins, 1979, p. 323

Small differences in permeability between sandstone reservoirs and siltstone barriers suggest that factors other than a lithologic change must be effective in the trapping of hydrocarbons in the Bell Canyon Formation. Reservoir porosity and permeability values typically are 20-25 percent and 10-50 md. Siltstone porosity commonly ranges from 10-20 percent and permeability values are 1-5 md. The siltstone could be considered as a possible reservoir in some areas. Oil stained siltstone between fields indicates that some migration has occurred through porous siltstone. Factors other than small changes in porosity and permeability must prevent the updip movement of oil and invasion into siltstone.

Williamson, 1979, p. 71

The additional factor which allows petroleum entrapment in the Bell Canyon is the hydrodynamic force that results from groundwater flow through the formation. Hydrodynamic entrapment will be discussed in subsequent paragraphs. The important information at this point is that the geologic and hydrologic data indicate that the Bell Canyon is a hydraulically continuous unit. Also note that the full three dimensional flow pattern in this unit will be strongly influenced by the presence of the higher conductivity channel sandstones.

The potentiometric surface in a permeable, water-bearing unit is a direct indicator of both the magnitude of the water moving forces and the direction of flow. "If the potentiometric surface is sloping, the water will be in motion, with the horizontal component of its flow in the approximate direction of the steepest downward slope of this surface" (Hubbert, 1953, p. 1974). The regional potentiometric map of the Delaware Mountain Group, constructed by Hiss (1975) shows an eastward dipping surface with gradients ranging from 4 feet per mile in the southern portion of the basin, to as high as 40 feet per mile in the northern portion of the basin (Figure 2-6). Given the permeable character of both the sandstone and siltstone facies, this potentiometric surface is a direct, physically based indicator of groundwater flow eastward across the basin. This eastward regional flow is also indicated by potentiometric maps constructed on the upper Bell Canyon by McNeal (1965, p. 316) and by Visher (1961, in Collins, 1975, p. 324).

In his classic paper, "Entrapment of Petroleum Under Hydrodynamic Conditions", Hubbert (1953) demonstrated that ground water flow can trap hydrocarbons in geologic structures that would not be traps under hydrostatic conditions (Figure 2-7). In fact, Hubbert cites the upper Bell Canyon Formation as an example of petroleum entrapment caused by regional groundwater flow.

> One of the best examples described in the literature of an oil accumulation in a completely unclosed structure is that of the Wheat field in the Delaware Basin. . .This accumulation occurs in a sand of the Delaware Mountain series which in this region dips homoclinally east at an average rate of 100 feet per mile. The field is located on a structural terrace on which the dip decreases to about 50 feet per mile for a distance of about 3 miles and then steepens again to the east. There is no evidence of faulting, and dry holes on the west, northwest and southwest indicated good permeability. These facts preclude the interpretation of the field being a fault or stratigraphic trap, and in the light of the present information, it appears to be a hydrodynamic trap produced by water flowing eastward from the Delaware Mountains.
>
> Hubbert, 1953, p. 2016

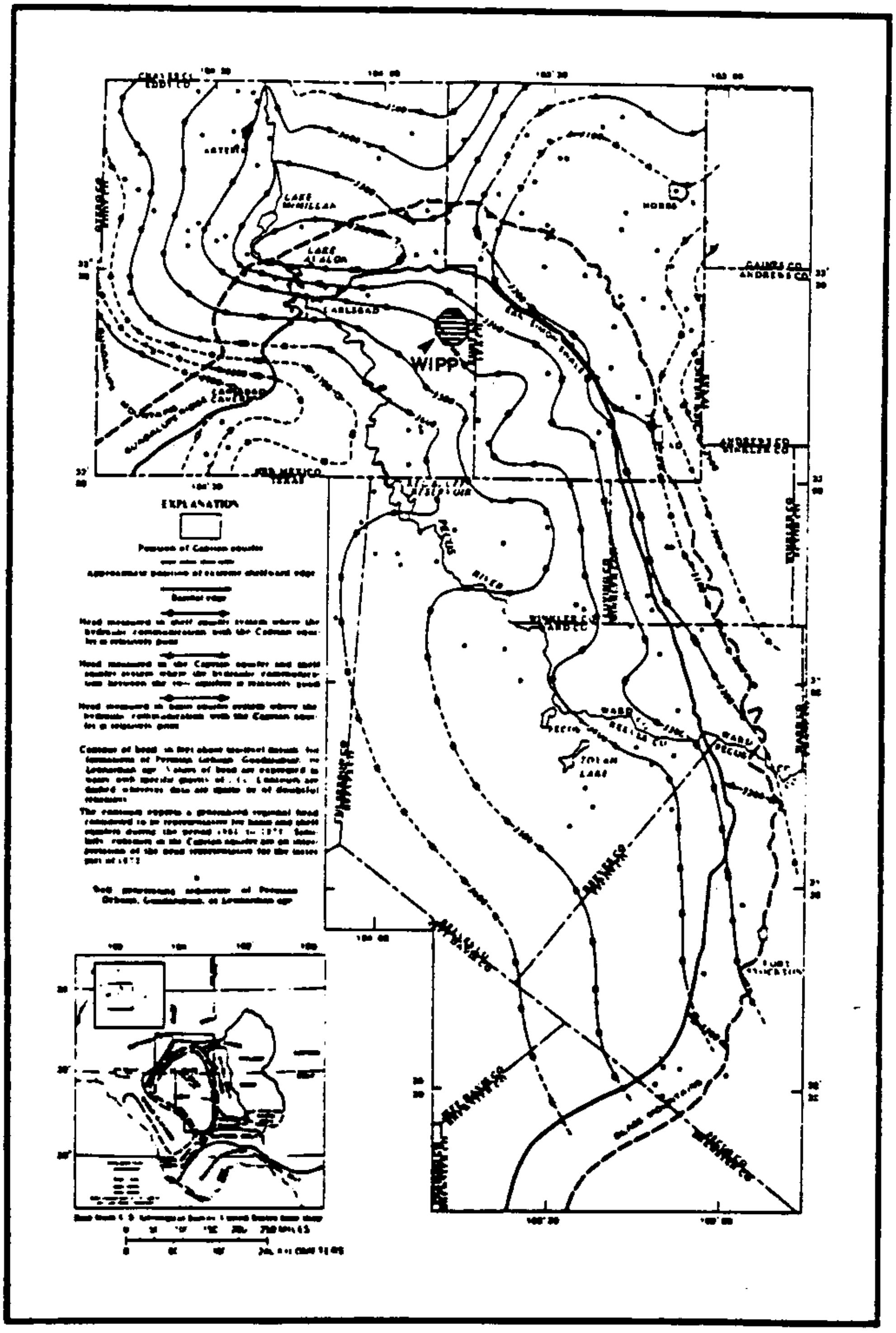


Figure 2-6. Regional potentiometric surface map for the Delaware Basin showing the eastward dipping potentiometric surface of the Delaware Mountain Group. (From Hiss, 1980).

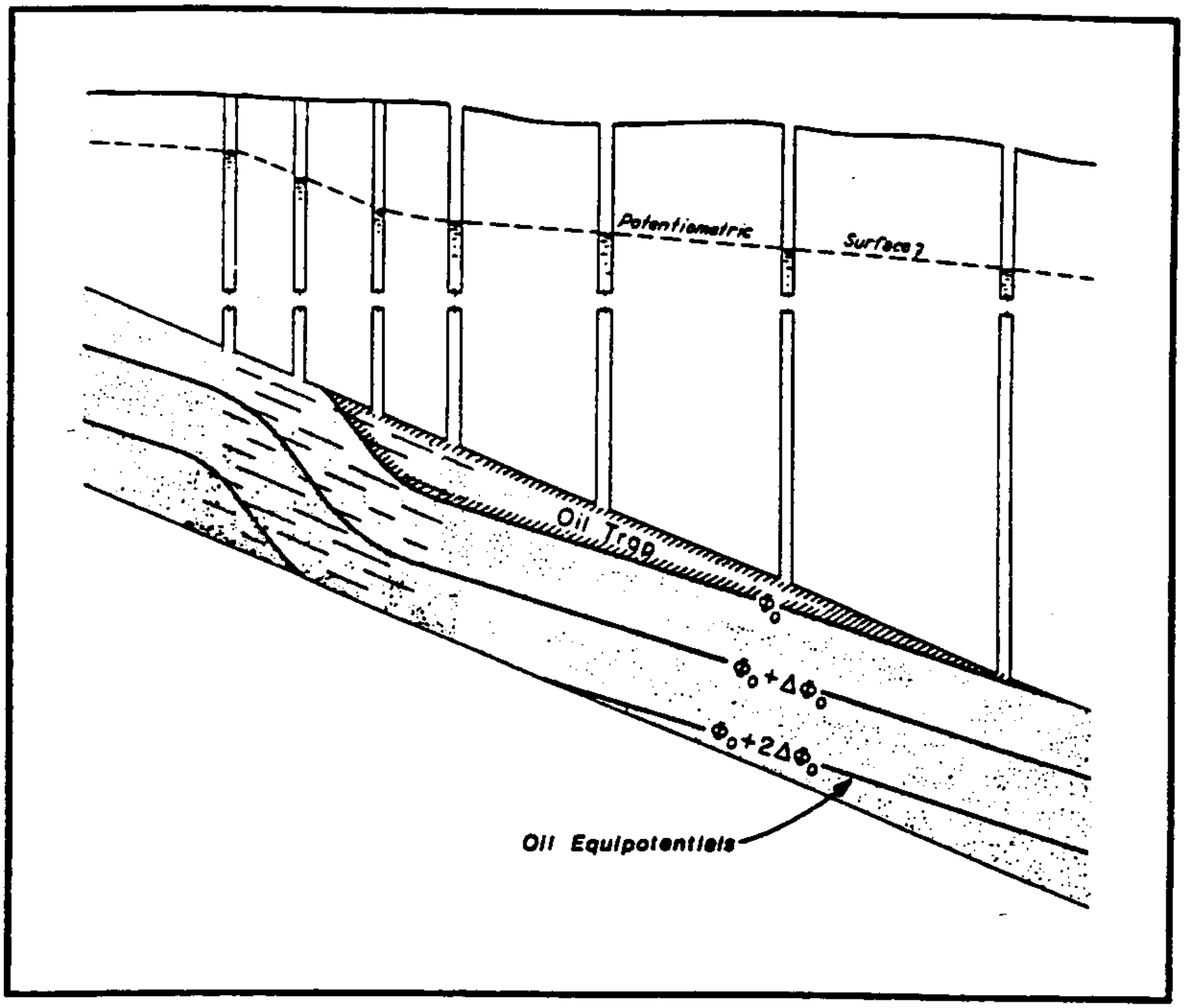


Figure 2-7. Oil entrapment under hydrodynamic conditions. The increase in groundwater potential gradient through the region of relatively lower permeability causes the oil equipotentials to slope upward and close at the top of the sand, creating a trap. This type of oil trap can be identified by the presence of a tilted oil-water interface. (Adapted from Hubbert, 1953).

More recent work by Berg (1975, p. 951-952) showed that groundwater flow through the Bell Canyon has created a hydrodynamic trap with a 50 feet per mile tilt in the oil-water contact at the Paduca Field, located approximately 17 miles south-southeast of the WIPP site. Berg calculates that of the 120 feet of observed oil column, only 30 to 40 feet is due to capillary forces, while the remaining 80 to 90 feet is the result of ground water flow through the Bell Canyon. Therefore, in addition to the observed sloping potentiometric surface, hydrodynamic oil traps provide direct physical evidence of the active flow of ground water through the Bell Canyon.

Lambert cites the existence of vertical changes in head as evidence that sandstone units within the Bell Canyon are hydraulically isolated from one another (i.e. there is no vertically connected flow).

> Shortly after dual completion of the hole [AEC-8]. . .static levels of water levels derived from the lower and upper sands were 615 and 560 ft, respectively, below land surface (Mercer and Orr, 1979). This conspicuous difference in levels of water of similar density attests to the stratabound, vertically isolated nature of the water in the Bell Canyon Formation.
>
> Lambert, 1983, p. 26

Though in many cases ground water flow is conceptualized in two dimensions (i.e. horizontal), flow in natural systems is in fact three dimensional. In flow systems where units of contrasting hydraulic conductivity are juxtaposed, vertical potential gradients are developed in the unit of lower conductivity with corresponding vertical flow across the unit (Toth, 1980, p. 125-129; Freeze and Witherspoon, 1967, p. 626-629). A vertical component in the potential gradient will develop under conditions in which the conductivity contrast is as little as one to two orders of magnitude. As the conductivity contrast increases, the vertical component of flow through the low hydraulic conductivity unit becomes more pronounced. The vertical changes in head observed in AEC-8 are not the result of "stratabound, vertically-isolated water". Rather, this vertical gradient is an integral component of groundwater flow in a heterogeneous rock unit and is associated with vertical flow in the lower conductivity unit that separates the upper and lower sands.

As further evidence that Bell Canyon water is not involved in either an active flow system or in active salt dissolution, Lambert points out that his geochemical analyses of water samples show non-meteoric stable isotope values and solute concentrations that are not in the same proportions as found in common evaporite minerals (p. 75-76). This interpretation is apparently based on stable isotope analyses from a single well and on solute analyses from four wells (Lambert, 1978, p. 34-36; Lambert, 1983, p. 70, 73). Interpretations based on a small number of samples may be appropriate in lithologically and hydrologically homogeneous rock types. The Bell Canyon Formation, however, is neither lithologically nor hydrologically homogeneous. Collins (1975) noted that significant changes in Bell Canyon water composition can take place over very short distances. For example, the chloride ion concentration increases from 50,000 mg/l to 150,000 mg/l over a distance of less than 5 to 6 kilometers in areas where there are sufficient data to examine local variations in groundwater chemistry (Figure 2-8). Collins attributes these changes to variations in groundwater flux due to local variations in Bell Canyon hydraulic conductivity.

> The reason for these rapid changes in formation water compositions may be explained by permeability changes within the Bell Canyon Formation. In areas of low permeability there is less circulation, less dilution, and more chance for the maintenance of an equilibrium relation between formation water and sediment.
>
> Collins, 1975, p. 326

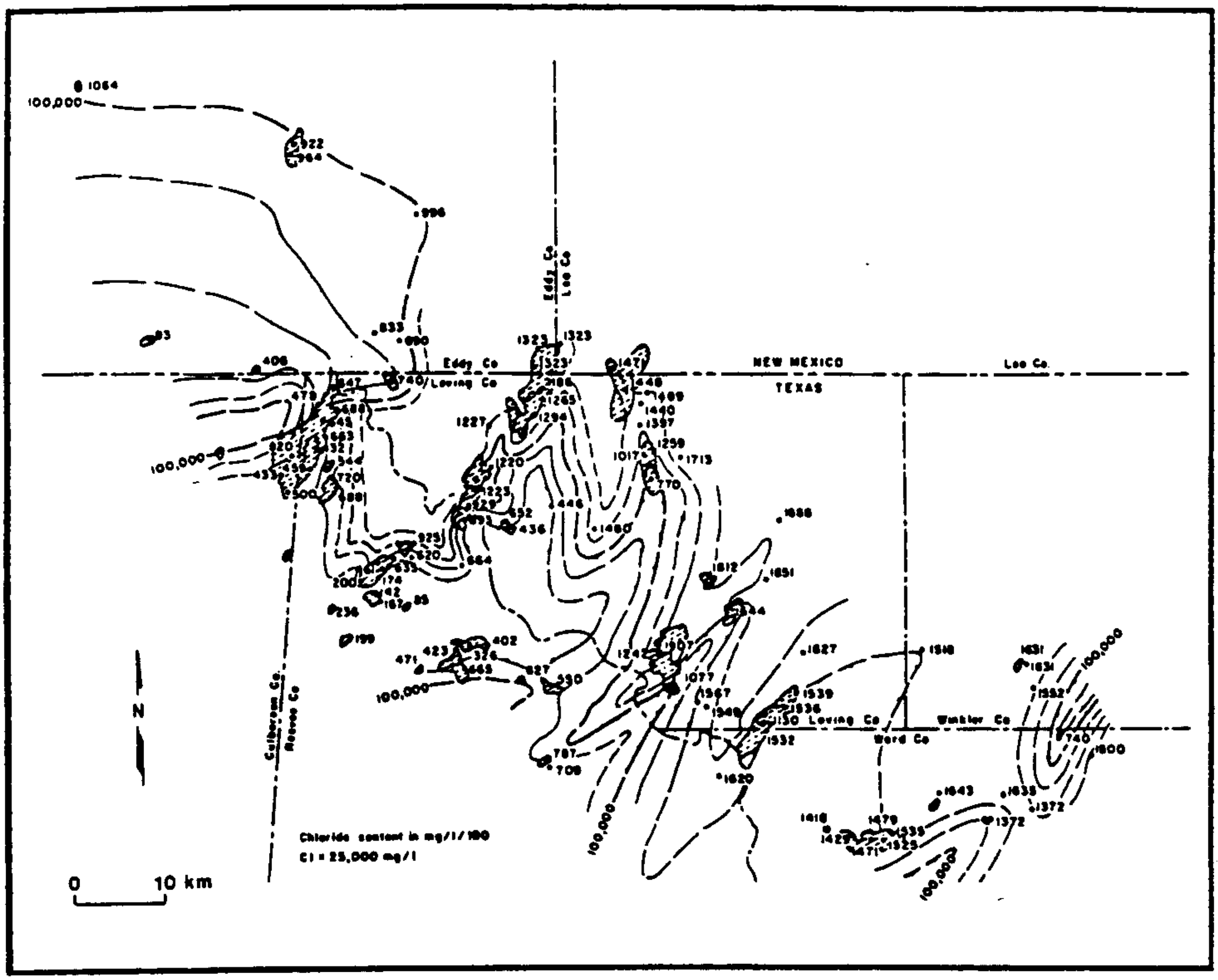


Figure 2-8. Map of chloride ion concentrations in Bell Canyon groundwater, central Delaware Basin. (From Collins, 1975).

Also, note that the location of the abrupt increase in the chloride content of the Bell Canyon roughly corresponds to the location of the eastern margin of the salt dissolution wedge in this portion of the basin (compare Figures 1-1 and 2-8). Therefore, an alternative (or perhaps complementary) explanation for the sudden increase in solute load is that this results from salt dissolution in the lower portion of the evaporite section.

Though there is much less oxygen isotope than solute data for the Bell Canyon, what data there are suggest a high degree of variability. Lambert (1978, p. 36-37; 1983, p. 70, 75) cites a $\delta^{18}O$ value of +2.2‰ (SMOW) as being representative for Bell Canyon water. Williamson (1978, p. 180-181), however, reports $\delta^{18}O$ values ranging from +1.6‰ to -4.4‰ for Bell Canyon water. Williamson notes that "stable oxygen and deuterium isotopes are one of the most useful means of tracing the origin of formation waters, but many more analyses are necessary before the relative contribution of various water sources can be interpreted."

In order to fully characterize the geochemistry of Bell Canyon water relative to its role in salt dissolution, both lithologic and hydrologic heterogeneities must be taken into consideration. Analyses of waters from both the low and high conductivity units must be carried out. Consideration must also be given to how NaCl would be dispersed once entering the top of the Bell Canyon from a localized source.

2.2. Recharge and Discharge

Lambert concludes that there is "virtually no involvement of the Bell Canyon in either recharge to or discharge from the Capitan" and "the Bell Canyon is not being actively and continuously recharged by any known meteoric or groundwater source in the Delaware Basin" (Lambert, 1983, p. 30). With reference to Hiss's pre-development potentiometric surface map of the Delaware Basin (Figure 2-6), Lambert cites the following observation and interpretation as evidence for the lack of recharge to the Bell Canyon from the Capitan.

> At all locations along the Basin margin, the Bell Canyon has a higher head than does the juxtaposed Capitan, even after corrections are made for salinities. . .Thus there is no tendency for even fresher Capitan water to flow into the Bell Canyon Formation.
>
> Lambert, 1983, p. 29

The observation and interpretation are accurate. In fact, to carry the interpretation one step further, the relatively high heads in the Bell Canyon are indicative of discharge flow, from the Bell Canyon into the lower Capitan along the northern and eastern margins of the basin. Neither Hiss, nor others working on the hydrodynamics of the Bell Canyon for petroleum development purposes, propose that Bell Canyon recharge occurs from the Capitan along the northern and eastern margins. Rather, recharge occurs on the western and southern margins of the basin, where the Bell Canyon comes up to the land surface.

> Aquifers in the Delaware Mountain Group including the Bell Canyon are naturally recharged at outcrops in the Delaware, Guadalupe, Apache and Glass Mountains and from leakage downward through young rocks in areas where the soluble Ochoan evaporites have been removed in the western and southern parts of the Delaware Basin.
>
> Hiss, 1975, p. 259

> An accepted opinion has been that meteoric water enters the rock unit Bell Canyon in the west and flows generally eastward, in the direction of dip.
>
> McNeal and Mooney, 1979, p. 187

> There is general agreement that the Delaware Basin is under hydrodynamic rather than hydrostatic conditions. The potentiometric surface of the Delaware Mountain Group generally dips to the east with a component of northward flow. . .The flow of formation water is away from the western outcrop area, down structural dip and down the potentiometric surface towards the east.
>
> Williamson, 1978, p. 177

As evidence of the "separateness of the waters in the Capitan and Bell Canyon", Lambert proposes the existence of a significant osmotic pressure differential between these two units. Based on "a typical reef-margin Capitan value of 3000 mg/l total dissolved solids, and an NaCl-saturated value of 300,000 mg/l for the Bell Canyon", Lambert computes an osmotic pressure differential of 1900 psi, "or a fresh-water equivalent head of approximately 4400 feet driving from Capitan into Bell Canyon" (p. 29).

The existence of osmotic conditions requires two basic components, (1) a pair of water-bearing units, each with a different solute concentration, separated by (2) a semi-permeable membrane, which allows the passage of water but not the solute. As noted by Lambert, the Capitan and Bell Canyon system definitely has the first of these two components. However, the second component, a semi-permeable membrane separating the Capitan from the Bell Canyon, does not exist. The occurrence of osmotic processes under geologic conditions has been studied both experimentally (Kemper, 1961; Hanshaw, 1962; McKelvey and

Milne, 1962; Young and Low, 1965) and in the field (Berry, 1959, 1966; Berry and Hanshaw, 1960; Bailey, et al., 1961; Bredehoeft, et al., 1963). The only rock types capable of acting as semi-permeable membranes are clay and shale, which possess electrostatic properties capable of blocking the passage of dissolved salts. At the contact between the Capitan Reef and the Bell Canyon, the fore-reef talus, consisting of fragments and boulders of limestone, dolomitic limestone and dolomite, interfingers with the sandstone and siltstone of the Bell Canyon (Figure 1-2). Since there is no material that acts as semi-permeable membrane between these formations, osmotic conditions can not exist. Therefore, along the northern and eastern margins of the basin, Bell Canyon water most likely discharges into the Capitan as originally proposed by Hiss (1975, 256-261). This influx of highly saline water contributes to the solute load of the Capitan, but since the total flux of water in the Capitan is much larger than the influx of Bell Canyon water, the Capitan has a much lower salinity (Hiss, 1975, p. 208-219).

During the past 50 years, fluid production from the Capitan aquifer has substantially lowered the potentiometric surface of the Capitan along the eastern margin of the basin (Hiss, 1975, p. 299-301, Figures 22 and 23; Hiss, 1980, p. 275). Hiss notes that the potentiometric surface in the Delaware Mountain Group has "probably been lowered by an unknown amount along the eastern margin of the Delaware Basin" in response to the drawdown in the Capitan (Hiss, 1975, p. 275). As further evidence of the "separateness of the waters in the Capitan and Bell Canyon", Lambert cites Hiss's (1975) pre- versus post-development potentiometric surface maps as showing no effect in the Bell Canyon from the Capitan drawdown (p. 29). Clearly these two conclusions are incompatible. Closer examination of the pre- and post-development potentiometric surface maps shows that for the Delaware Mountain Group, both data sets are identical (Figure 2-9). The Delaware Mountain Group wells were measured only once and therefore both the pre- and post-development potentiometric surface maps show essentially the same surface. The reason for this apparent discrepancy is that Hiss's study was primarily focused on the Capitan Aquifer and the only wells that he monitored through time were those in his network in the Capitan. Lambert has apparently misinterpreted Hiss's maps by assuming that they show the Bell Canyon potentiometric surface at two different times, when in fact they show only one time.

2.3 Summary

The Bell Canyon Formation is a complex sequence of predominantly channel sandstones and interchannel siltstones, with hydraulic conductivities ranging from $<10^{-7}$ to 10^{-4} cm/sec. Because of the complex morphology of elongate, overlapping channel sandstones with interchannel siltstones, hydraulic conductivity is variable on local and subregional scales. Recharge to the Bell Canyon occurs along the western and southern margin of the basin, where the Bell Canyon comes up to the land surface. The Bell Canyon discharges into the Capitan Aquifer along the northern and eastern margins of the basin. Direct, physically based evidence for this active regional flow system includes an eastward dipping potentiometric surface, hydrodynamic entrapment of oil, and significant changes in water chemistry over short distances due to local changes in hydraulic conductivity. In terms of the potential for localized salt dissolution, the most important component of this hydrologic system is the major trends of relatively high conductivity channel sandstone in the upper portion of the Bell Canyon.

A

B

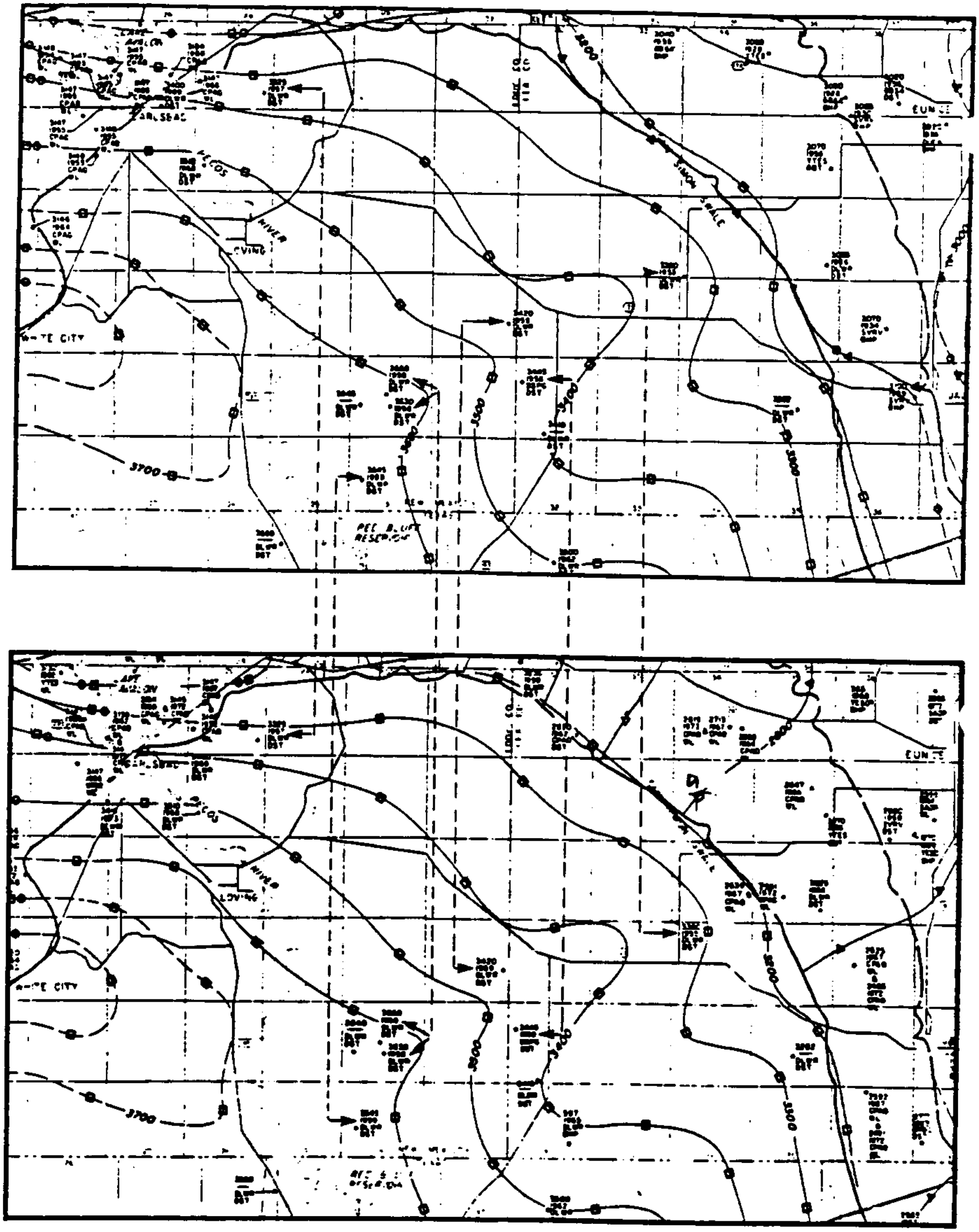


Figure 2-9. Hiss's (1975) pre-development (A) and post-development (B) potentiometric surface maps for the northern Delaware Basin. Note that the Delaware Mountain Group wells were measured <u>only once</u>, and therefore both maps show essentially the same surface. (Adapted from Hiss, 1975).

3. SALT DISSOLUTION RATES - A REVIEW OF WOOD, ET AL. (1982)

The Wood, et al. (1982) study utilizes a simplified, NaCl-H_2O system to illustrate the rate-controlling components of the dissolution process, which include molecular diffusion, free convection (driven by gravity acting on a vertical concentration gradient), and forced convection (driven by a regional groundwater flow system). The role of each of these mass transport mechanisms is then examined for the geologic and hydrologic conditions that are expected to exist in the Delaware Basin.

3.1 Diffusion-Only Numerical Model

The Wood, et al. study utilizes a numerical solute transport model to simulate salt dissolution in the WIPP site area (p. 72-81). The model assumes that dissolution occurs in the lower portion of the lowermost halite unit (Halite I) in the Castile Formation and that diffusion is the only transport process acting to move dissolved salt through the anhydrite unit (Anhydrite I) that lies between Halite I and the Bell Canyon Aquifer (Figure 3-1). The model also assumes that variations in fluid density in the Bell Canyon can be neglected. The dimensions and parameter values used in the model are summarized in Table 3-1.

The model was run under steady-state conditions and calibrated by varying the effective diffusion coefficient in the anhydrite layer until the

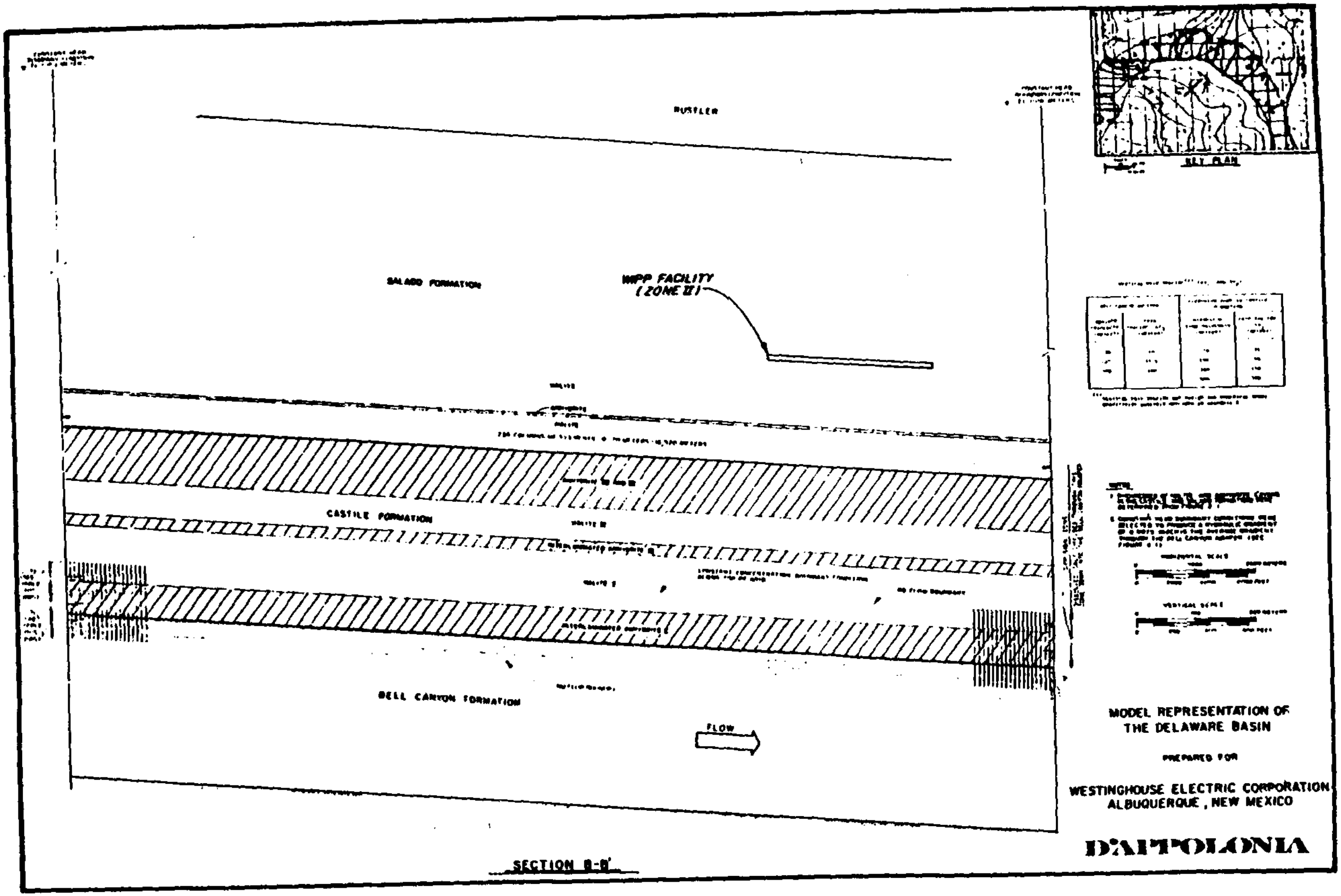


Figure 3-1. Configuration of the Wood, et al. (1982) diffusion-only salt dissolution model for the WIPP site area. (From Wood, et al., 1982).

TABLE 3-1

Input Parameters for Wood, et al. (1982)
Diffusion-Only Salt Dissolution Model
(from Wood, et al., 1982)

INPUT PARAMETER	VALUE	UNITS
Hydraulic Conductivity of Bell Canyon Aquifer, K	1.8	Meters per year (m/yr)
Effective Porosity of Bell Canyon Aquifer, n_e	0.16	Dimensionless
Molecular Diffusion Coefficient, D_m	8.7×10^{-3}	Square meters per year (m^2/yr)
Longitudinal Dispersivity of Bell Canyon Aquifer, D_L	3.048	Meters (m)
Transverse Dispersivity of Bell Canyon Aquifer, D_T	3.048	Meters (m)
Retardation Factor for Chloride, R_d	1.0	Dimensionless
Effective thickness of Bell Canyon Aquifer, b	30	Meters (m)
Thickness of Diffusion Zone in Castile Formations(2)	100	Meters (m)
Hydraulic Gradient, i	0.0025	Meters per meter (m/m)
Upgradient Chloride Concentration Boundary Condition in Bell Canyon Aquifer, C_u	100	Kilograms per cubic meter (kg/m^3)
Halite Density	2,160	Kilograms per cubic meter (kg/m^3)

modeled chloride distribution matched the chloride distribution shown in Hiss's (1975) regional map for the Delaware Basin (Figures 3-2 and 3-3). The calibrated value for the effective diffusion coefficient was 8.7×10^{-3} m^2/yr (2.8×10^{-6} cm^2/sec). From this result, the following conclusion has been drawn: "Since chloride diffuses through the Castile anhydrite, the magnitude of the diffusion coefficient is the key indicator of whether diffusion is a valid mechanism to explain the existing dissolution rates near the WIPP site. Accepted values for the chloride diffusion coefficient in groundwater range from 0.003 to 0.03 m^2/yr (Freeze and Cherry, 1979), which indicates that the value of 0.0087 m^2/yr determined in the model is valid for a diffusion process" (p. 76). The report further concludes, ". . .that a diffusive mechanism is a valid explanation for the observed chloride concentrations in the Bell Canyon aquifer" (p. 78).

In order to examine this interpretation of the model results, consider the 2.8×10^{-6} cm^2/sec calibrated value for the effective diffusion coefficient. Effective diffusion coefficients depend on the porous material under consideration. The physical characteristics of a porous material that influence diffusion are effective porosity, n, and tortuosity, T^*. The relationship between the coefficient for diffusion in a fluid-filled porous material, D_e, and the coefficient for diffusion in a continuous body of liquid, D, is as follows:

$$D_e = nT^*D \qquad (3\text{-}1)$$

where

D_e = coefficient for diffusion in a fluid-filled porous material

D = coefficient for diffusion in a continuous body of fluid [$D = 1.5 \times 10^{-5}$ cm^2/sec for a concentrated aqueous solution of NaCl at 25^oC (Longsworth, 1972, p. 2-223)]

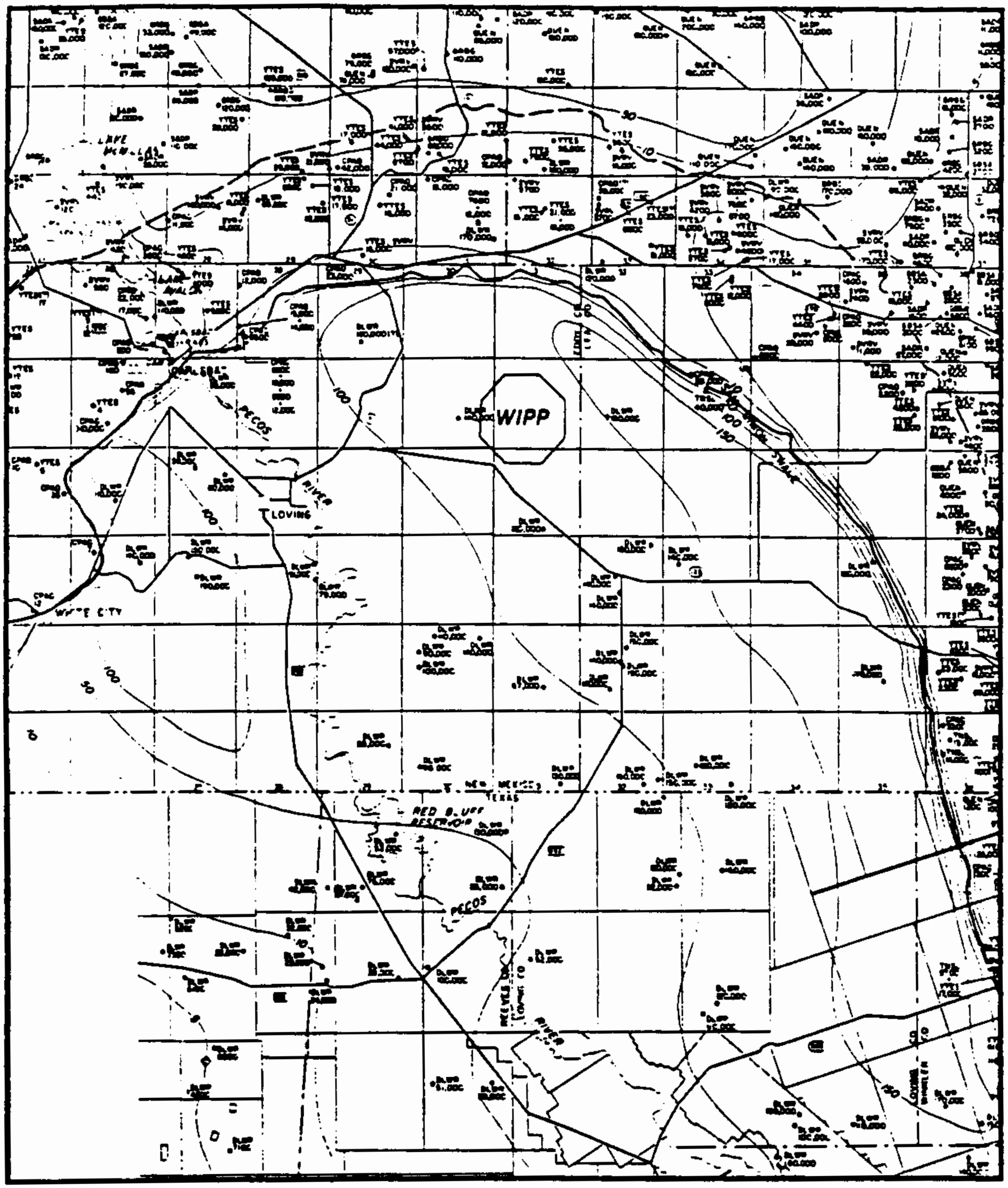


Figure 3-2. Map of regional chloride ion distribution in the northern Delaware Basin. Contours are in thousands of milligrams per liter and contour interval is 50,000 mg/l. (Adapted from Hiss, 1975).

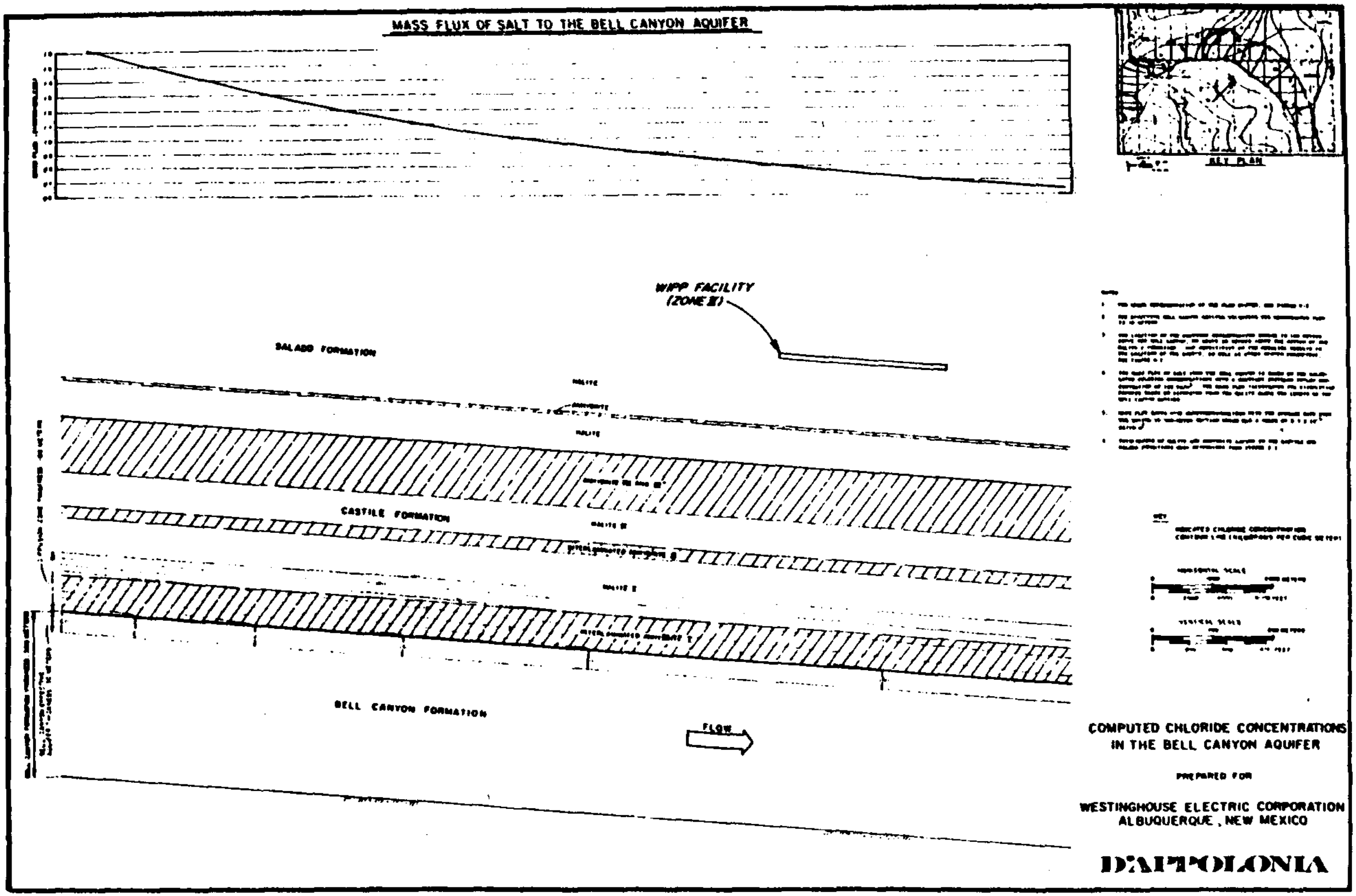


Figure 3-3. Computed chloride distribution from Wood, et al. (1982) diffusion-only salt dissolution model for the WIPP site area. (From Wood, et al., 1982).

n = effective porosity of the material

T^* = Tortuosity of the material [T^* is a measure of the nonlinearity of diffusion pathways. $T^* \leq 1.0$]

By rearranging equation 3-1, the physical characteristics of the porous material that are implicit in a given D_e value can be examined.

$$\frac{D_e}{D} = nT^* \qquad (3\text{-}2)$$

For the Wood, et al. model:

$$\frac{D_e}{D} = \frac{2.8 \times 10^{-6} cm^2/sec}{1.5 \times 10^{-5} cm^2/sec} = 0.19 = nT^*$$

Therefore, since $T^* \leq 1.0$, the Wood, et al. model D_e value assumes that the lowermost Castile anhydrite has an effective porosity oi 19 percent or greater over the entire WIPP area. Anhydrite is a relatively dense, crystalline rock and an effective porosity of 19 percent or greater is not physically reasonable for an anhydrite unit at well over 1000 meters depth, which has measured hydraulic conductivities in the 10^{-9} to 10^{-10} cm/sec (Sandia, 1980) range.

The report concludes that the model calibrated D_e value of 8.7×10^{-3} m^2/yr (2.8×10^{-6} cm^2/sec) is physically reasonable because it falls into the range of 3×10^{-3} to 3×10^{-2} m^2/yr (1×10^{-6} to 1×10^{-5} cm^2/sec) cited by

Freeze and Cherry (1979) for groundwater conditions. However, Freeze and Cherry's comment on this range of D_e values actually reads as follows: "Values for coarse-grained unconsolidated materials can be somewhat higher than 1×10^{-10} m^2/sec [1×10^{-6} cm^2/sec] but are less than the coefficients for the chemical species in water [i.e., $<1.5 \times 10^{-9}$ m^2/sec or $<1.5 \times 10^{-5}$ cm^2/sec]" (p. 393). According to Freeze and Cherry, the Wood, et al. D_e value falls into the range of values for coarse-grained unconsolidated materials. Therefore, an implicit assumption in the model calibrated D_e value is that the lowermost Castile anhydrite is hydrologically similar to a coarse-grained, unconsolidated material. This assumption is not physically reasonable.

3.2 Localized Dissolution Associated with Fractures

Because the diffusion-only numerical model results do not preclude more intense, local dissolution, the Wood, et al. study also examined dissolution rates associated with density driven convective flow through the lowermost Castile anhydrite in a fracture and in a cylindrical porous zone. Because the existence and/or creation of fracture systems by faulting is geologically realistic for the WIPP site (note the presence of faults passing through the Bell Canyon and into the Castile in Figures 4.4-3 and 4.4-5 in Powers, et al, 1978, and in Figures 2-5 and 2-6 in Borns, et al., 1983), the following discussion will focus on the fracture model.

As noted in Sections 3.2.3 and 5.2.1 of the Wood, et al. report, the rate of salt dissolution associated with a vertical fracture through the lowermost Castile anhydrite is controlled by a combination of convective mass flux through the fracture and through the underlying Bell Canyon aquifer. Convective mass flux in a fracture is driven by gravity acting on a vertical density gradient and is a function of the Rayleigh and Nusselt numbers for a given fracture geometry and concentration gradient. Convective mass flux in the Bell Canyon aquifer is driven by the regional groundwater flow system and is a function of the aquifer's total water flux and solute load. The computations of Wood, et al. show that density-driven convection in a fracture is capable of transporting relatively large quantities of dissolved salt (6×10^4 kg of dissolved salt per square meter of fracture per year, p. 50). On the other hand, computations for the transport capacity of the Bell Canyon aquifer show that this aquifer is capable of transporting only 16 kg of dissolved salt per meter thickness per year (p. 90). Therefore, the rate limiting component of the mass flux system is the transport capacity of the Bell Canyon aquifer.

The Wood, et al. study assumes that the removal of halite by dissolution will result in a cavity that has a volume equal to the volume of halite removed. This assumption does not account for the fact that halite has a very low yield strength, and for the long period of time under consideration significant deformation of the overlying halite beds will occur. However, computing the volume of a cavity that is equal to the volume of salt removed does help to visualize the relative magnitude of various dissolution scenarios. In the Wood, et al. study, a cylindrical cavity, propagating radially away from the fracture was assumed (Figure 3-4).

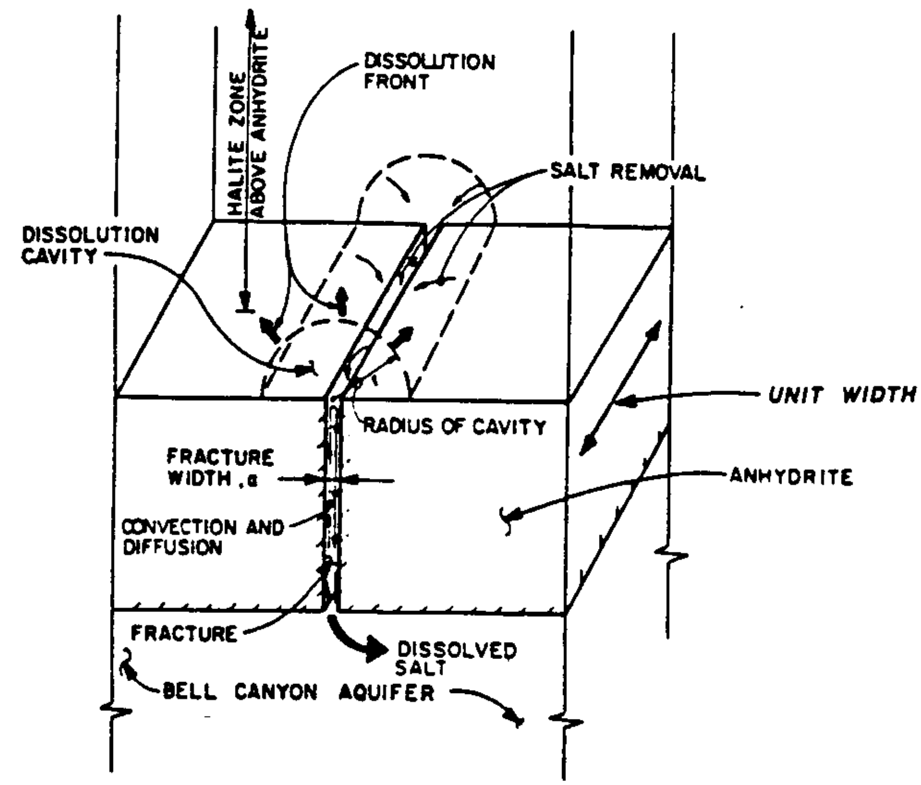


Figure 3-4. Illustration of Wood, et al.'s model for salt dissolution associated with density-driven flow through a fracture. (Adapted from Wood, et al., 1983).

In order to evaluate Wood, et al.'s results, their computed salt dissolution rates, cavity volumes, and assumed parameter values have been compared with two other fracture dissolution analyses (Table 3-2). The Wood, et al. baseline and worst case analyses (Table 3-2, Cases I and II), result in cavities with volumes (per unit width, Figure 3-4) of 72 and 232 cubic meters respectively. The Bell Canyon conductivities assumed for these scenarios were 5.7×10^{-6} and 9.2×10^{-6} cm/sec for the average and worst cases respectively. Wood, et al. reach the following conclusion regarding the impact such cavities would have on the WIPP repository: "Considering the extremely small volume of salt removed in comparison with the total strata thickness, the vertical propagation of this deformation would probably be limited to the lower section of Halite I" (p. 100-101).

Because mass flux under these conditions is limited by the transport capacity of the Bell Canyon, the disssolution rate is very sensitive to the hydraulic conductivity of this aquifer. In light of the $<10^{-7}$ to 2×10^{-4} cm/sec range of measured conductivities for the Bell Canyon (Figure 2-4), Wood, et al.'s range of 3.5×10^{-6} to 9.2×10^{-6} cm/sec (1.1 to 2.9 m/yr, p. 24, 26) cannot be considered representative. In particular, their analysis using 9.2×10^{-6} cm/sec (2.9 m/yr) as a maximum conductivity does <u>not</u> constitute a worst case. Wood, et al. do use a broader range of parameter values for their sensitivity analysis of the diffusion-only numerical model (Wood, et al., 1982, p. 130). If the maximum parameter values from the Wood, et al. sensitivity analysis of the diffusion-only model are applied to the fracture dissolution analysis, the volume (per unit width) of the resulting cavity is 11,213 cubic meters (Table 3-2, Case III). This scenario assumes that the Bell Canyon consists of 300

TABLE 3-2

Localized Dissolution Associated with Fracture Zone

	NaCl dissolution rate (kg/yr) (per unit width)	Volume of cavity in 10,000 yrs. (per unit width)	Radius of cavity in 10,000 yrs.	Bell Canyon conductivity m/yr (cm/sec)	Thickness	Gradient	Net increase in NaCl	Implicit minimum porosity of 1 meter wide fracture zone
Case I: Wood, et al. baseline conditions	$16_{(1)}$	$72\ m^3_{(2)}$	$7\ m_{(1)}$	1.8 $(5.7\times10^{-6})_{(3)}$	$30\ m_{(3)}$	$0.0025_{(3)}$	$115\ kg/m^3_{(3)}$	$.0005_{(2)}$
Case II: Wood, et al. worst conditions	$50_{(1)}$	$232\ m^3_{(2)}$	$12\ m_{(1)}$	2.9 $(9.2\times10^{-6})_{(3)}$	$60\ m_{(3)}$	$0.0025_{(3)}$	$115\ kg/m^3_{(3)}$	$.002_{(2)}$
Case III: Assuming maximum values of parameters used for numerical model sensitivity analysis (Wood, et al., 1982, p. 130)	$1054_{(2)}$	$11,213\ m^3_{(2)}$	$84\frac{1}{2}\ m_{(2)}$	18 $(5.7\times10^{-5})_{(3)}$	$300\ m_{(3)}$	$0.0039_{(3)}$	$115\ kg/m^3_{(3)}$	$.07_{(2)}$
Case IV: Assuming channel sandstone with physical characteristics from petroleum literature (Figure 2-4 and Williamson, 1979)	$380_{(2)}$	$1,761\ m^3_{(2)}$	$33\frac{1}{2}\ m_{(2)}$	31.5 $(1.0\times10^{-4})_{(4)}$	$35\ m_{(5)}$	$0.0030_{(3)}$	$115\ kg/m^3_{(3)}$	$.01_{(2)}$

(1) Wood, et al. (1982) computation
(2) Author's computation
(3) Source of parameter value - Wood, et al. (1982)
(4) Source of parameter value - Petroleum literature (Figure 2-4, this paper)
(5) Source of parameter value - Williamson (1979)

meters of sandstone with a hydraulic conductivity of 5.7×10^{-5} cm/sec (18 m/yr), which is not geologically realistic because the Bell Canyon does contain a significant proportion of lower conductivity siltstone. However, this analysis does illustrate the sensitivity of fracture-related dissolution to the assumed values for hydraulic conductivity and thickness of the Bell Canyon.

A geologically more realistic worst case scenario is a fracture zone through the lowermost Castile anhydrite that is connected to a major channel sandstone trend in the upper Bell Canyon (Table 3-2, Case IV). Using a sandstone thickness of 35 meters and hydraulic conductivity of 10^{-4} cm/sec (from Williamson, 1979, and Figure 2-4 respectively), the volume (per unit width) of the resulting cavity would be 1761 cubic meters. If the cavity had the cylindrical form assumed by the Wood, et al. study, it would be 33.5 meters high above the fracture and 67 meters wide at the base. For both this and the previous scenarios, the volume of salt removed is significant in comparison with the thickness of overlying halite and anhydrite units, and the deformation associated with subsidence would most likely affect higher stratigraphic horizons.

3.3 Summary

The Wood, et al. (1982) study utilizes a $NaCl-H_2O$ system to examine salt dissolution rates under a variety of geologic and hydrologic conditions in the WIPP site area. From the diffusion-only numerical model, the conclusion is drawn "...that a diffusive mechanism is a valid explanation for the observed chloride concentrations in the Bell Canyon Aquifer." This conclusion is based on a model calibrated value of 2.8×10^{-6} cm^2/sec for the effective diffusion coefficient (D_e). In judging the acceptability of a given D_e value, the implicit material characteristics must be consistent with the geologic material under consideration. The Wood, et al. model calibrated D_e value assumes that the material has an effective porosity of 19 percent, or greater, and is hydrologically similar to coarse-grained unconsolidated materials. Neither of these assumptions is physically reasonable for an anhydrite unit at 1000^+ meters depth, with measured hydraulic conductivity in the 10^{-9} to 10^{-10} cm/sec range. Therefore, diffusion alone is not "a valid explanation for the observed chloride concentrations in the Bell Canyon aquifer."

Localized dissolution associated with a fracture zone in the lowermost Castile anhydrite has also been examined. In this scenario, the dissolution rate is controlled by the transport capacity of the Bell Canyon aquifer. The Wood, et al. study examined this type of dissolution using Bell Canyon conductivities ranging from 3.5×10^{-6} to 9.2×10^{-6} cm/sec. The volume (per unit width) of their worst case cavity is 232 cubic meters in 10,000 years. Considering the $< 10^{-7}$ to 2×10^{-4} cm/sec range of Bell Canyon hydraulic conductivity (Figure 2-4), Wood, et al.'s limited range of hydraulic conductivity values cannot be considered as being representative. In particular, their analysis using 9.2×10^{-6} cm/sec as a maximum conductivity does not constitute a worst case. A geologically realistic, worst case scenario of fracture dissolution associated with a 35 meter thick channel sandstone trend ($K=10^{-4}$ cm/sec) in the uppermost Bell Canyon results in the removal of 1761 cubic meters of salt (per unit width) in 10,000 years. The subsidence deformation associated with the removal of this volume of material would most likely affect higher stratigraphic horizons.

4. A FIELD EXAMPLE OF LOWER CASTILE DISSOLUTION ASSOCIATED WITH A CHANNEL SANDSTONE IN THE UPPER BELL CANYON

In terms of the salt dissolution process, the most important components of the Bell Canyon hydrologic system are the relatively high conductivity, channel sandstones in the upper portion of the formation. The distribution of these channel sandstones will strongly influence the location of dissolution-subsidence structures. If the Bell Canyon acts as both the source of unsaturated water and the sink for salt-rich brines (Anderson, 1980; Wood, et al., 1982), then the optimum location for dissolution activity is directly above, or immediately adjacent to, the major channel sandstones. On the other hand, if dissolution occurs as the result of groundwater flow in fractured anhydrite beds (Anderson, 1981), then the location of dissolution could be somewhat further removed from the associated channel sandstone. Either, or both, of these models could apply in the Delaware Basin.

Dissolution-subsidence structures consist of a localized area where salt has been removed with corresponding subsidence deformation of the overlying strata. Anderson (1982) has suggested that localized areas of anomalously thick halite (sometimes flanked by simlar-size areas of anomalously thin halite) may also be associated with groundwater having access to the Castile halites. These structures resemble gravity-induced salt-flow structures in other basins. However, the Castile Formation is not, and has not been, buried to the depths at which such gravity-induced flow normally occurs. The presence of interstitial water in halite significantly reduces halite's effective viscosity, as noted in laboratory (Ode, 1968), field (Talbot and Rogers, 1980), and theoretical (Wenkert, 1979) studies. Therefore, in addition to dissolving salt, groundwater may also play a significant role in the gravity-flow process by reducing the effective viscosity of the salt to the point where flow will occur under the conditions present in the Delaware Basin.

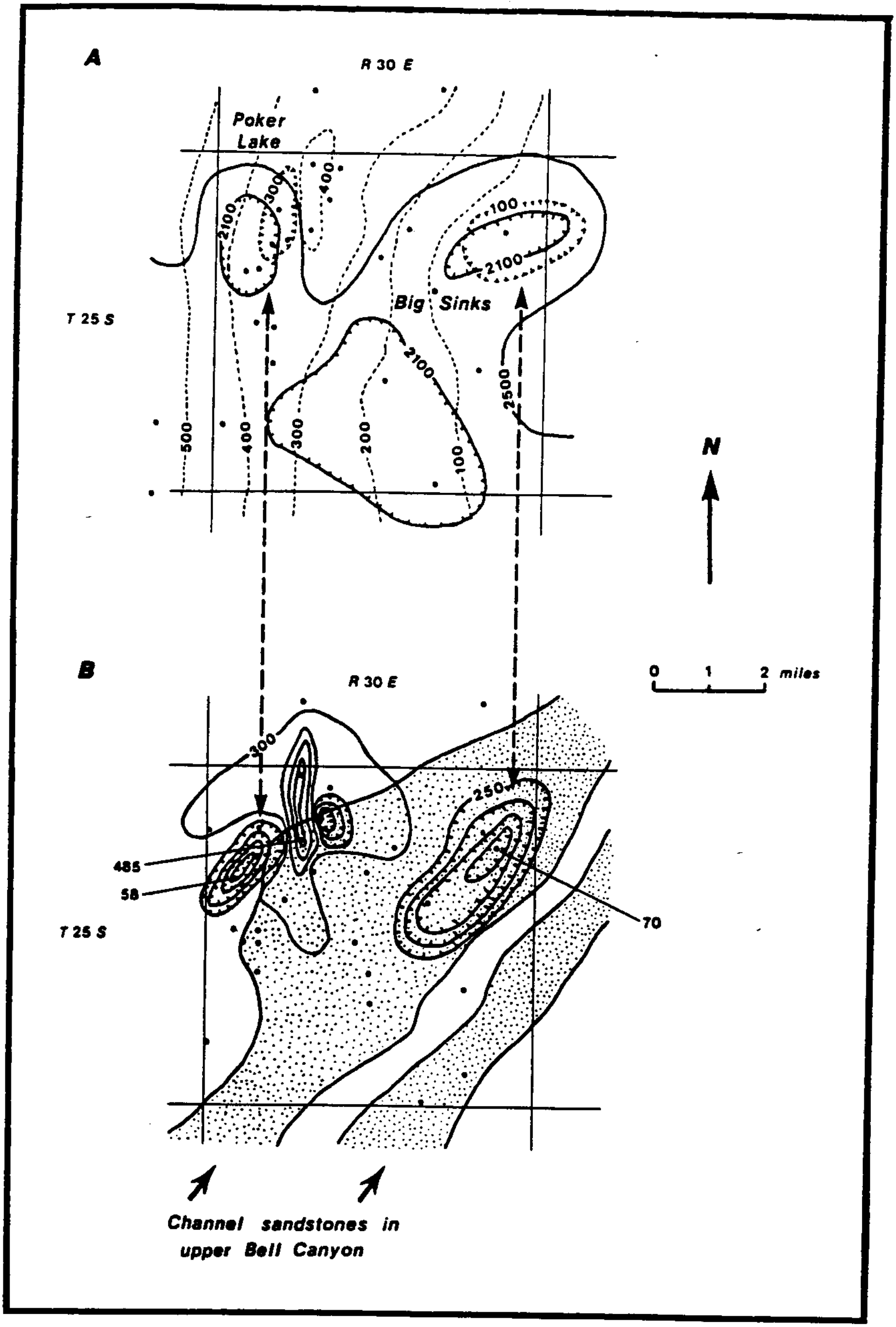
Figure 4-1 illustrates the association of two subsidence structures (Anderson, 1982) with a major channel sandstone in the uppermost Bell Canyon (Ramsey Sandstone). These two structures are characterized by anomalously thin halite in the lower Castile with corresponding structural depressions in the upper Castile and in the Rustler Formation, which is located 2000^{+} feet higher in the stratigraphic section. The Poker Lake structure is more complex and includes an area of anomalously thick halite. Near the ground surface, these structural depressions are filled with thick accumulations of Cenozoic age fill. Note that the northern Big Sinks structure directly overlies, and the Poker Lake structure abuts and partially overlies, a major channel sandstone in the uppermost Bell Canyon.

For the northern Big Sinks structure, the spatial association of (1) a channel sandstone in the upper Bell Canyon, (2) a local area of anomalously thin halite, (3) a large structural depression in the overlying strata, and (4) a thick accumulation of Cenozoic age fill near the ground surface, strongly suggests that salt dissolution associated with groundwater flow in the channel sandstone is the process by which this feature formed. The Poker Lake structure is more complex and the relative contribution of salt dissolution versus gravity-induced salt flow cannot be differentiated without more subsurface information. However, as pointed out by Anderson (1982), groundwater may also play an important role in the gravity-induced salt flow process by reducing the effective viscosity of the salt. Therefore, the spatial association of the Poker Lake structure with a channel sandstone in the Bell Canyon may also be significant.

Figure 4-1. See Figure 2-2 for location and Figures 1-2 and 3-1 for stratigraphic positions.

(A) Structure contours on top of Rustler Formation (solid contours) superimposed on structure contours on top of Halite II in the Castile Formation (dashed contours). In the northern Big Sinks area and at Poker Lake, note that the structural depressions in the Rustler correspond with depressions in the Castile, located 2000 feet lower in the section. (Contours are in feet above sea level. Adapted from Anderson, 1982).

(B) Isopach map of lowermost halite unit in the Castile (Halite II) superimposed on a map of the channel sandstone distribution in the uppermost Bell Canyon. Note that the localized areas of anomalously thin halite (B) are overlain by structural depressions higher in the section (A). Note also that these structures overlie and abut a major channel sandstone in the underlying Bell Canyon. (Contour interval 50 feet. Adapted from Anderson, 1978; Anderson and Powers, 1978; Williamson, 1978, 1979).


A
R 30 E
Poker Lake
Big Sinks
T 25 S
2100
300
400
100
2500
500
200
N
0 1 2 miles
B
R 30 E
300
250
485
58
70
T 25 S
Channel sandstones in upper Bell Canyon

5. CONCLUSIONS AND RECOMMENDATIONS

When constructing a hydrogeologic model, the characterization of a given aquifer must be compatible with the scale of the problem under consideration. When Hiss constructed his conceptual model for groundwater flow in the Delaware Basin, he chose to characterize the Delaware Mountain Group with an average hydraulic conductivity of 0.015 feet per day (5.7×10^{-6} cm/sec)(Hiss, 1975, p. 206). The furthest he broke down his conductivity data was an average for each of four counties (p. 154-157). If the Delaware Mountain Group, and therefore the Bell Canyon Formation, was a homogeneous aquifer, then the use of these average hydraulic conductivity values for modeling a localized process such as salt dissolution associated with a fracture zone (Wood, et al., 1982) would be appropriate. However, the Bell Canyon is neither lithologically nor hydrologically homogeneous. The Bell Canyon is a complex sequence of channel sandstones and interchannel siltstones, with hydraulic conductivities ranging from $<10^{-7}$ to 10^{-4} cm/sec. The clean sands in the major channel sandstones have conductivities at the high end of this range and groundwater flux through the Bell Canyon will be concentrated along these trends. Because the rate of salt dissolution associated with density-driven, convective flow in a fracture zone is controlled by the transport capacity of the Bell Canyon Formation (Wood, et al., 1982, p. 88-96), hydrologic and solute transport modeling of this process must account for the effect of localized higher groundwater fluxes in the major channel sandstones in the upper Bell Canyon. As noted in Sections 2 and 3, neither Lambert (1983) nor Wood, et al. (1982) consider this important aspect of Bell Canyon hydrology relative to the salt-dissolution process, and as a result, both of these studies underestimate the solute transport capacity of the Bell Canyon.

How can the potential for deep seated salt dissolution and subsidence be evaluated for the WIPP site? Options for the analysis of potential salt dissolution rates include the following:

- Either sufficient subsurface exploration (drill holes) should be carried out to fully characterize (1) the distribution of channel sandstones in the Bell Canyon and (2) the hydraulic conductivity of these units, or a conservative assumption about the presence of such channels must be made. For example, a hydrogeologic model could be constructed that assumes at least one major channel sandstone in the upper Bell Canyon with conservative characteristics taken from the petroleum industry literature [e.g. thickness of channel equal to 35 meters (Williamson, 1979) and hydraulic conductivity equal to 10^{-4} cm/sec (Figure 2-4)].

- Using this hydrologic information, a salt-dissolution, solute transport model should be constructed using a strategy similar to that used in the Wood, et al. (1982) study. The goal of the modeling would be to predict salt dissolution rates. The modeling should focus on dissolution associated with density-driven, convective flow in fracture zones, as this is the most likely source of localized dissolution at WIPP.

- For solute transport in the Bell Canyon, either a numerical model capable of handling density-dependent flow should be used, or a conservative assumption made in specifying the net salt flux into the aquifer. The numerical solute transport model used by Wood, et al. was not designed to handle density-dependent flow situations (Wood, et al., 1982, p. 73-74). Models capable of handling density dependent flow have been used to examine saltwater intrusion problems (Pinder and Cooper, 1970; Segol, Pinder and Gray, 1975; Segol and Pinder, 1976). An alternative (or possible precursor) to such modeling is to make a simple conservative assumption about the net solute flux in the aquifer at a fracture zone (e.g. assume that the solute load increases to saturation at the fracture zone -Wood, et al., 1982, p. 92).

The analysis of potential salt dissolution rates does not, by itself, fully address the problem of assessing the dissolution-subsidence hazard at WIPP. The analysis of salt dissolution rates should be complemented by a structural analysis of the subsidence deformation that results from removing salt from the lower portion of the evaporite section. Salt deformation is a strongly rate dependent process (Figure 5-1). At low loading (strain) rates, salt deforms in ductile flow with no strain hardening. At higher loading rates, a small amount of ductile strain is followed by brittle failure. In the salt dissolution-subsidence process, the rate of salt deformation is primarily controlled by the rate of salt dissolution [i.e. the rate at which support is removed from the lowermost portion of the salt unit] (Figure 5-2) (Davies, 1982, 1983 - in preparation). In Figure 5-2, note that for the case of completely ductile subsidence, a repository constructed in the middle of the salt unit would maintain its hydrologic integrity through a large portion of the subsidence (over a very long period of time), until it was lowered to the level of active salt dissolution. At the other extreme, brittle collapse, associated with high dissolution rates, would allow groundwater access to the repository much sooner. The goal of the structural analysis for WIPP should be to determine the type and timing of subsidence that would occur at WIPP given the salt dissolution rates computed for this area. A possible strategy for this analysis would be to use the computed salt dissolution rates as the boundary condition in a salt deformation model such as COUPLEFLO, which has been used to model salt-deformation associated with mine excavations (Dawson and Chavez, 1978; Munson and Dawson, 1980). The model results would be analyzed by examining the deformation field above the dissolution zone to identify the presence, or absence, of strain rates that exceed a pre-established ductile-brittle threshold. The result of such analysis would be a determination of the general character of subsidence-related deformation potential affecting the WIPP repository.

In summary, the potential for deep seat salt dissolution and subsidence at the WIPP site has not yet been adequately evaluated. Both Lambert (1983) and Wood, et al. (1982) have underestimated the solute carrying capacity of the Bell Canyon aquifer by overlooking the importance of localized trends of high ground-water flux associated with major channel sandstones in the Bell Canyon. The preceding paragraphs outline specific suggestions for a more complete analysis of potential salt dissolution rates in the WIPP area and of the character of subsidence deformation.

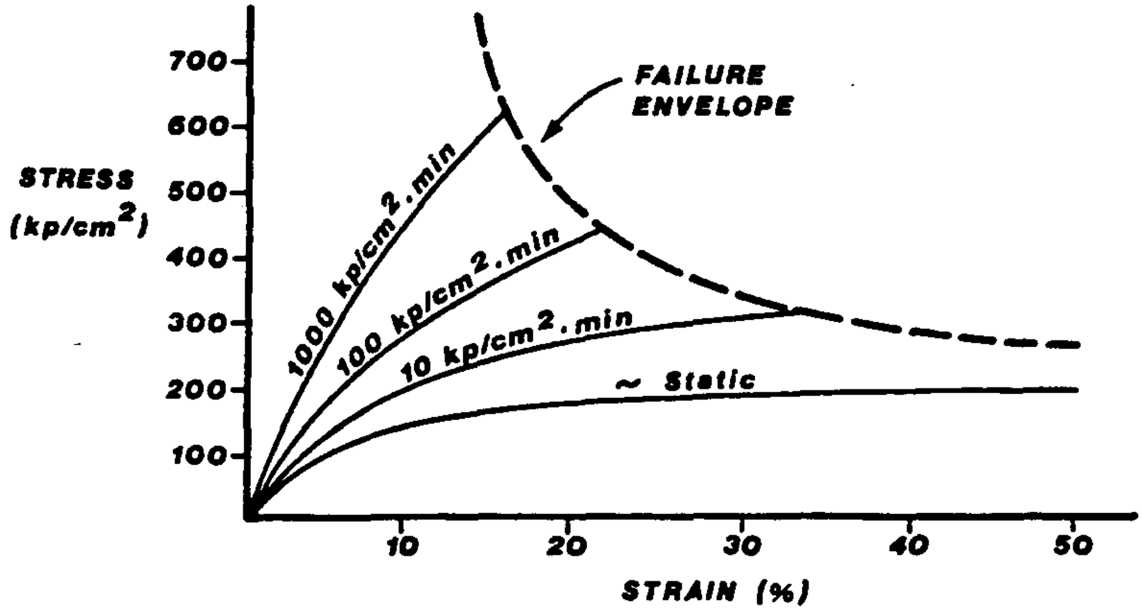


Figure 5-1. Laboratory test data illustrating the rate dependent character of salt deformation behavior. (Adapted from Dreyer, 1972)

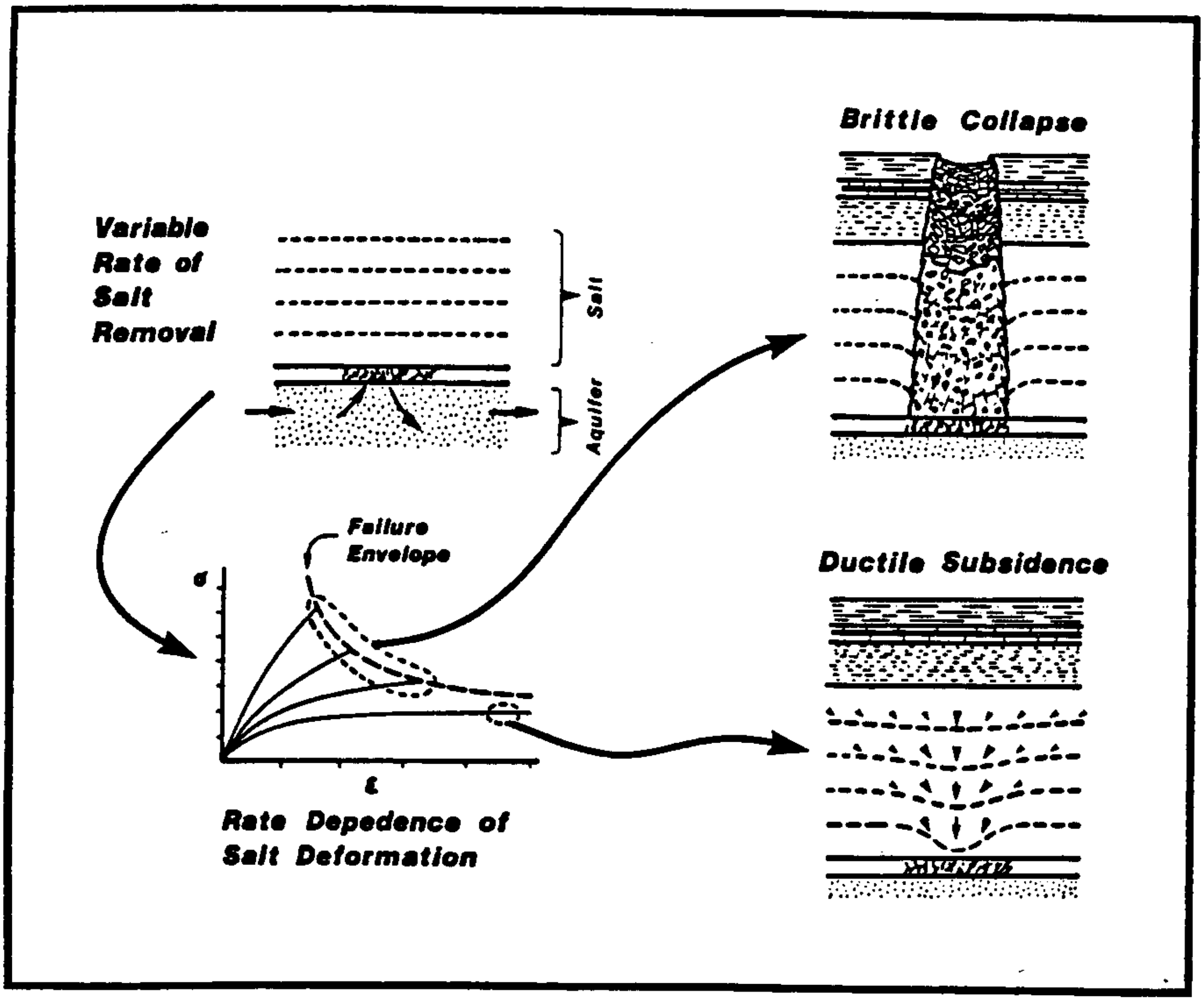


Figure 5-2. Schematic diagram illustrating the relationship between the rate of salt dissolution and the structural form of subsidence.

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