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THE EFFECT OF FAULTS UPON GROUND WATER FLOW IN THE BATON ROUGE FAULT SYSTEM

A Thesis

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements for the degree of

Master of Science
in
The Department of Geology and Geophysics

by

Mosa Nahid Nasreen

M.S., Jahangirnagar University, 1998

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ABSTRACT

The Baton Rouge Fault (BRF), a growth fault, traverses Baton Rouge Parish, the study area. This fault is a part of the Baton Rouge Fault System (BRFS), located in South Louisiana. There are ten aquifers in the Baton Rouge area, which are the main source of freshwater. Beds dip and thicken toward the south. Aquifers in the Baton Rouge area are disrupted by the BRF. Aquifers contain fresh water in the updip (north of the BRF) and saline water in the downdip (south of the BRF) directions.

Saline water has intruded into some of the aquifers north of the BRF as a result of overpumping. It was assumed until 2000 that the BRF is acting as a leaky barrier for the movement of saline water north of the fault. Later, in 2002 two abstracts assert that this fault is acting as a conduit. The main purpose of this work was to analyze this controversy by reviewing previous literature, modeling, and chemical analysis. This work has been done using the USGS model "MOCDENSE", a density-driven 2-D fluid flow. Five different scenarios have been developed. Chemical analysis has been done using available USGS data sources and data collected by Professor Stoessell. Modeling indicates that the fault can act as either a leaky barrier or a conduit for saline water to migrate north of the fault. Chemical analysis also shows a dual role is likely.

CHAPTER I: INTRODUCTION

Southern Louisiana is underlain by thick sequences of alternating coarse and fine sedimentary deposits representing sequences of marine transgression and regression. Generally all the beds are dipping southward (Figure 1). Beds thicken toward the south. The sand layers from Miocene to Recent act as aquifers in the Baton Rouge area. These aquifers vary in thickness from 75ft to more than 200ft thick (Tomaszewski, 1996), and the thickness of the clay layers between the aquifers range from 100ft to 500ft (Whiteman, 1980). These unconsolidated shallow sediments of gravels, sands, silts, and clays were deposited by fluvial, deltaic, and coastal processes. These aquifers are irregular in thickness and extent, interfingering with leaky confining beds (Kuniansky 1989). Local aquifers of Southeast Louisiana are named after their depth of deposition from the surface in the Baton Rouge industrial area: the "400-, 600-, 800-, 1,000-, 1,200-, 1,500-, 1,700-, 2,000-, 2,400-, and 2,800-foot" sands (Meyer & Turcan, 1955). The aquifers carry fresh water in the updip and saline water in the downdip directions. Fresh water comes into these aquifers from infiltration of rainwater. The average precipitation over the surrounding areas, such as East and West Baton Rouge, East and West Feliciana, and Point Coupee Parishes ranges from 54 to 60 in/yr.

Due to its tectonic history and geologic position, South Louisiana contains many local faults, salt domes, and other structural features. Two active normal faults, the Baton

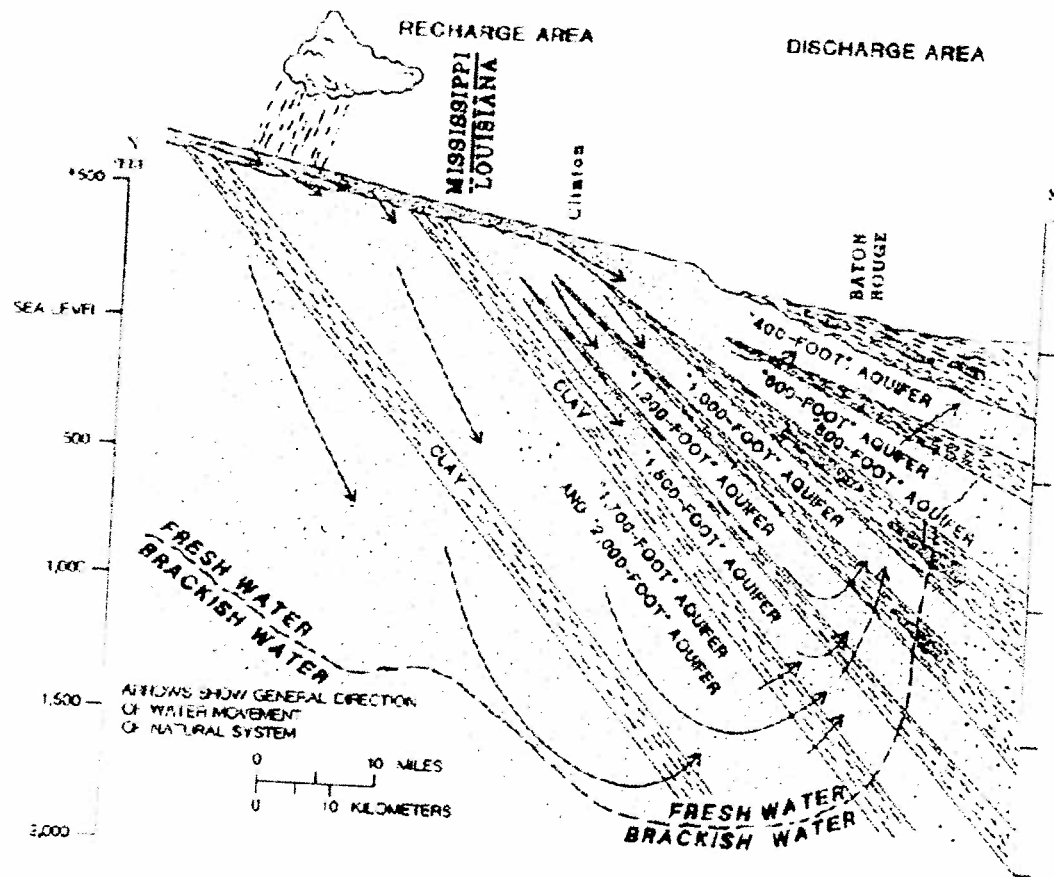


Figure 1: Discharge and recharge system of the regional aquifers in South Louisiana (modified from Morgan, 1963).

Rouge Fault (BRF) and Denham Springs-Scotlandville (DSS) Fault, pass through southern Louisiana and together comprise the Baton Rouge Fault System (BRFS).

The BRF is a northwest-southeast trending normal fault, showing increasing displacement with depth, which is a characteristic of growth faults. It dips at 45° to the south to a maximum depth of 6.1km (Lopez et al., 2002). Whereas Spearing (1995) mentioned that it dips south at an angle of 70° and flattens to about 50° or less at 10,000ft below surface. It traverses south Louisiana from east to middle (Figure 2). The DSS fault traverses the western portion of South Louisiana. The northern part of the faults is upthrown. The BRFS in some parts of South Louisiana disrupts the fresh groundwater aquifers. This has resulted in freshwater north of the fault and saline water south of the fault (Figure 1).

By analyzing a test well drilling program, Rapp (1994) indicated that the Baton Rouge fault disrupts ground-water flow at intermediate depths in some areas of South Louisiana, such as northern St John the Baptist Parish, southern Tangipahoa Parish, the southwestern part of St. Tammany Parish, and the northwestern part of Lake Pontchartrain.

Most growth faults develop during the slow accumulation of sediments. Some common features of growth faults in the Gulf of Mexico area are as follows (Carver, 1968; Smith, 1976): 1. Fault traces are arcuate and normally concave toward the coast. 2. The average dip of the fault plane is 45° , being steeper near the surface and diminishing with depth. 3. Displacement tends to increase at some depth to a maximum, and then to decrease at greater depth. The displacement of the Baton Rouge fault varies from

between a few feet and tens of feet in shallow sands to 350ft at the top of the “2,000-foot” sand. According to Lopez et al., (1997) this fault system is still active.

A fault can play different roles for fluid migration. A fault can act as a barrier (seal), a conduit or a combination of both.

- i. A fault is sealing (or a barrier) when fluids are unable to flow laterally across it due to an impermeable layer along the fault plane.
- ii. A fault is a conduit when fluid can pass vertically along a fault plane.
- iii. A fault is barrier-conduit when fluid can pass partially across and partially along a fault at the same time. This is a combination of the first two cases.

Knott (1993) discussed some important parameters contributing to fault seals: fault orientation, burial depth, fault displacement, net-to-gross shale ratio, net sand connectivity, and age of faulting. These points are discussed later in this thesis in the literature review chapter. Marler and Ge (2003) studied the influence of a range of hydraulic properties for the Elkhorn fault zone on ground water flow in the South Park, Colorado, region by using modeling. In that case they found that the fault zone acts as a low-permeability barrier. Hooper (1991) discussed some mechanisms for faults acting as a seal, also discussed in the literature review chapter.

A fault zone is mainly composed of three principal components: the fault core, damage zone, and protolith (Figure 3). Caine et al. (1996) defined the fault core as the structural, lithologic, and morphologic portion of a fault zone where most of the displacement occurs. It may include single slip surfaces (Caine et. al., 1991), unconsolidated clay-rich gouge zones (Sibson, 1977). Reductions in grain size and/or mineral precipitation generally give the fault core lower porosity and permeability than

the adjacent protolith (Chester and Logan, 1986; Antonellini and Aydin, 1994; Goddard and Evans, 1995; Caine et al., 1996). The damage zone is the associated zone bounded by the fault core. It may enhance fault zone permeability relative to the core and the protolith. It includes small faults, veins, fractures, cleavage, and folds, which cause heterogeneity and anisotropy in the permeability structure and elastic properties of the fault zone (Bruhn et al., 1994; Caine et al., 1996). The protolith is a regional structure surrounding the damage zone. When a fault acts as a conduit, fluid moving through relatively widely spaced fractures in the protolith is fed to the fault zone and transmitted within the more intensely fractured and permeable damaged zone (Forster & Evans 1991; Lopez & Smith, 1995; Evans et al., 1997).

Generally, ground water north of the BRFS contains fresh water. However, except in the "1,200-foot" sand, saline water has been detected north of the fault in all ten aquifers (Tomaszewski, 1996). Tomaszewski (1996) also stated that saline water might be present in the "1,200-foot" sand just north of the fault at the Westminster station. Water having chloride content more than 250mg/l is defined as saline water. This is equivalent to a dissolved solids content of approximately 750mg/l in the Baton Rouge area.

Cardwell and others (1967), Rollo (1969), Smith (1976), Whiteman (1979), Torak and Whiteman (1982), and Tomaszewski (1996) asserted that the Baton Rouge Fault acts as a leaky barrier for the northward movement of saline water. However, recent research by Miller (2002) and Stoessell (2002) argues that the fault acts as a conduit for saline water intrusion from deeper sources.

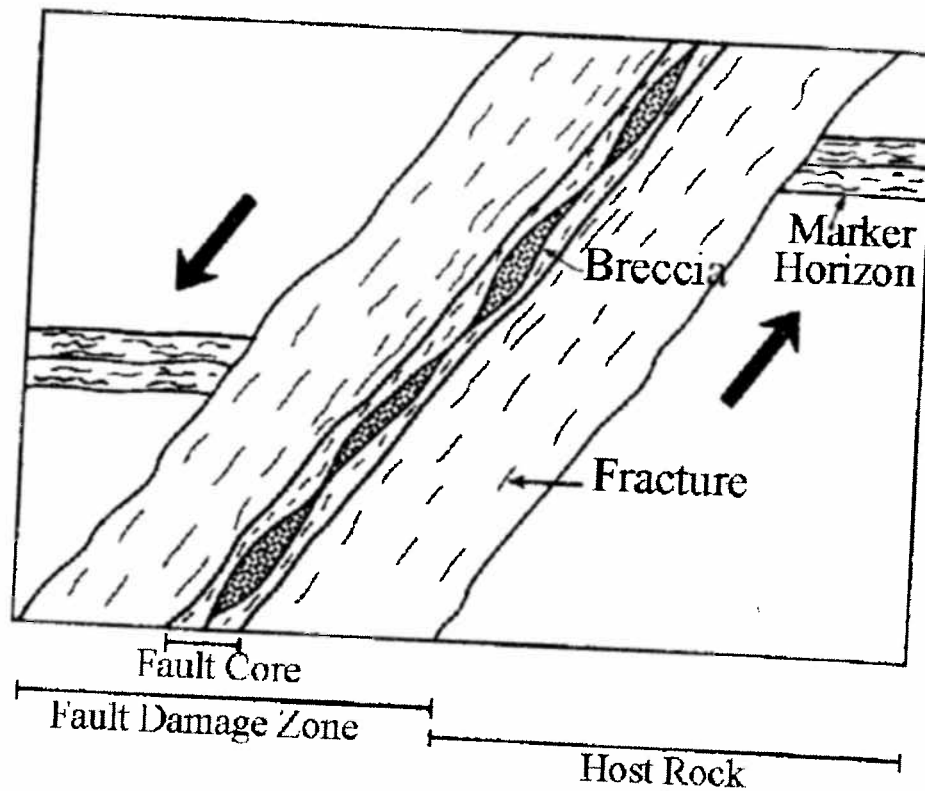


Figure 3: Components of a fault zone (modified from Gudmundsson, 2001).

Testing both hypotheses for explaining the presence of saline water north of the fault is the goal of this thesis. To obtain this goal, the thesis has three main objectives:

- i. Review all relevant literature about fault systems and the water quality of the BRFS.
- ii. Develop a computer model to compare predictions based on the two hypotheses.
- iii. Analyze available chemical data to determine if either hypothesis best explains ground water composition.

CHAPTER II: LITERATURE REVIEW

2.1 *Geologic history of Louisiana.*

The history of the Gulf of Mexico began when Pangaea started to break apart in Triassic time. The continental crust began to sag and created a depression between South America and North America, which filled with shallow water. As the water between these two continents started drying up, left behind were thick layers of minerals, such as salt, anhydrite, and gypsum. This salt deposition continued as Pangaea continued to come apart in the Jurassic period. These salt deposits are known as the Luann salt. As North America moved away from South America, the Gulf of Mexico developed by Late Jurassic time, reaching its present position in the Cretaceous period. As the Gulf opened, layers of sediments were dumped into the Gulf over the Luann salt (Figure 4). Today, the Luann salt deposits lay buried 20,000 to 50,000ft beneath Louisiana (Spearing, 1995). The different sedimentary layers dip toward the Gulf of Mexico (Figure 4). The salt flows under pressure, deforming the overlying strata and forming salt domes. Luann salt domes are distributed underneath the whole of Louisiana (Figure 5).

The weight of the overburden sediments is still increasing because sediments are continuously deposited into the Gulf of Mexico. Because the load of the overburden sediments gets thicker toward the gulf side, the Gulf side collapses and creates

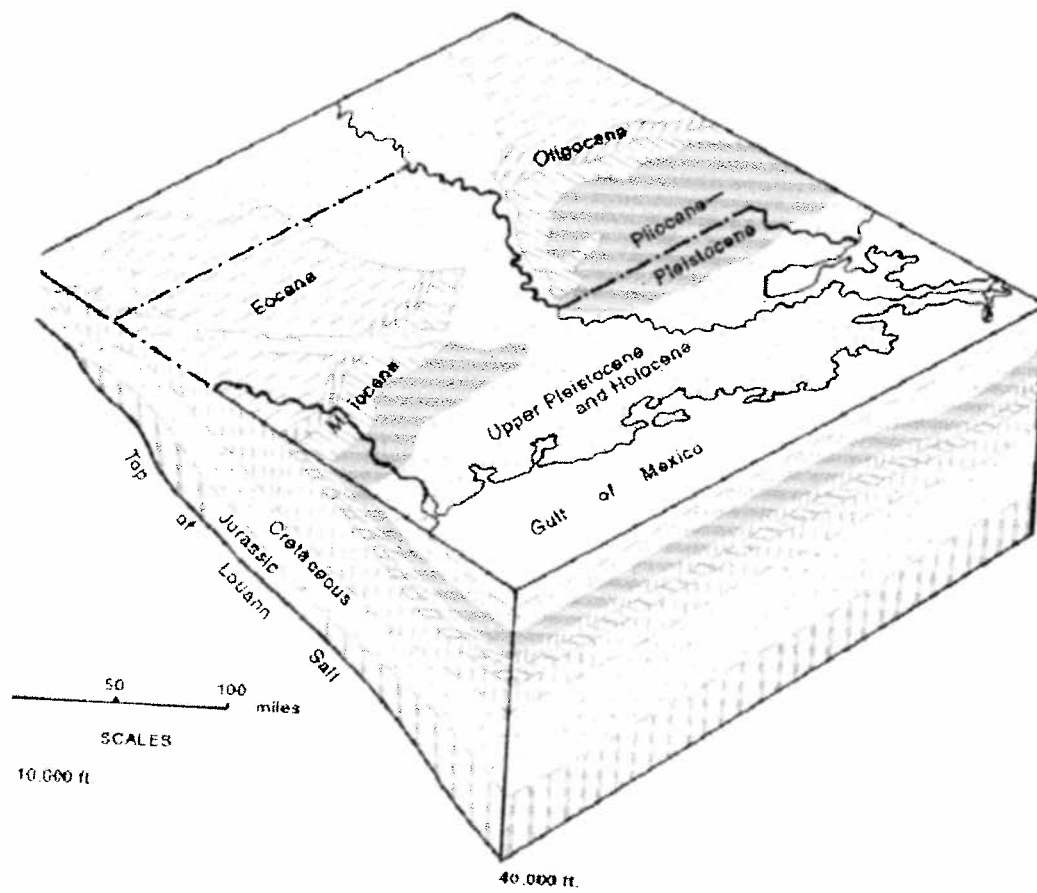


Figure 4: Luann salt and other deposits underneath Louisiana and in the Gulf of Mexico (modified from Spearing, 1995).

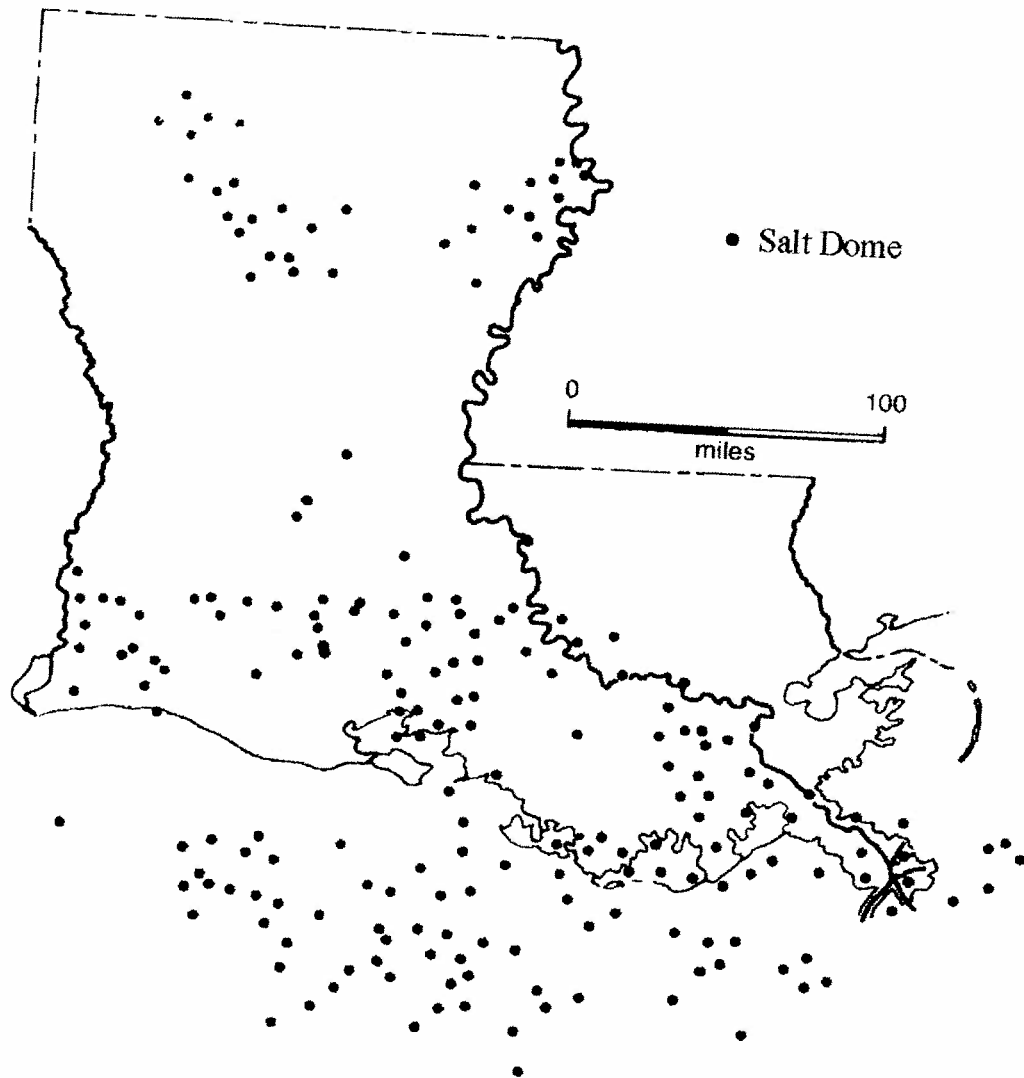


Figure 5: Distribution of Luann salt underneath South Louisiana (adopted from Spearing, 1995).

growth faults (Figure 6). Some of the growth faults formed in the Gulf of Mexico are also due to salt domes. This overburden sediment creates pressure on the buried salt (Luann), and forces the salt to move vertically upward. As salt moves upward, the overlying sediments are deformed. Faults are created around the resulting salt dome. If sedimentation continues during movement on the fault, a growth fault is formed.

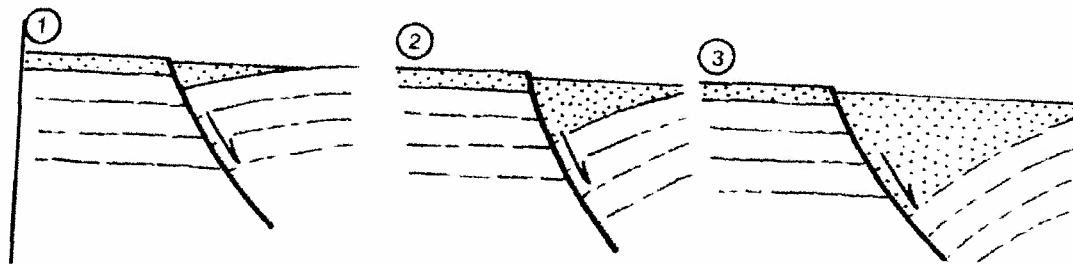


Figure 6: Sediment-load-related growth faults in Louisiana. 1, 2, and 3 show increasing sediment load and formation of growth faults (adopted from Spearing, 1995).

2.2 Stratigraphy and hydrogeology of the aquifer units in the Baton Rouge Area

The aquifer sands in the Baton Rouge Industrial area were identified and named for their approximate depth of deposition by Meyer & Turcan (1955), the "400-, 600-, 800-, 1,000-, 1,200-, 1,500-, 1,700-, 2,000-, 2,400-, and 2,800-foot" sands (Figure 7). Aquifer nomenclature varies from in East & West Baton Rouge, East & West Feliciana, and Point Coupee Parish (Halford and Lovelace, 1994) (Figure 8). The "1,500-, 2,000, and 2,800-foot" sand are the most heavily pumped aquifers in the Baton Rouge area (Tomaszewski, 1996).

The aquifer sediments are mainly composed of fine to coarse sand and have different ranges of transmissivity, thickness and storage co-efficient (Table 1). The major clay units between the aquifers range from less than 1 ft to 100 ft in thickness over the greater Baton Rouge area (Bear 1979; Halford and Lovelace, 1994). Moreover some aquifers merge locally. Aquifers are also hydraulically connected by leakage through clay layers. The hydraulic conductivity of clay units ranges from $3\text{E-}08$ to 0.3ft/d (Bear, 1979; Halford and Lovelace, 1994). The vertical hydraulic conductivity of clay units based on laboratory analysis of some samples collected from the industrial area at a depth of 447 to 455 ft is 0.000011ft/d . Samples taken at a depth of 2,113 to 2,116 ft, yielded the value of 0.000016ft/d (Whiteman, 1980, Halford and Lovelace, 1994). The confining units found in East & West Baton Rouge Parish, East & West Feliciana Parish, and the Point Coupee area contain considerable amounts of silt and sand. The overall hydraulic conductivity is more likely about 0.0005 ft/d (Halford and Lovelace, 1994).

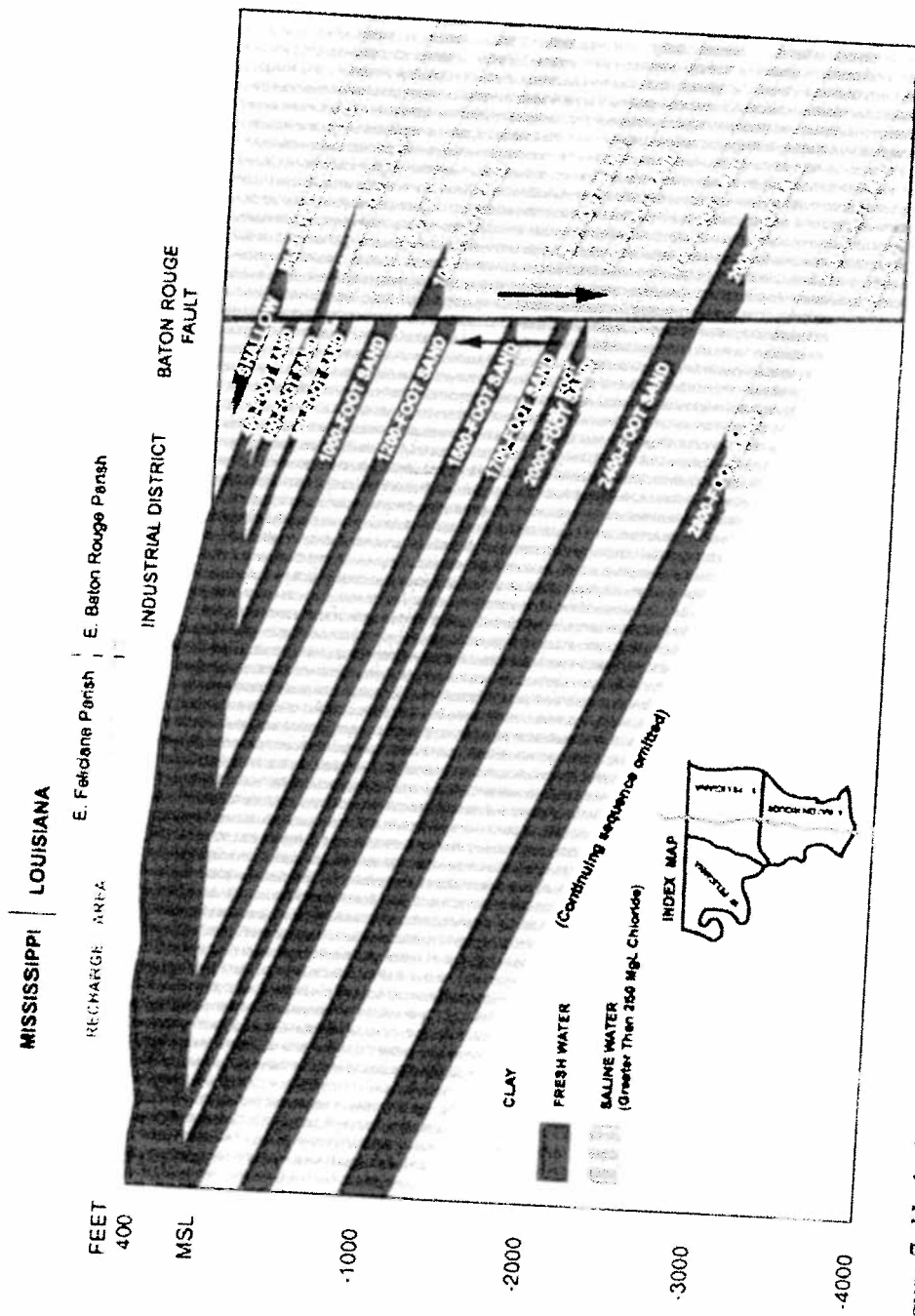


Figure 7: Hydrologic cross section including saline water intrusion in the East Baton Rouge Parish and the surrounding region. (adopted from Tomaszewski, 1996 and Hanson, 2000).

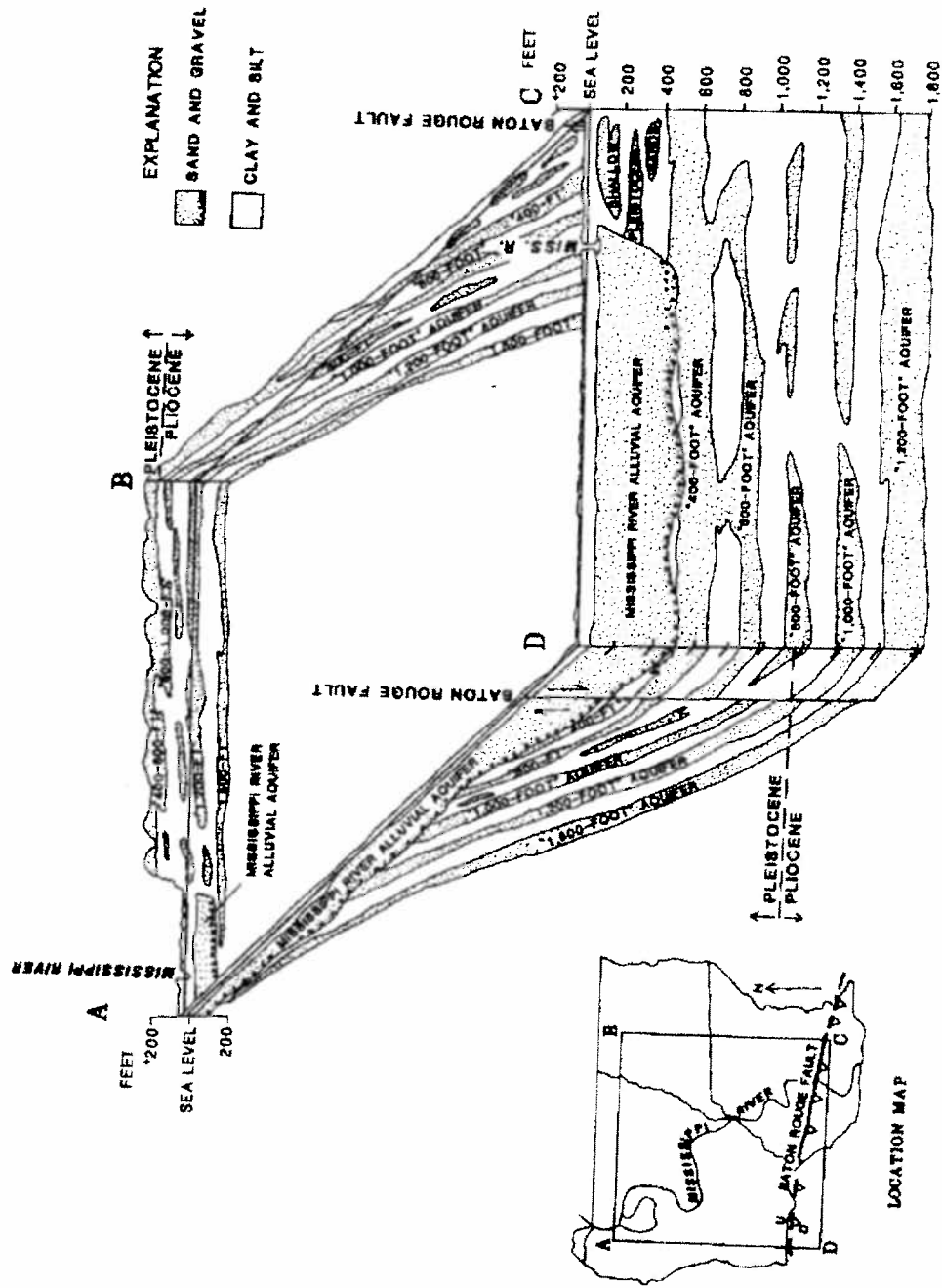


Figure 8: Variation of aquifer nomenclature over five parishes such as, East and West Baton Rouge, East and West Feliciana and Point Coupee (adopted from Kuniansky et al., 1989).

Table 1. Description of the hydrogeologic units of the Baton Rouge area, Louisiana. (Modified from Tomaszewski, 1996; Huntzinger et al., 1985; & Hanson and Boniol, 1988).

System	Series	Formation	Aquifer (hydrogeologic units)	Lithologic description	Transmissivity (ft ² /day)	Thickness (ft)	Storage Coefficient (dimensionless)
Tertiary	Quaternary	Pleistocene & Holocene	Citronelle Formation	Fine sand to pea gravel	1,700-26,000	75-400	0.0001-0.0025
			400-foot sand & "600-foot" sand				
	Pliocene	Pascagoula Formation Homochitto member Fort Adams member	800-foot sand	Fine to medium sand	3,400	50-150	0.0001-0.001
			1,000-foot sand	Fine to coarse sand	9,500	40-90	0.0001
			1,200-foot sand		10,000-17,000	40-100	0.0002-0.0008
			1,500-foot sand & "1,700-foot" sand	Fine to medium sand	4,300-12,000	20-300	0.0001-0.001
			2,000-foot sand	Medium sand	22,000-39,000	100-300	0.0006-0.0008
			2,400-foot sand	Fine to medium sand	13,000	50-250	0.0001
			2,800-foot sand	Fine to coarse sand	17,000	50-350	0.0001
	Miocene	Hattiesburg Formation					

2.2.1 Description of the Aquifers:

2.2.1.1 "400-foot" & "600-foot" sand

Saline water encroachment has been found in the "600-foot" sand north of the fault (Rollo, 1969). Saline water was first detected in the "600-foot" sand in 1948 (EB-123 which is 0.5 mile north of the Baton Rouge fault and 4 miles south of the center of pumping from the "400-foot" and "600-foot" sands). The source of saline water in the "600-foot" sand north of the fault is the downthrown "400-foot" aquifer south of the fault. The saline water is moving in the "600-foot" sand at a rate of about 325ft/year (Rollo, 1969). The water level in the "400-foot" sand south of the fault is 50 ft higher than the water level in the "600-foot" sand north of the fault (Whiteman, 1979). The rate of northward movement of saline water across the fault was about 500,000gallons/day in 1971(Whiteman, 1979). Based on the map of the base of the "600-foot" aquifer, the thickness and the position of the saline-fresh water interface within the aquifer, and a porosity of 0.25 Whiteman (1979) estimated 11×10^9 gallons of salty water in the "600-foot"sand north of the Baton Rouge fault was subjected to encroachment (Whiteman, 1979). He also mapped the configuration of the "600-foot" sand to determine the path the saline water will follow as it moves northward toward the major well fields of the industrial district. Chemical analysis on the wells EB- 871 & EB- 869 north of the fault is discussed later in this chapter. A six-inch production well, EB-876, was drilled that is 25ft from the well EB-869 with 40ft of screen set from 595 to 635 ft below the land surface in the "600-foot" sand (Whiteman, 1979). The well EB-876 indicated that the water levels in wells EB-868 and EB-871 south of the fault did fluctuate in response to changes in the pumping rate of well EB-876 (Figure 9).

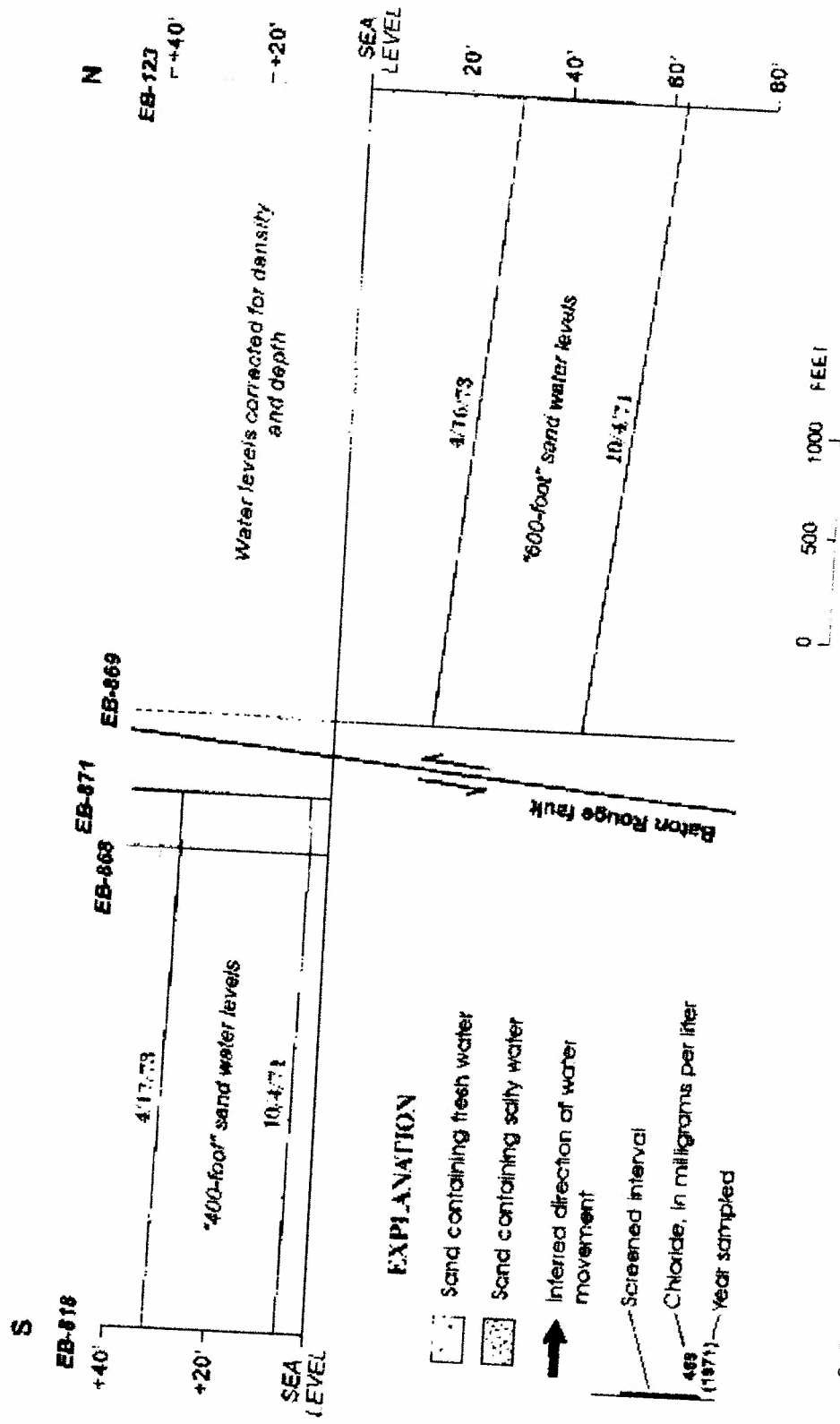


Figure 9: Water levels in both sides of the Baton Rouge Fault in the "400-foot" and "600-foot" sand (adopted from Whiteman, 1979).

Thus, Whiteman (1979) confirmed leakage across the fault. No saline water has been found north of the fault in the "400-foot" aquifer in the East Baton Rouge area but saline water has been found in this aquifer north of the fault in the west-central part of the west Baton Rouge Parish (Figure 10). Tomaszewski (1996) estimated the head difference had decreased to about 20ft by 1990. According to this 1990 data, saline water moving across the fault probably was about 200,000 gallons/day.

Pumpage in both the aquifers started declining in 1960 (pumpage totals are always combined for both "400- and 600-foot" sands). In 1966 when pumpage was 21.4mgd, the hydraulic gradient was about 7-13 ft/mile in the vicinity of the saltwater front (Cardwell & Dial, 2000). This gradient was 10 ft/mile in April 1976 when the average pumping rate was 17.9 mgd (Cardwell & Dial, 2000). In 1996 when the pumping rate was 7.0 mgd, the hydraulic gradient in the area of the saltwater front was 2-3ft/mile. Under these conditions the rate of saline water movement would be about 80ft/yr (66 yrs to move 1 mile) (Cardwell & Dial, 2000). The following table 2 shows the gradual variations of the pumpage from 1978-1999.

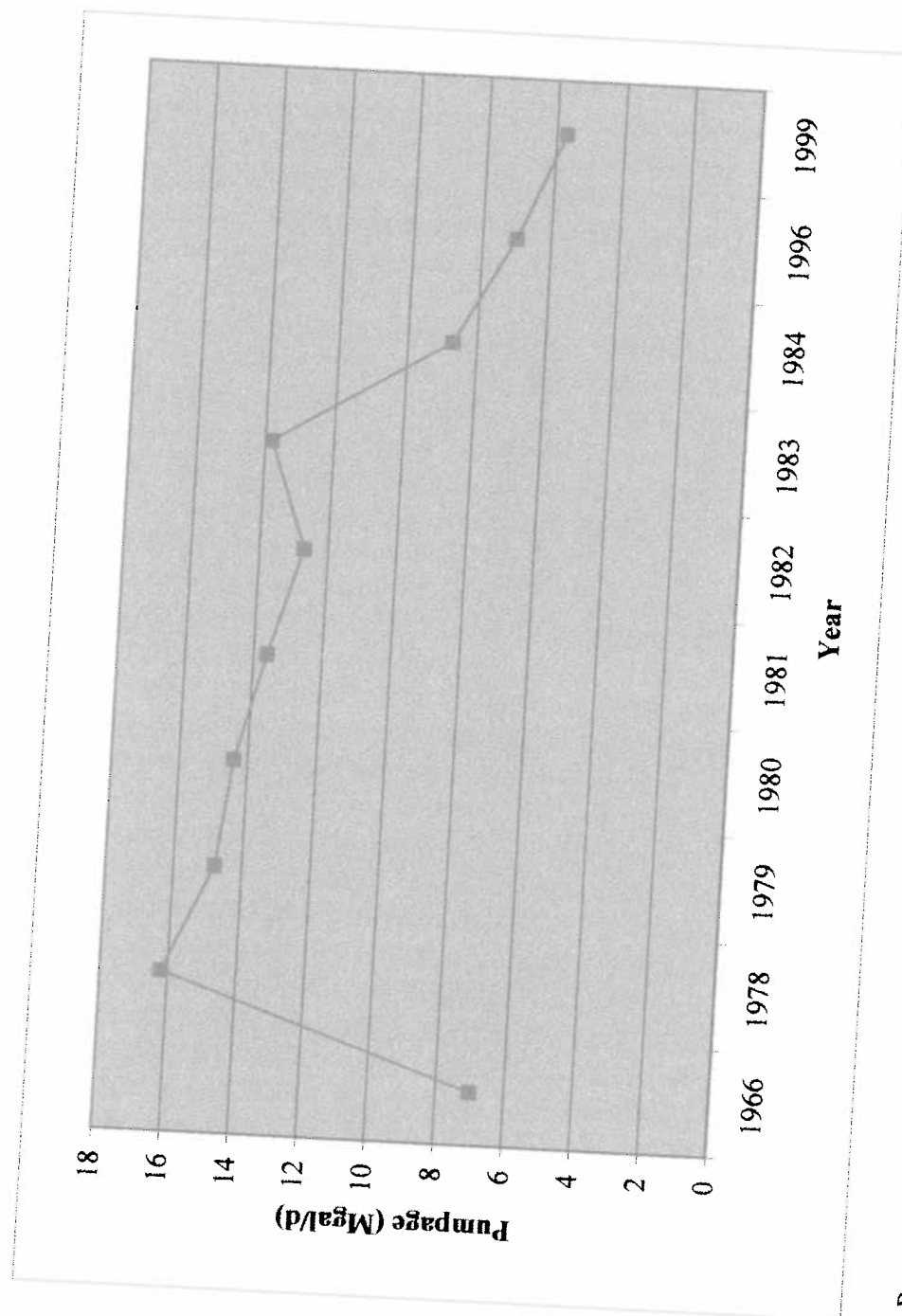


Figure 11. Pumpage from the "400-foot" and "600-foot" sand from the year of 1966-1999 (source of data: Cardwell & Dial, 2000).

2.2.1.2 "800-foot" sand

The "800-foot" is a minor aquifer in the Baton Rouge area. Whiteman (1979) mentioned a narrow strip of saline water encroachment north of the fault (Figure 12). Tomaszewski (1996) stated no saline water encroachment has been found. The average pumping in this aquifer was about 2.8Mgal/d in 1966 and 1.1Mgal/d in 1977 (Whiteman, 1979). Based on the seasonal water level fluctuations in the "800-foot" sand in the Baton Rouge area, Whiteman (1979) stated that this layer is hydraulically connected to the overlying "600-foot" sand. Saline water is moving into this aquifer by leakage across the fault at a low rate from the downthrown "600-foot" sand (Whiteman, 1979). Cardwell and Dial (2000) stated, based on log analysis, that they did not find any evidence of direct connection between the "600-foot" and "800-foot" sand. However, Kuniarsky et al. (1989) stated that these two aquifers might be connected in the area near and south of the saline water front.

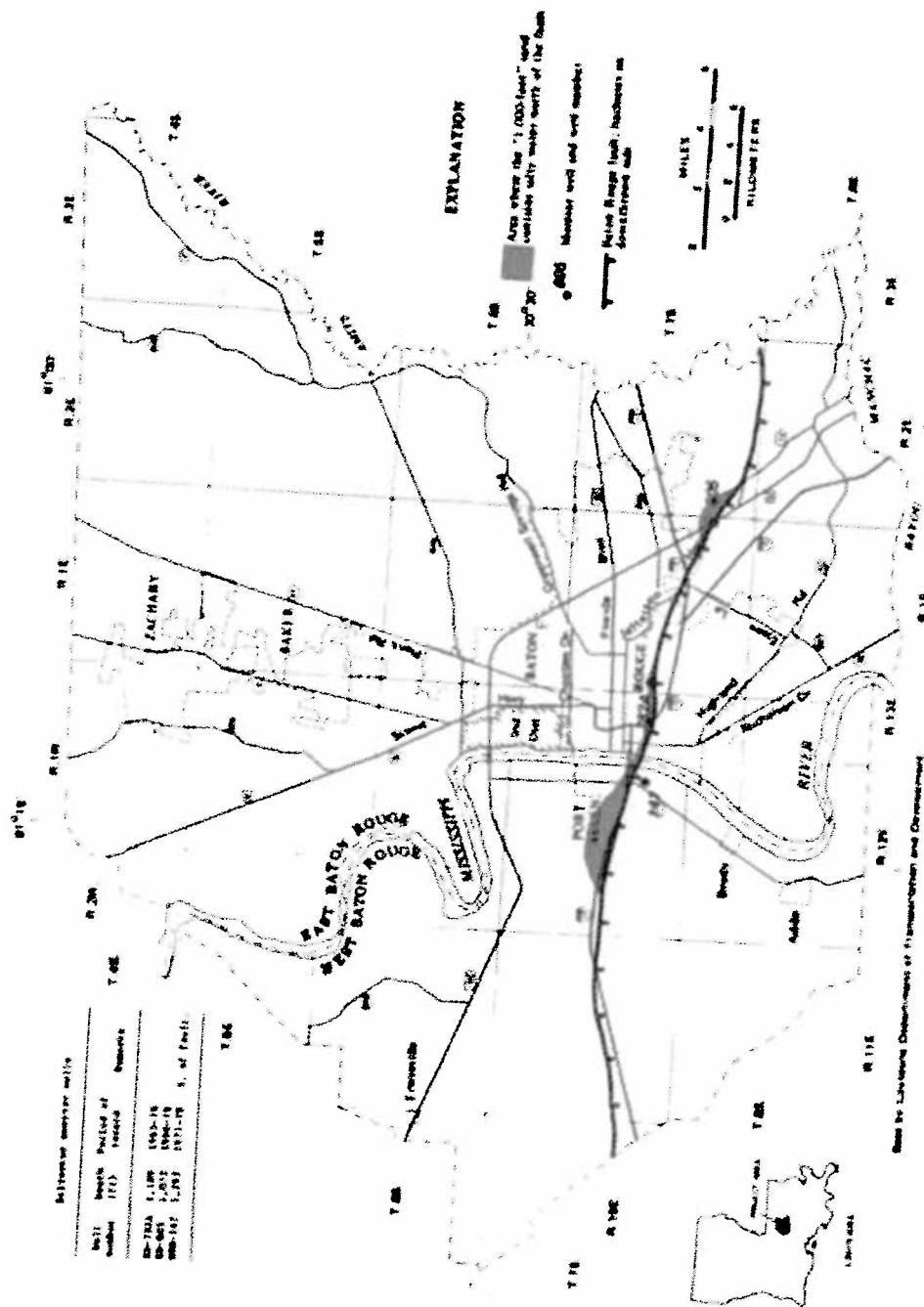


Figure 13: Location of saline water intrusion into the "1,000-foot" sand at north of the Baton Rouge Fault (adopted from Whiteman, 1979).

2.1.1.1 "1,000-foot" sand

The "1,000-foot" is also a minor aquifer in the Baton Rouge area. The average pumping was about 3Mgal/d from the "1,000-foot" sand in 1979 (Whiteman, 1979) and 6.5Mgal/d in 1990 (Tomaszewski, 1996). Data from several electrical logs near the fault showed that the saline water occurs north of the fault in both East & West Baton Rouge Parishes (Whiteman, 1979; Figure 13). Well EB-805 showed a steady increase in chloride concentration from 650mg/L in 1967 to 4,600 mg/L in 1978 (Whiteman, 1979). The continuous increase of chloride concentrations in well EB-805 is explained by Whiteman (1979) as indicating that the saline water is moving northward due to leakage across the fault from the highly saline aquifer to the south. The saline water leakage showed in well EB-805 is caused by water level differences across the fault due to pumping from the "1,000-foot" sand in eastern East Baton Rouge Parish (Tomaszewski, 1996). Whiteman (1979) stated that an electrical log of EB-990, located 0.8 mile north of the EB-805, in 1976 showed no evidence of saline water in the "1,000-foot" sand. Therefore, the saline water has progressed less than 0.8 miles in this area (Whiteman, 1979). Whiteman estimated the northward movement of saline water to be less than 200ft/yr based on the EB-805 well data (1979) but later the rate was estimated to be about 110ft/yr by Tomaszewski (1996) based on an average hydraulic gradient of about 10.6ft/16,000ft, hydraulic conductivity of 110 ft/d, and porosity of 25 percent between the Cortana station and well EB-805.

2.1.1.2 "1,200-foot" sand

Saline water has not been detected in the "1,200-foot" sand north of the Baton Rouge fault (Whiteman, 1979). There is a possibility of saline water intrusion at only well EB-621 (Tomaszewski, 1996). Saline water is probably not moving toward the pumping centers (Rollo, 1969). The pumpage rate in the "1,200-foot" sand was about 13Mgal/d in 1990 in the Baton Rouge area (Tomaszewski, 1996). During this year the largest pumping concentration of about 5.5Mgal/d was at the nearby industrial district and second largest was 2.5Mgal/d at the Bankston station (Tomaszewski, 1996).

2.1.1.3 "1,500-foot" sand

The "1,500-foot" sand is one of the most heavily pumped aquifers in the Baton Rouge area. Saline water encroachment has been documented in the "1,500-foot" sand north of the fault (Morgan & Winner, 1964; Rollo, 1969; Whiteman, 1979). The pumping rate in the "1,500-foot" sand in the Baton Rouge area was 8.8 Mgal/L in 1966 (Rollo, 1969), 15.1 Mgal/L in 1977 (Whiteman, 1979), and 20Mgal/d in 1990 (Tomaszewski, 1996). In 1990 the most concentrated pumping was at the Lula station and Government station and the rate was about 7.5 Mgal/d and 2.3Mgal/d respectively (Tomaszewski, 1996). Rollo (1969) estimated the area underlain by saline water in the "1,500-foot" sand north of the fault to be less than 1 mile from the heavy pumping area. Tomaszewski (1996) stated that saline water under the "1,500-foot" aquifer north of the fault occupied about 1.5 sq. miles in 1992. Based on the distribution of pumping stations, pumping rates and aquifer characteristics, Tomaszewski (1996) stated that saline water is moving in a north to northeasterly direction from the main body of saline water near the fault (Tomaszewski, 1996). Whiteman (1979) stated that the "1,200-foot" sand south of the

fault and "1,500-foot" sand north of the fault are hydraulically connected because the "1,200-foot" sand south of the fault responds in subdued fashion to water level changes in the "1,500-foot" sand north of the fault. Thus, Whiteman (1979) concluded that the saline water is coming across the fault into the "1,500-foot" sand north of the fault from the downthrown "1,200-foot" sand south of the fault. Water quality data from these two aquifers are discussed later in this chapter. Whiteman (1979) stated that the northward gradient was between 1.5 and 2ft/mi since 1969 toward the Government station and that the northward rate of movement of saline water was between 80 and 120ft/yr. Data collected from wells EB-413 and EB-917 in 1992 also supported the consistency of the rate of northward movement (80 & 120ft/yr) of saline water with Whiteman's (1979) previous estimation toward the Government station (Tomaszewski, 1996). With this gradient (from 1.5 to 2ft/mile) saline water at the base of the "1,500-foot" sand has proceeded northward from 1,200 to 1,800 ft since 1977. The saltwater- freshwater interface may be within 1,600 feet of the Government station in 1992 (Tomaszewski, 1996).

2.1.1.4 "1,700-foot" sand

No saline water has been found in "1,700-foot" sand north of the fault (Whiteman, 1979 and Tomaszewski, 1996). Pumpage was about 2.5Mgal/d in 1990 in the Baton Rouge area (Tomaszewski, 1996). Pumpage from this aquifer is low and wells are located north of the fault so saline water encroachment is unlikely (Tomaszewski, 1996).

2.1.1.5 "2,000-foot" sand

The "2,000-foot" sand is another of the most heavily pumped aquifers in the Baton Rouge area. Saline water has been found north of the fault at EB-781 in the "2,000-foot" sand (Rollo, 1969; Whiteman, 1979; Smith, 1976) (Figure 14). The water level difference between north and south of the fault in the "2,000-foot" sand is about 200 ft although water levels on both sides are declining with time (Rollo, 1969). The water level contours indicate that this salt-water is moving westward parallel to the fault (Rollo, 1969). Rollo (1969) mentioned that the "1,500-foot" sand south of the fault might be the source of saline water of the "2,000-foot" sand north of the fault. The well EB-871 shows an increase in chloride content from 1000mg/l in 1965 to 2100mg/l in 1972 and this level remained constant through 1975 (Smith, 1976). Smith also states that evidence of movement of saline water in this aquifer across the fault are: 1. increase of salinity in well EB-781, and 2. similarity in water level fluctuations across the fault in response to pumping changes in the Baton Rouge area. He estimated the volume of saline water crossing the fault to be 450,000gal/d in 1976 (which is more than 1% of average daily pumpage (36Mgal/d in 1976) from the "2,000-foot" sand in the East Baton Rouge parish. With this rate, saline water would require 100years to reach the public water supply wells at the Lafayette Street and Government Street pumping stations (Smith, 1976). The average daily pumpage during 1977 was more than 33 Mgal/d, approximately 24% of the total pumpage in the East Baton Rouge Parish (Whiteman, 1979). The pumpage was 39Mgal/d in 1990 from the "2,000-foot" aquifer (Tomaszewski, 1996). Saline water covers an area of about 4 sq. miles. Salt-water leakage across the fault from 1977 to 1992

is estimated to be 0.57 Mgal/d (Tomaszewski, 1996). In the "2,000-foot" sand, saline water has reached the Lafayette and Convention pumping stations (Tomaszewski, 1996).

2.1.1.6 "2,400-foot" sand

Saline water has not been found north of the fault in the "2,400-foot" sand (Rollo, 1969; Tomaszewski, 1996). The pumpage rate from this sand was 11.5 Mgal/d in 1990. Saline water is unlikely because the "2,000-foot" sand south of the fault that is against the "2,400-foot" sand north of the fault and it contains fresh water (Tomaszewski, 1996).

2.1.1.7 "2,800-foot" sand

Whiteman (1979) mentioned that the "2,800-foot" sand is the principal source for industrial and public water supplies in northern East Baton Rouge Parish. In 1977 average pumping was about 27 Mgal/d in East Baton Rouge Parish (Whiteman, 1979). In 1990 the total pumping was 29 Mgal/d in the Baton Rouge area (Tomaszewski, 1996). This aquifer dips southward at a rate of approximately 60 to 100 ft/mile (Smith, 1976). This aquifer contains saline water over an extensive area north of the Baton Rouge fault in East and West Baton Rouge Parishes (Tomaszewski, 1996). The saline water in the "2,800-foot" sand north of the fault in East and West Baton Rouge Parish is naturally occurring and is a result of incomplete flushing of the aquifer rather than encroachment in response to pumping (Whiteman, 1979; Tomaszewski, 1996). A large amount of fresh water overlies much of the area containing saline water. The transitional zone starts 3 to 5 miles north of the fault, and width is about 4 miles (Tomaszewski, 1996) (Figure 15).

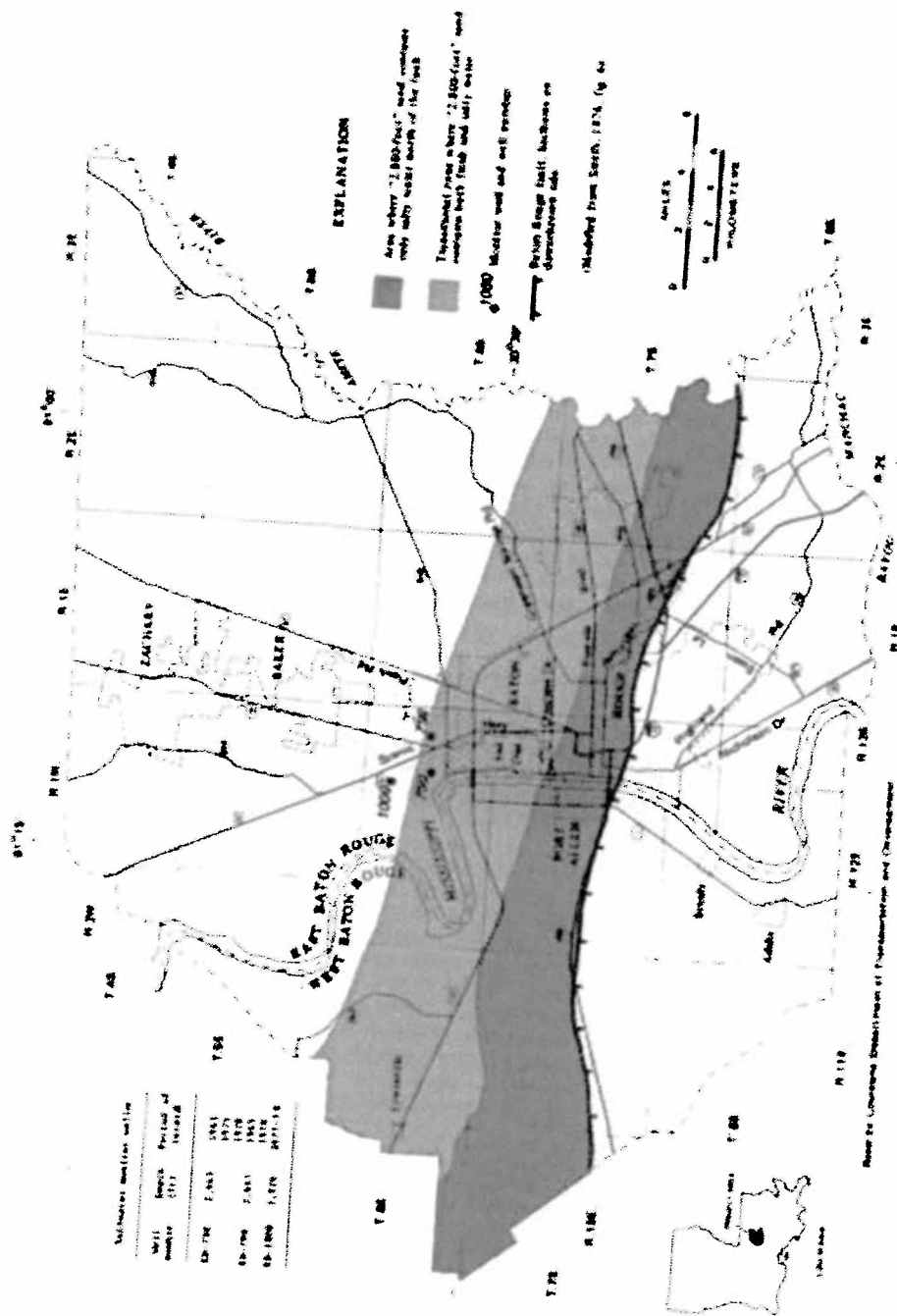


Figure 15: Location of saline water intrusion into the "2,800-foot" sand at north of the Baton Rouge Fault (adopted from Whiteman, 1979).

The Baton Rouge fault probably creates a hydraulic discontinuity in this aquifer but northward movement of saline water of the interface is not significantly restricted because the saline water- fresh water interface is already north of the fault in this aquifer (Smith, 1976). The well data from EB-750 and EB-798 indicate that the wells installed within the transitional zones have chloride concentrations that have increased at each well since monitoring began (Tomaszewski, 1996). Tomaszewski didn't find any further northward movement of saline water though this sand contains naturally occurring saline water north of the fault (1996).

2.1 Description of the Baton Rouge Fault System:

Durham and Peebles first traced the Baton Rouge fault in 1956 from the Mississippi floodplain in south Baton Rouge eastward into Livingston Parish, a distance of 25 miles. Torak and Whiteman (1982) indicated the hydraulic conductivity of the fault to be $0.00005d^{-1}$ based on numerical methods.

The displacement of the aquifers at the Baton Rouge fault is about a few feet to tens of feet in shallow sands to 350ft at the top of the "2,000-foot" sand (Durham & Peebles, 1956; Whiteman, 1979). Due to the displacement, aquifers north of the fault are interconnected with stratigraphically overlying aquifers that have been downthrown south of the fault. Previous test drilling investigations indicated that some of the downthrown sands are interconnected to the sands north of the fault. For example the "400-foot", "1,200-foot", and 1,500-foot" sand south of the fault are interconnected to the "600-foot", "1,500-foot", and 2,000-foot" sand north of the fault (Tomaszewski, 1996). This fault system is still active, as confirmed by Lopez et al. (1997).

This fault creates an important hydrogeologic barrier, which restricts the northward movement of saline water. In addition depressions and ridges present at the base of some sands may influence saline water movement. The density of the saline water affects movement of the fresh water in the aquifers because saline water is denser than the fresh water. Saline water is thus more likely to be present at the base of the fresh water aquifer. Moreover, the slope of the base of the aquifers can affect the saline water movement toward the north (Tomaszewski, 1996). Variations in permeability such as an undiscovered conductive channel of sand could allow for a faster rate of saline water movement toward pumping stations than previously estimated (Tomaszewski, 1996). Tomaszewski indicates that saline water is moving across the fault in response to heavy pumping and then sinking to the base of the fresh water aquifer (1996).

2.2 *Subsidence in the Baton Rouge area:*

Natural subsidence happens in the Gulf coastal plain due to the slow compaction of the sediments, especially clays and silts, under the weight of the accumulating overburden. Smith and Kazmann (1978) mentioned two types of localized subsidence in the Baton Rouge area, in addition to the long term, widespread, slow, regional subsidence due to tectonic activities. One is associated with local water-level declines caused by ground water pumpage, and the other is associated with natural downward movement of the south side of the Baton Rouge fault. The Baton Rouge industrial area shows total subsidence of about 1.67ft from 1935-1976 (Smith and Kazmann, 1978). Of this total subsidence, 1.26ft is estimated to be due to local effects of ground water pumpage and 0.41ft due to natural regional subsidence (Smith and Kazmann, 1978). The NGS (National Geodetic Survey) surveyed in an east-west trending zone approximately one

mile wide and measured the subsidence south of the Baton Rouge fault to be more than 0.2ft between 1964 and 1976 (Smith and Kazmann, 1978). The maximum subsidence rate south of the Baton Rouge fault was 0.017ft/yr, and this amount varied with different location (Smith and Kazmann, 1978).

2.3 Water quality near the fault:

Composition of salty water in the "600-foot" sand north of the fault and in the "400-foot" sand south of the fault (Whiteman, 1979) is shown in table 2. Two wells, EB-869 in the "600-foot" sand north of the fault and EB-871 in the downthrown "400-foot" sand south of the fault, are located near the fault. Chemical analyses of water from these two wells showed identical composition, which Whiteman (1979) interpreted as indicating leakage across the fault (Whiteman, 1979). Water from the well EB-869 is equivalent to diluted water from the well EB-871. None of the major ionized constituents differ in their contributions to the total ionized dissolved-solids contents by as much as 0.5%. Based on the water chemistry, Whiteman (1979) indicated that the downthrown "400-foot" sand could be the source of the saline water entering into the "600-foot" sand. Composition of salty water in the "1,500-foot" sand north of the fault and in the "1,200-foot" sand south of the fault is shown in table 3 (Whiteman, 1979). Water samples collected in 1965 from well EB-780A in the "1,200-foot" sand and EB-782B in the "1,500-foot" sand showed a similarity in composition of the water with only minor differences in the relative concentrations of individual constituents.

Table 2. Saline water compositions in the "600-foot" and "400-foot" sand near the Baton Rouge fault (modified from Whiteman, 1979).

Dissolved constituents and properties	Well EB-869 "600-foot" sand north of fault			Well EB-871 "400-foot" sand south of fault		
	Milligrams/liter	Milliequivalents /Liter	Percentage ionized constituents	Milligrams/liter	Milliequivalents /Liter	Percentage ionized constituents
Calcium	180	80982	4043	190	9.481	4015
Magnesium	51	4.185	2.07	48	3.986	1.75
Sodium	2,040	88.699	43.79	2,320	100.873	44.19
Potassium	10	0.256	0.13	16	0.409	0.18
Bicarbonate	237	3.884	1.92	248	4.065	1.78
Carbonate	0	0	0	8	0.267	0.12
Sulfate	58	1.208	0.6	68	1.416	0.62
Chloride	3,380	95.35	47.07	3,820	107.762	47.21
Hardness as CaCO ₃	659			674		
Specific conductance (micromhos at 25° C)	10,400			11,600		
p ^H	8.1			8.4		

Table 3. Saline water compositions in the "1,200-foot" and "1,500-foot" sand near the Baton Rouge fault (modified from Whiteman, 1979).

Dissolved constituents and properties	Well EB-782B "1,500-foot" sand north of fault					Well EB-780 "1,200-foot" sand south of fault			
	22-Apr-65			26-May-77		19-Apr-65			
	Milligrams/liter	Milliequivalents/Liter	Percentage ionized constituents	Milligrams/liter	Milliequivalents/Liter	Percentage ionized constituents	Milligrams/liter	Milliequivalents/Liter	Percentage ionized constituents
Calcium									
Magnesium	5	0.25	0.95	26	1.297	3.54	20	0.998	3.16
Sodium	0.9	0.07	0.27	4.1	0.341	0.93	3.4	0.291	0.92
Potassium	294	12.8	48.8	390	16.957	46.29	334	14.5	45.86
Bicarbonate	0.8	0.02	0.08	1.6	0.041	0.11	1.2	0.031	0.1
Carbonate	0	0	0	0	0	0	0	0	0
Sulfate	0.4	0.008	0.03	5.6	0.117	0.32	5.6	0.117	0.37
Chloride	344	9.704	37	530	15.064	41.12	460	12.977	41.04
Hardness as CaCO ₃	16			82			64		
Specific conductance (micromhos at 25°C)	1430			2030			1770		
pH	7.8			8.3			7.1		

The sample collected from EB- 782B in 1977 from the "1,500-foot" sand north of the fault showed increased salinity and the relative differences in relative concentrations had almost disappeared. Thus, Whiteman (1979) concluded that the "1,200-foot" sand south of the fault was likely the source of saline water in the "1,500-foot" sand north of the fault. The main bodies of saline water have been found in the "1,500-foot" sand north of the fault near the wells EB-872B, EB-807A, and EB-917 (Tomaszewski, 1996). In 1965 when the well EB-782B was initially completed, it had chloride concentrations of about 250mg/L. Chloride concentrations in this well increased into 840mg/L in 1973 but sampling was discontinued due to a casing leak (Tomaszewski, 1996). A chloride concentration in well EB- 807A increased since 1972 and was greater than 3,000mg/L since 1990. It was screened between 7ft and 12ft above the base of an unbroken sand interval (Tomaszewski, 1996). Chloride concentrations in the well EB-917 started increasing between 1985 and 1988. Chloride concentrations of 52mg/L have been detected in a water sample at this site but chloride concentrations of 3,000mg/L have been detected in water samples from nearby well EB-807A, although screened in the same sand. The reason was that the well EB-917 north of the fault is screened in an interval between 9 and 14 ft above the base of the "1,500-foot" aquifer (Tomaszewski, 1996). The location and amount of the Government and Lula stations control the rate and direction of saline water movement in the "1,500-foot" aquifer because these two stations provide half of the total pumpage (1990) in the Baton Rouge area (Tomaszewski, 1996).

2.4 Previous modeling studies:

Models have been created to infer the ground water flow in different aquifers in the Baton Rouge area. A model by Kuniansky (1989) was created to evaluate the

geohydrology and ground water flow in the "400-foot" and "600-foot" in East & West Baton Rouge, East & West Feliciana Parish, and the Point Coupee Parish area. This model determined that subsidence might have reduced the conductance of clay beds that underlie the industrial district (Kuniansky, 1989). He mentioned that less than 1 in/yr of recharge in the outcrop area goes into the regional flow system. The "400-foot" and "600-foot" aquifers in the southern part of the Baton Rouge parish quickly recover from the pumping effects due proximity of the outcrop area and the Mississippi River. Kuniansky et al., (1989) mentioned a large area north of the fault where the "600-foot" aquifer, which contains saline water, that may be leaking into the "800-foot" aquifer through vertical leakage. They also identified an area where the "600-foot" aquifer is interconnected to the "800-foot" sand and merged. Kuniansky states that the Baton Rouge fault is a barrier to ground water flow in the "800-foot" and deeper aquifers throughout southern Louisiana (Kuniansky, 1989). During 1935-65, ground water withdrawal caused a head decline of about 200 ft and compaction of sediments. The model was calibrated for 1940-48 and 1983-84. Past water level and pumpage data indicated that more drawdown occurs with less pumpage in the industrial district around the year of 1986 than occurred in 1944-48 because of compaction. In the industrial district, compaction of sediments between the land surface and 833 ft below land surface has ceased due to reduction of water withdrawal from 36Mgal/d in 1940 to 14Mgal/d in 1983, and spreading out of the major pumping centers to other parts of the metropolitan Baton Rouge area resulted in an overall rise of water levels. Water levels declined by 190ft in the period of 1940 to 1950 but recovered by nearly 100ft by 1986.

Halford and Lovelace (1994) created a finite-difference model to simulate the flow in the "1200-foot" aquifer and adjacent aquifers and determine the pumping effect in the Baton Rouge area. The "1,200-foot" aquifer is a major source of ground water supply for the Baton Rouge area. From 1953 to 1969 pumpage from this aquifer increased from 2.5 to 25 Mgal/d but decreased to 15Mgal/d by 1987. The Baton Rouge fault restricts flow through the "1,200-foot" aquifer due to vertical displacement of about 300ft below a depth of 1,000ft. From 1980 to 1988 ground water levels recovered by 15ft in response to decreased pumping. Flow in the "1,200-foot" aquifer converged from all directions in 1988 toward the pumping centers in Baton Rouge. Head decreased 40ft on average with a maximum of 120ft (Halford and Lovelace, 1994) in the Baton Rouge industrial district. Long term pumping changed the area west of the Mississippi River from a discharge area into a recharge area. All of the 6 pumping simulations in the "1,200-foot" aquifer showed maximum drawdown of 50ft to 60ft per 10 Mgal/d of additional pumpage north of the BRF in the southeast Baton Rouge area.

Dial and Sumner (1989) used a finite difference ground-water flow model to evaluate the New Orleans aquifer system. Saline water encroachment has been identified in the Industrial Canal and Michoud areas. Their model indicated that the additional development and increased required water supply in the Gonzalez-New Orleans area would help to move the saline water toward the areas of well fields (Dial and Sumner, 1989).

2.5 *Studies indicating the fault are laterally permeable, conduit or barrier-conduit:*

A fault can act as a barrier for fluid migrating laterally across it due to clay smear, cataclasis, or cementation along the fault plane (Figure 16). Shale smearing happens because it can be deformed more than sandstone before faulting occurs (Handin et al., 1963). A fault can act as a conduit when fluid moves through the fault zone. The fault zone is mainly fed by the more permeable damaged zone and relatively widely spaced fractures in the protolith. (Forster & Evans 1991; Lopez & Smith, 1995; Evans, et al., 1997).

2.5.1 *Fluid migration along growth faults:*

Growth faults are mentioned as active conduits by, for example, Jones and Wallace (1974), Weber and Dakoru (1975) and Price (1980). Perkins (1961), Smith (1966 and 1980), and Fowler et al., (1971) mentioned faults as barriers to vertical flow. On the other hand some authors, such as Chapman (1981), Seeburger (1982), and Hooper (1991) suggest growth faults act as both barriers and conduits.

Hooper (1991) mentioned that the movement of fluid through growth faults is periodic. Periodic flow is that when faults can be both barriers and allow fluid migration. When a fault is active, permeabilities and drawdowns are increased and movements of the fluid upward are possible. Along with that, fluid can migrate both sub-vertically and laterally across and along the fault. When the fault is inactive, permeabilities are reduced and fluid movement is retarded (Hooper, 1991). In this way, a fault can act as a conduit or barrier at different geologic times.

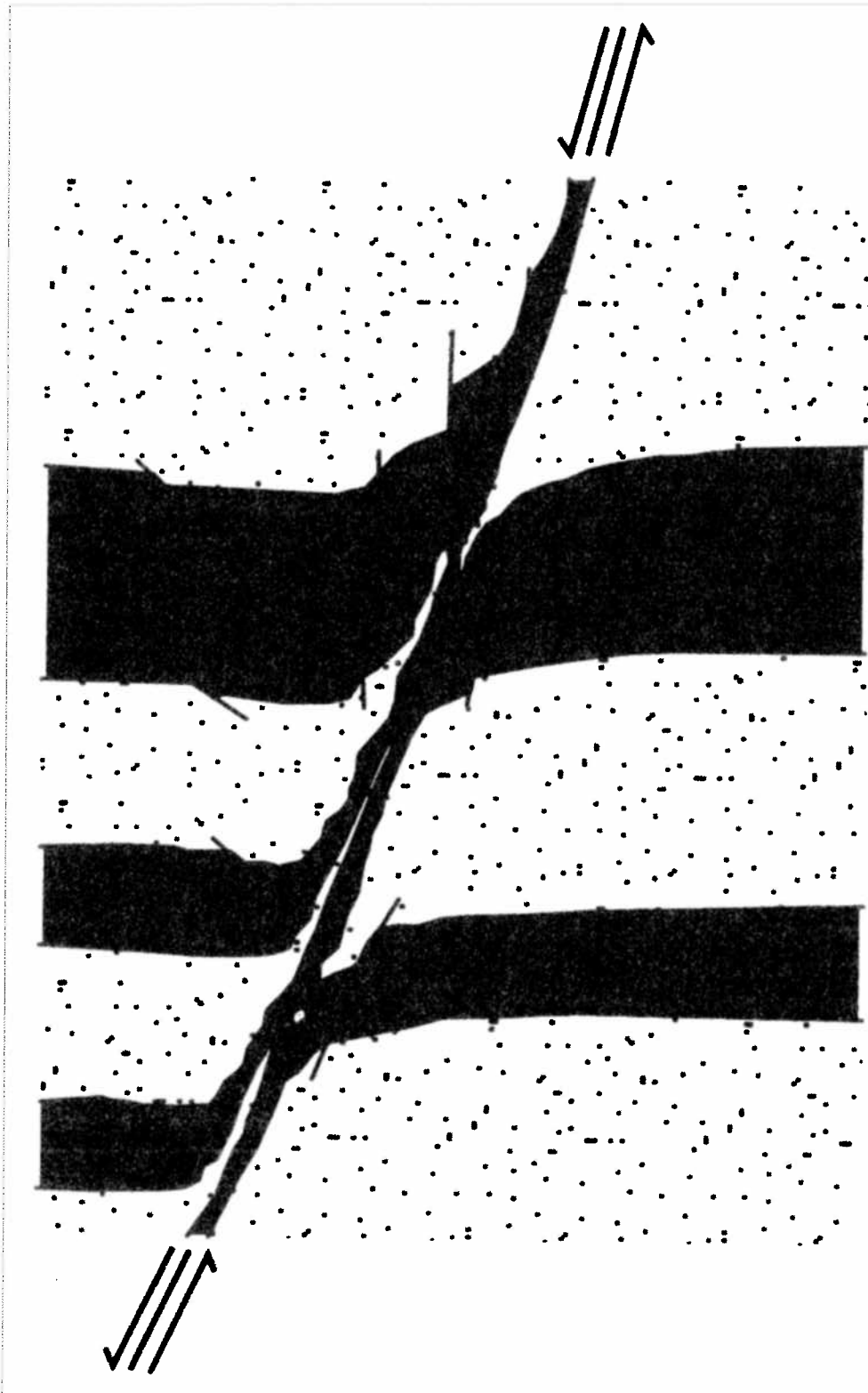


Figure 16: Clay smearing along the fault plane (adopted from Yielding et al., 1997).

Hooper (1991) also discussed some evidence near the fault planes which may indicate that water is moving up fault planes, such as mineralization along the growth fault planes, fluid potential, thermal anomalies, and salinity anomalies. If fault were leaking, fluid potential “drawdowns” would be higher, and if the fluid moves up the fault plane, then the geothermal gradient would also be higher around the fault zone than the surrounding regional thermal gradient. Hooper (1991) indicated that, based on thermal anomalies, some local and regional scale faults in the Gulf of Mexico act as conduits. Mineralization along the fault plane can indicate that the fault is active or not because large volumes of fluid must flow through a rock before the matrix is altered (Blatt, 1979 and Hooper, 1991).

Flourney and Ferrell (1980) found low salinity zones in the high salinity transition zone around some of the growth faults in southern Louisiana. They explained that growth faults are leaking low salinity fluids from the fresh overpressured section. They also mentioned that this evidence contradicts the hypothesis that faults are conduits to high salinity fluids but he explains this situation into two ways: 1. The difference in fluid in the fault zone depends on the size of the fault. The fluids are saline in the case of a large fault, which cuts the high-salinity section below maximum overpressures. On the other hand fluids are fresh if the fault is smaller and dies out in overpressured rocks. 2. The faults are periodically permeable, and conduct fluids of varying salinity at different times (Flourney and Ferrell, 1980).

2.5.2 Mechanism of fluid flow along growth faults:

There are several different ways fault conductivity may increase the fault becomes more active. As Hooper (1991) mentioned, growth faults act as conduits for

fluid flow. He discussed some mechanisms for generating episodic flow along fault as follows:

- i. Dilation: Dilation can increase fault permeability because microcracks form parallel and subparallel to the fault plane where stresses are close to failure. This can lead fluids to move along the zone of anisotropic permeability. Deviatoric stresses are highest close to the fault plane so dilation effects are highest.
- ii. Refracturing of mineralized zones: Reactivation of the faults can help to refracture mineralized zones along the fault plane, which can increase the permeable pathways by connecting the cracks again, that had become cemented.
- iii. Seismic pumping: Seismic pumping increases fault conductivity by increasing fluid potentials in the fault zones.

2.5.3 Different parameters considered important to fault sealing:

Knott (1993) discussed some parameters that are important for fault sealing:

- i. Fault orientation: It may influence sealing such as, normal faults are considered to less sealing than reverse and strike-slip faults (Hardings and Tuminas, 1989; Knott, 1993).
- ii. Fault displacement: The larger the throw on faults, the wider the fault zone and greater the mechanical reduction in porosity and permeability for a particular type of lithology (Evans, 1990 and Knott, 1993).
- iii. Net sand connectivity: Sand to sand connection across the fault helps determine how well the fault seals. Knott (1993) states that lower connectivity lead to a greater possibility of sealing.

- iv. Net-to-gross shale ratio: This is the percentage of the shale in an interbedded sequence. This percentage of shale and clay in a succession increased the likelihood of smearing along the fault zone.
- v. Burial depth: Deformation mechanisms and diagenetic reactions generally increase with depth, temperature, and strain rate, which usually reduce porosity and permeability, possibly providing fault sealing.
- vi. Age of faulting: In case of syndepositional sediments, mud is generally more undercompacted than in the postdepositional cases. Syndepositional faulting thus usually favors membrane sealing (Figure 17).

Knott (1993) also classified the fault-related seals according to the following:

- i. Juxtaposition fault: Faults can form a trap an isolated hydrocarbon accumulation because of sealing due to juxtaposition of the reservoir section against a sealing lithology.
- ii. Partially sealing fault: Faults may separate reservoir sections with different hydrocarbon-water contacts in a single pool with no pressure drawdown between adjacent compartments during the production life of a field and over a range of pressure differentials. Sealing is mainly provided by the fault plane due to mechanical and chemical reduction of porosity and permeability of the reservoir rock within the fault zone. A juxtaposition seal also may be at the top of the structure and the other part is farther down the fault plane.

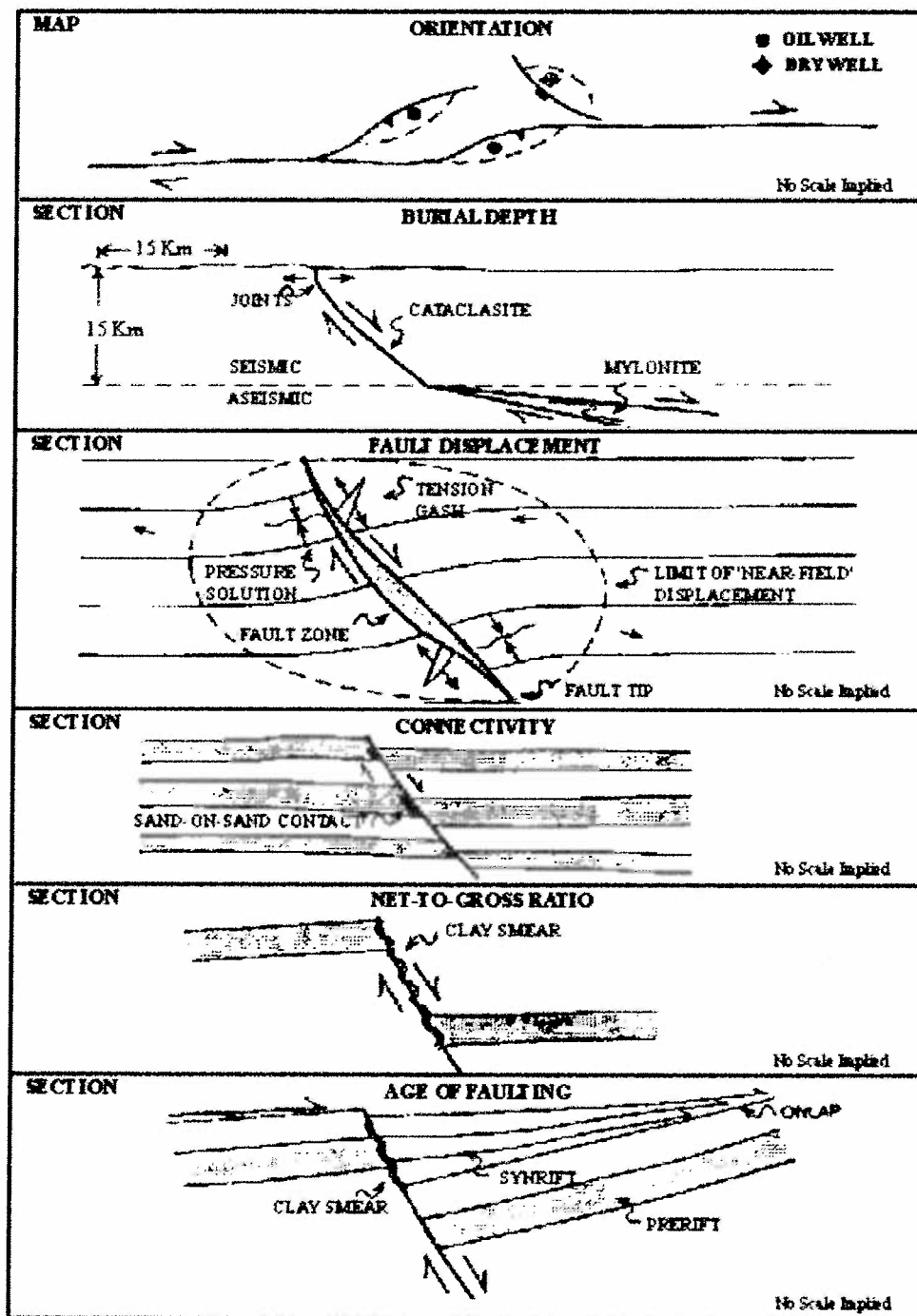


Figure 17: Parameters for sealing faults (modified from Knott, 1993).

iii. Temporary sealing fault: Faults can also provide temporary sealing by creating pressure barriers during production but may not seal over geologic time. In this case sealing occurs across the upper part of the fault due to juxtaposition and in the rest of the part sealing occurs with the combination of both juxtaposition and membrane sealing (Figure 18).

2.1.1 Sealing and nonsealing faults in the Gulf of Mexico in Louisiana:

Perkins (1961) studied some sealing faults in the Gulf of Mexico. He mentioned that sealing happens due to soft shale smearing and impregnating the faulting sandstone face during the fault movement. He also stated that a natural mudcake is formed, in essence, over the sand interface, and an impervious barrier is created against which migrating hydrocarbons may accumulate.

Smith (1980) studied ten normal-fault-related hydrocarbon-bearing fields in the Louisiana Gulf of Mexico to see whether they are sealing or nonsealing. These fields are sand and clay alterations. He found in more cases that faults are sealing to lateral migration than the nonsealing faults where sandstone of different ages is juxtaposed.

Morton and Land (1987) proposed some growth faults in the Gulf of Mexico as conduits for very saline brines, whereas, Flourney and Ferrell (1980) found some faults in the same basin conduct fresh water. In this case, Hooper (1991) discussed the reason of this contradictory situation according to periodic flow hypothesis that when the flow is active, fluid can move up the fault plane in short, sharp bursts. If a growth fault cuts the saline section, saline water can be injected through the overpressured section into the transition zone without being diluted.

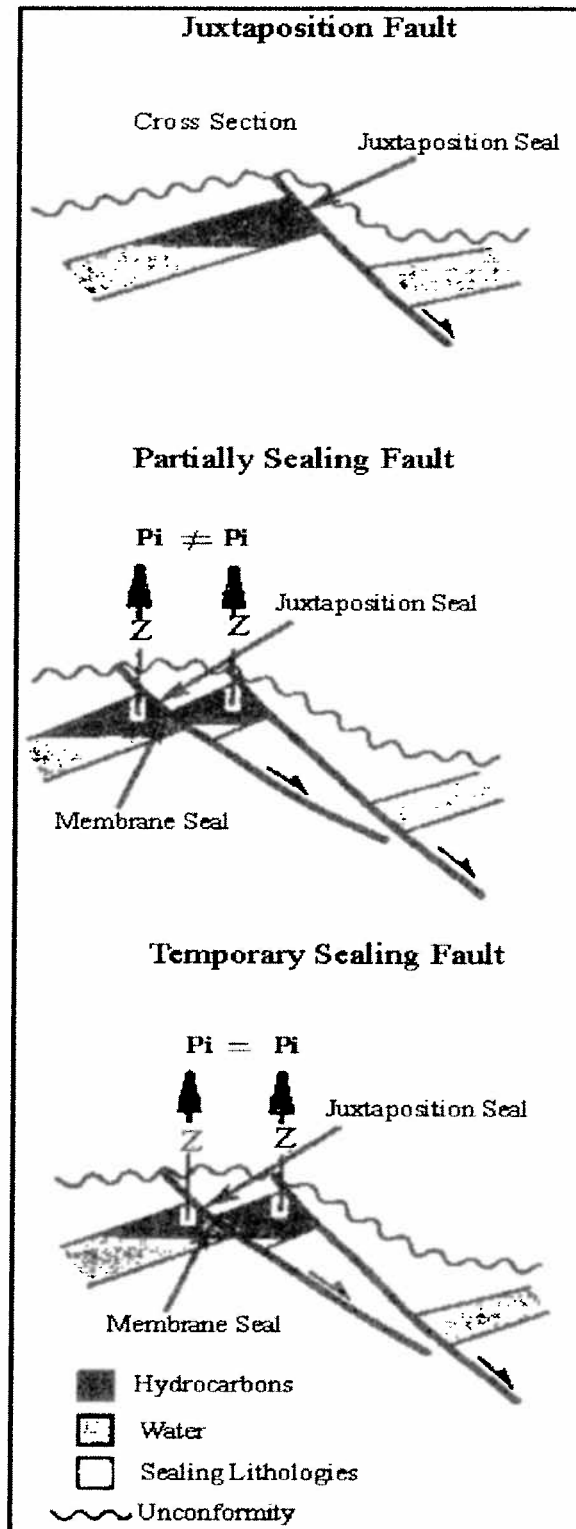


Figure 18: Different types of sealing faults (modified from Knott, 1993).

But when fault is less active, flow is retarded and water from the overpressured section can dilute the upwelling fault-concentrated flow. As a result, water moving into the transition zone is fresher. So when the fault is active/permeable, faults are conduits for highly saline brines and are conduits for low salinity brines during time of less activity.

2.2 Studies indicating the Baton Rouge fault acts as a leaky barrier and conduit:

Some authors mentioned the Baton Rouge fault as a leaky barrier for northward movement of saline water such as, Cardwell and others (1967), Rollo (1969), Smith (1976), Whiteman (1979), Torak and Whiteman (1982), and Tomaszewski (1996).

Stoessell (2002) collected water samples (data unpublished) from the “1,000-foot” aquifer from well EB-782A in the East Baton Rouge Parish. In general, seawater has a molar Na:Cl ratio of about 0.86 whereas halite is 1. He found molar Na:Cl ratio is more than 1 in his studied samples (Figure 19). On the other hand, the same sample shows lower molar ratio of bromide and chloride (Figure 20). He also compared the molar Na:Cl ratio for that well EB-782A with the samples of Big Branch aquifer near Lacombe, Louisiana, which produces brackish water.

Located several kilometers south of Lacombe, in Lake Pontchartrain, is the active Goose point fault, an extension of the Baton Rouge-Denham Springs fault system .The northwest-southeast trending fault dips at 45° to the south to a maximum depth of 6.1km (Lopez et al., 2002).

Based on molar ratio and some other chemical components behavior, Stoessell (2002) concluded that saline water in well EB-782A is coming due to halite dissolution.

The only known source of halite is the deep Luann salt following vertical migration pathways into the Big Branch aquifer because there is no report of presence of any near-surface salt domes and the closest known salt dome is at depths of about 6 km in the Upper Jurassic (Stoessell, 2002). Stoessell believes the process is similar for the “1,000-foot” aquifer north of the fault in the East Baton Rouge area (Personal communication, 2003).

Miller (2002) mentioned in a poster session that the Baton Rouge fault acts as a barrier to fresh water flow but moderate its behavior because of increased pumping of freshwater. He concluded that the Baton Rouge fault has begun acting as a conduit for saline water intrusion, north of the fault.

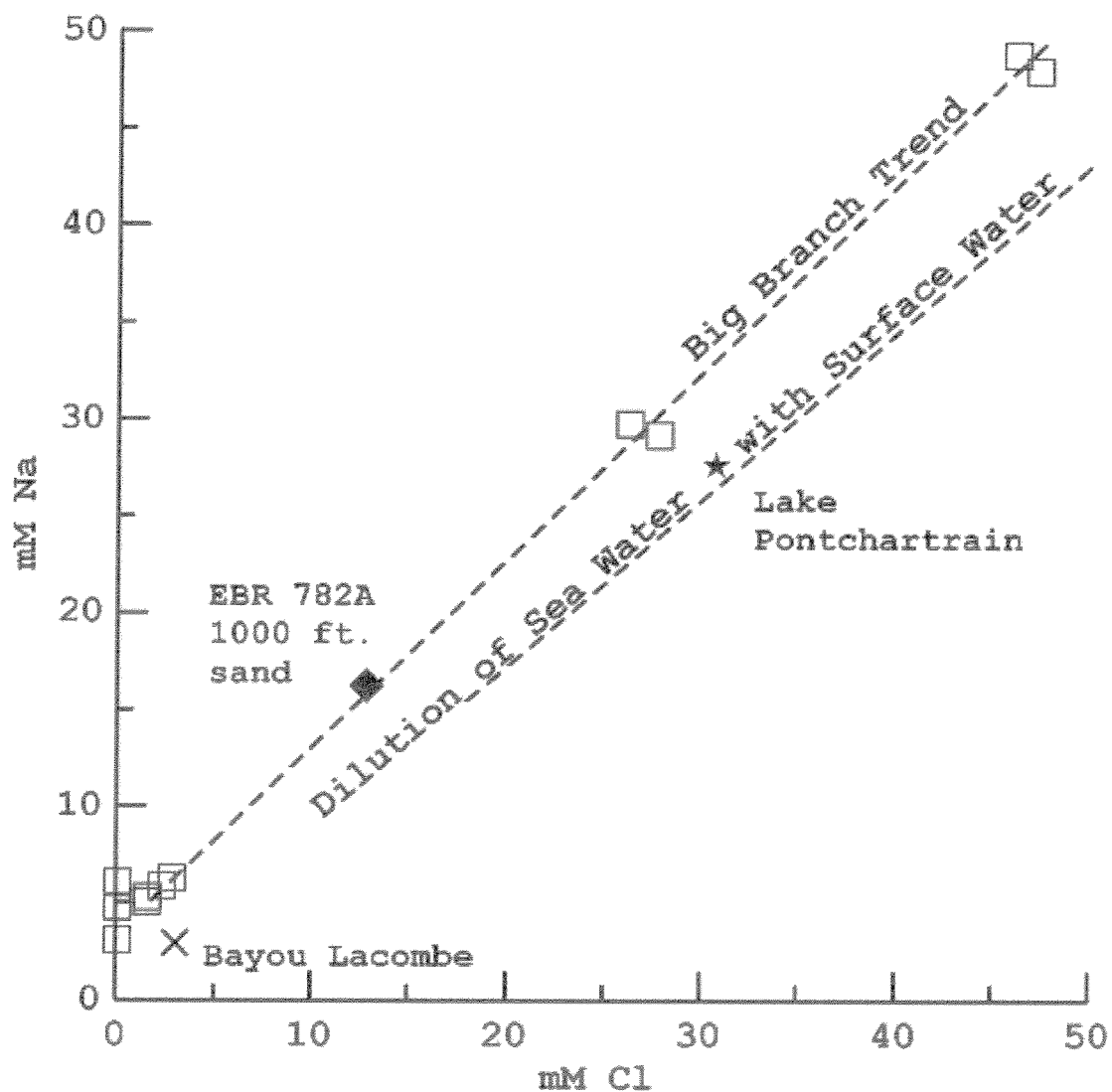


Figure 19: Na vs. Cl concentrations for the Big Branch aquifer near Lacombe, LA., and for surface water in Bayou Lacombe and Lake Pontchartrain (Stoessell, 2002) and in one East Baton Rouge Parish well (Stoessell, 2003, unpublished data).

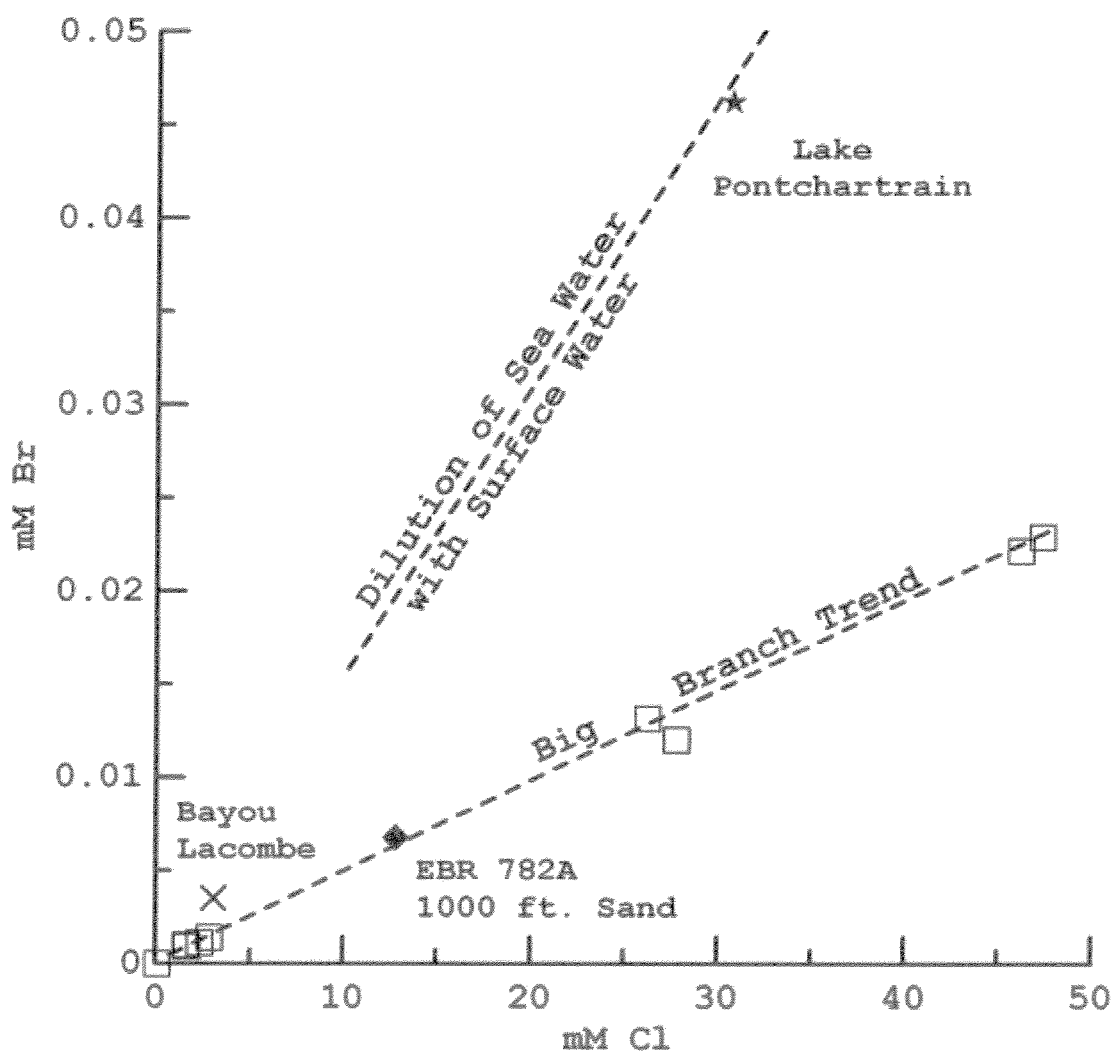


Figure 20: Br vs. Cl concentrations for the Big Branch aquifer near Lacombe, LA., and for surface water in Bayou Lacombe and Lake Pontchartrain (Stoessell, 2002) and in one East Baton Rouge Parish well (Stoessell, 2003, unpublished data).

CHAPTER III: METHODS

3.1 Computer Modeling:

The objective in computer modeling was to reproduce observed patterns of saline water north of the BRFS. To achieve this objective, I used a USGS model, MOCDENSE, which accounts for density-driven flow (Sanford and Konikow, 1985). I created five modeling scenarios:

Scenario 1: A sloping aquifer with no fault where fresh water recharged the aquifer from updip and saline water was held constant at the downdip boundary.

Scenario 2: The model from scenario 1 with a low permeability normal fault that blocks all saltwater updip from the fault.

Scenario 3: The model from scenario 2 with decreased recharge to simulate updip pumping resulting in saline water migration across the fault.

Scenario 4: The model from scenario 2 with saline water input by conduit flow up the fault.

Scenario 5: The model from scenario 2 with 90% more saline water input than scenario 4 by conduit flow up the fault.

These five scenarios were not created to be representative of one specific aquifer in the BRFS. Instead, they were created to give insight into the reasonableness of

assertions by Stoessell (2002) and Miller (2002) that conduit flow were a possible explanation for observed salinity patterns in the BRFS.

Method for scenario 1: “MOCDENSE,” developed by the USGS, is a block-centered, finite-difference model. The input is structured in the form of a grid with aquifer properties specified throughout the grid. Initial and boundary conditions for both fluid flow and salinity must be specified. In this study, the number of columns and rows were 32 and 22, respectively. Each grid cell in the X direction is 164.00 ft. Each grid cell in the Z direction (thickness) is about 16.4 ft. By turning off some grid cells, an inclined aquifer, such as the study area has, was created. Fresh water enters from the left boundary of the grid; simulating recharge of fresh water resulting from infiltration. The right boundary was held at a constant concentration of seawater. In the input models the thickness of the aquifer is considered to about 230 ft, the dip of the fault is about 67 degrees, the dip of the aquifer is about 3.5 degrees and the permeability of the aquifer is about 203 ft/day. These values are representative of published data for aquifers cut by the BRFS. Some other parameters such as thickness of the fault zone, fault permeability, and fault throw are discussed in the discussion chapter. Input data for this model is attached in Appendix A.

Method for scenario 2: In this case, the model was the same as in scenario 1, but a low permeability normal fault was added along the middle of the grid area to determine the effect of the fault on ground-water movement. The permeability of the fault zone was 3% of the permeability of the surrounding aquifers (Figure 21), cut across the entire aquifer, and was one cell wide. Input data for this model are enclosed in Appendix B.

Method for scenario 3: In this case, the model was same as it was for the scenario 2 but recharge of freshwater through the left boundary was reduced by 1/3 order of magnitude to simulate pumping up dip. Input data for this model are enclosed in Appendix C.

Method for scenario 4: This model was changed from the scenario 2 by adding input of saline water to the very leftmost grid of the bottom of the fault zone to simulate the fault acting as a conduit. Input data for this model are enclosed in Appendix D.

Method for scenario 5: This model was changed from the scenario 4 by increasing the input of saline water at the bottom of the aquifer at the fault zone to simulate the fault acting as a conduit. Input data for this model are enclosed in Appendix E.

Figure 21 uses the output model for scenario 2, where the aquifer is affected by the fault, to show the grid arrangement used throughout the study. The X and Y-axes represent the total number of cells with length and thickness, respectively. Each cell length is 164ft and thickness is 16.4ft. The left side (north) of the figure represents the continuous flushing of fresh water, which is coming from the outcrop area due to infiltration. The right side (south) of the grid area shows the constant concentration boundary. In south different color represents different concentration (in percentage) of saline water. Saline water concentration becomes less as we go to the north because of continuous flushing of fresh water. The middle line represents the fault. Clay units lie on the top and bottom of the aquifer.

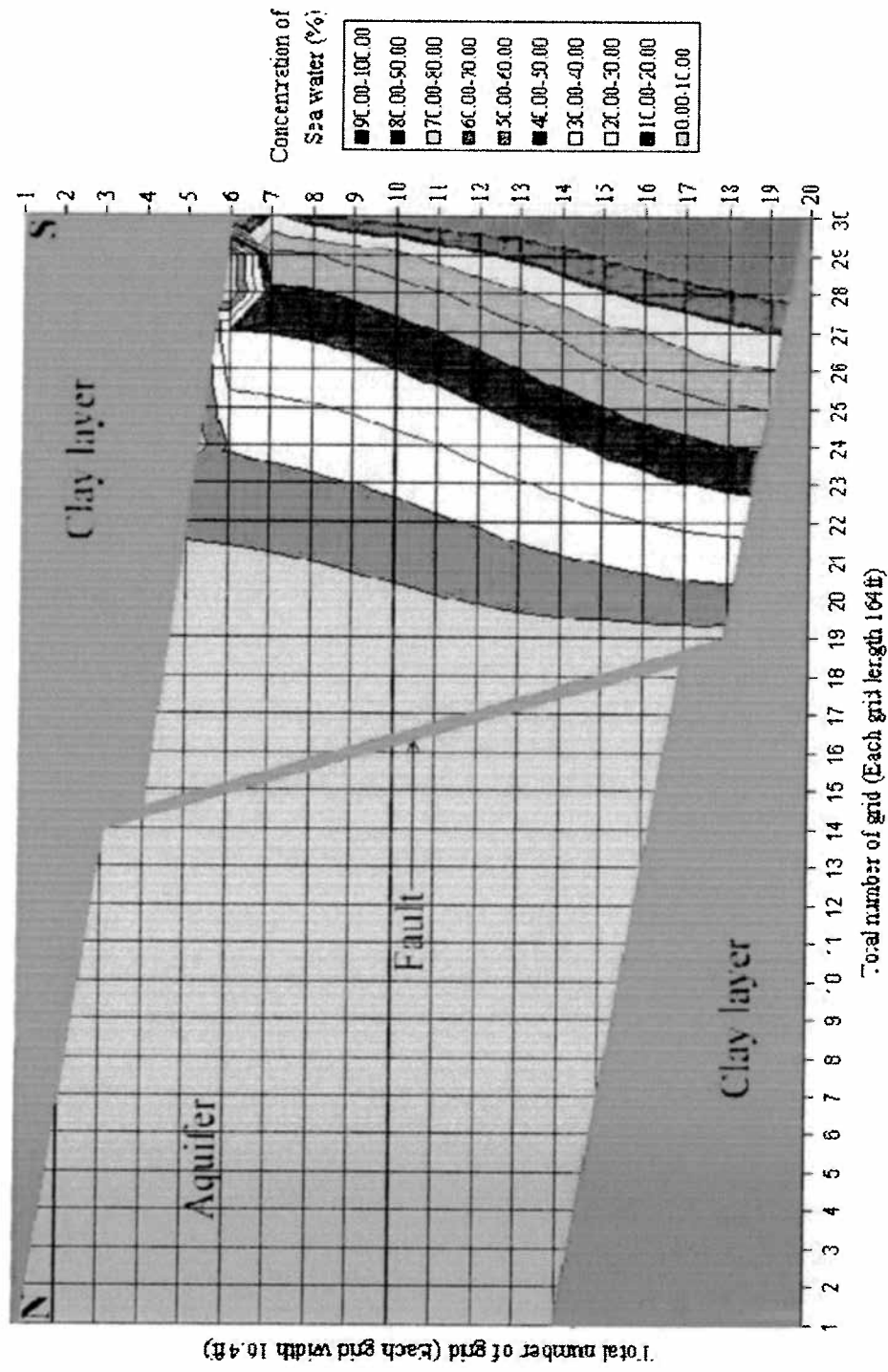
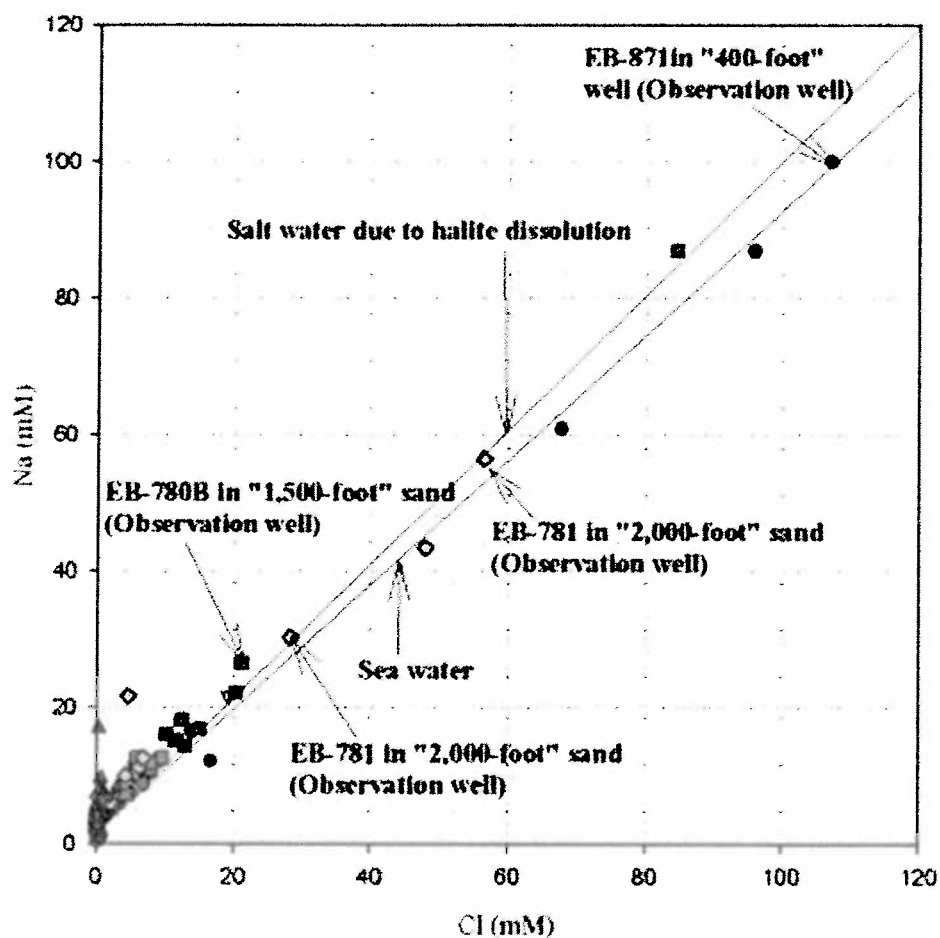


Figure 21: An example model for Scenario 2.

3.2 *Analysis of the chemical data:*

Chemical data were collected from published Water Resources Technical Report No 21. This report has ground water quality data for East and West Baton Rouge, East and West Feliciana and Point Coupee Parishes, Louisiana, from the water years 1944-97. East Baton Rouge sodium and chloride data were tabulated and their molar ratio was computed (Figure 22). These ratios were then graphed and compared to values by Stoessell (2002). Bromide data were not available for the area of interest and cannot be compared with the analysis of Stoessell (2002).



- Cl (mM) vs. Na (mM) for "400-foot" aquifer
- Cl (mM) vs. Na (mM) for "600-foot" aquifer
- ▼ Cl (mM) vs. Na (mM) for "800-foot" aquifer
- ▽ Cl (mM) vs. Na (mM) for "1,000-foot" aquifer
- Cl (mM) vs. Na (mM) for "1,200-foot" aquifer
- Cl (mM) vs. Na (mM) for "1,500-foot" aquifer
- ◆ Cl (mM) vs. Na (mM) for "1,700-foot" aquifer
- ◇ Cl (mM) vs. Na (mM) for "2,000-foot" aquifer
- ▲ Cl (mM) vs. Na (mM) for "2,400-foot" aquifer
- ▲ Cl (mM) vs. Na (mM) for "2,800-foot" aquifer

Figure 22: Na vs. Cl concentration for the East Baton Rouge Parish wells (Source of data: Walter and Lovelace, 1998).

CHAPTER IV: RESULTS

In this study, scenario 1 was developed without a fault to provide a base to work from when studying the impact of the fault. Input parameters (such as fault and aquifer permeability, aquifer thickness, dip of the fault and aquifer, fault throw, fault zone thickness etc.) were chosen so that saline water migrated across the aquifer past the point where the fault was to be placed. In figure 23 the right most side shows the higher concentration of saline water (blue), and to the left concentration of saline water decreases because of infiltration of fresh ground water (red). Different colors on the figure represent percentages of the salinity of water at the right boundary

In the scenario 2, the output model (Figure 24) shows the effects of a normal fault on ground water movement. The boundary conditions and other input parameters are the same as scenario 1. In this case the fault is acting as a barrier, preventing saline water from entering the updip (left side) of the fault.

Scenario 3 shows (Figure 25) the effect of pumping. In this model, the input of fresh water on the left boundary was adjusted by lowering the amount by 66% of the original input. The input of fresh water was reduced to simulate nearby pumping. In this case it has been observed that saline water has moved laterally across the fault. In scenario 4, the amount of fresh water was the same as in scenario 2. By adjusting the amount saline water injected at the base of the aquifer it was found that saline water moving along the fault could cover approximately the same area north of the fault

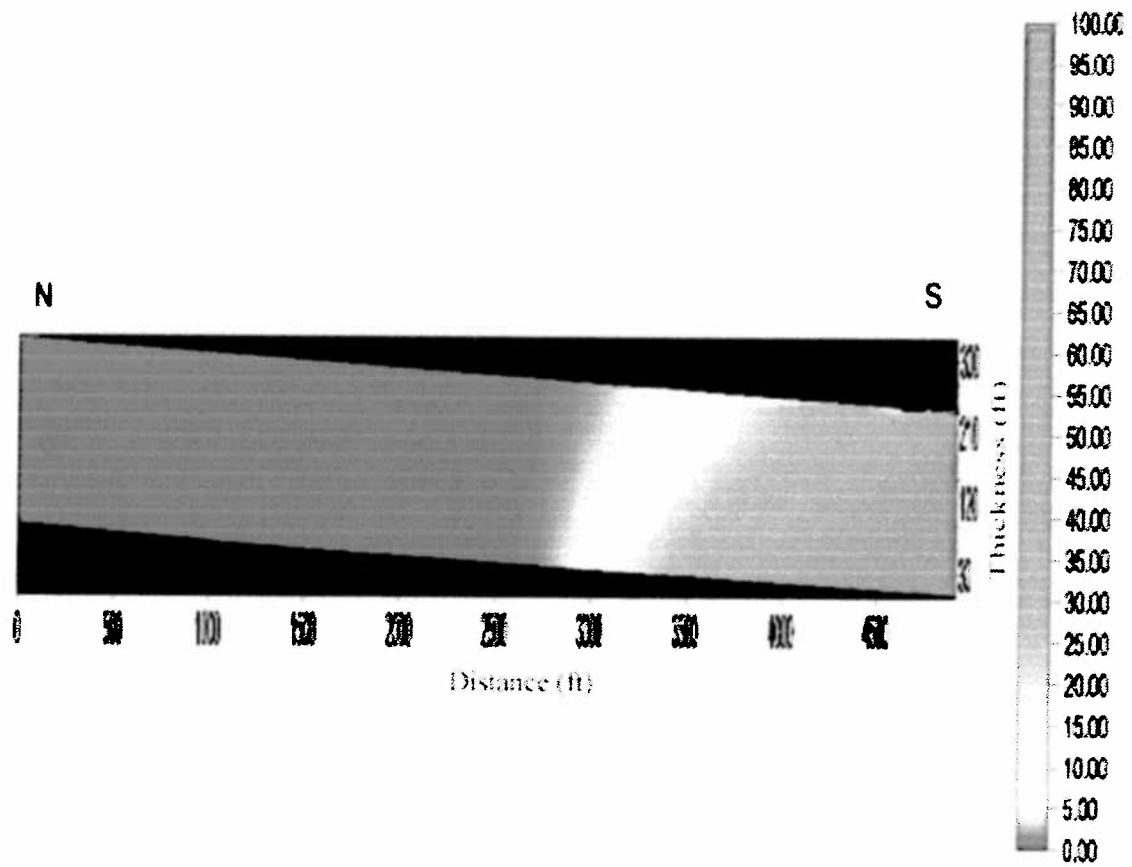


Figure 2 (scenario 1): Distribution of freshwater-salinewater into an inclined aquifer (The right side bar shows the colors representing each concentration of seawater in percentage).

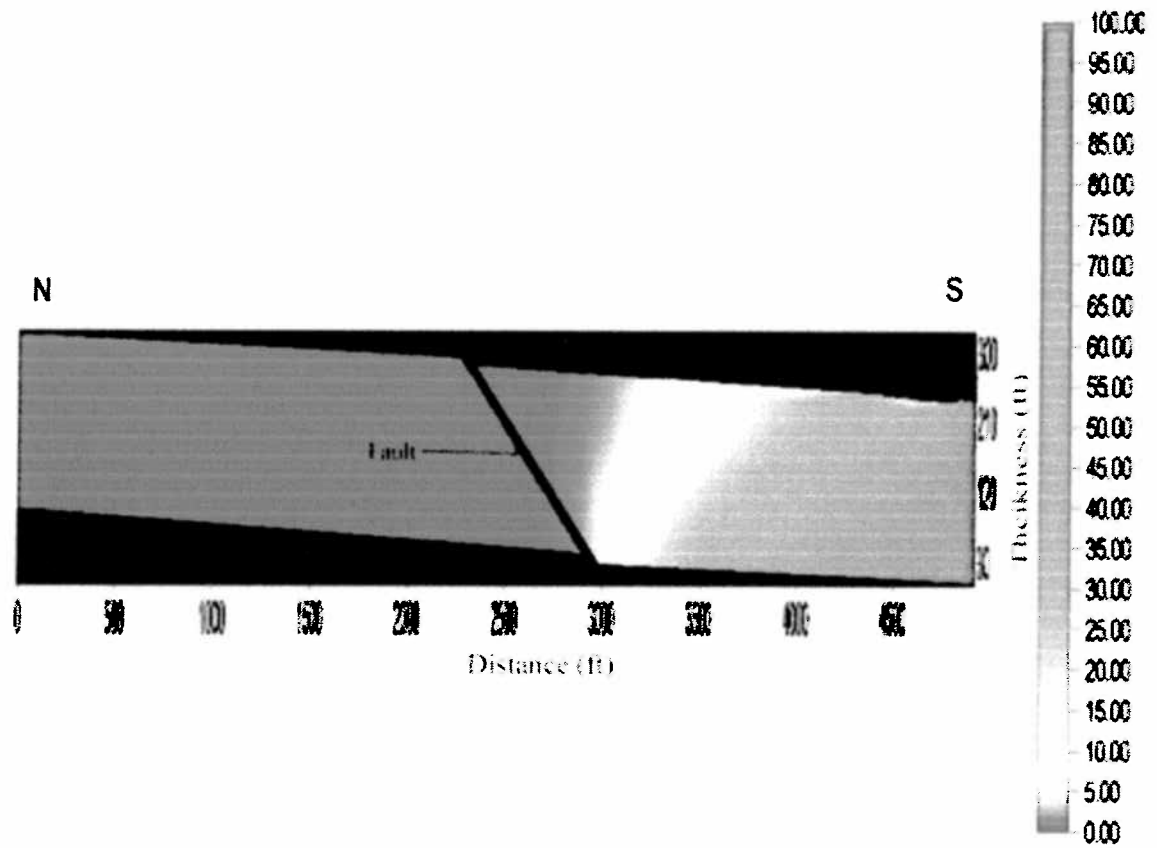


Figure 24 (scenario 2): Effect of fault on ground water distribution (The right side bar shows the colors representing each concentration of seawater in percentage).

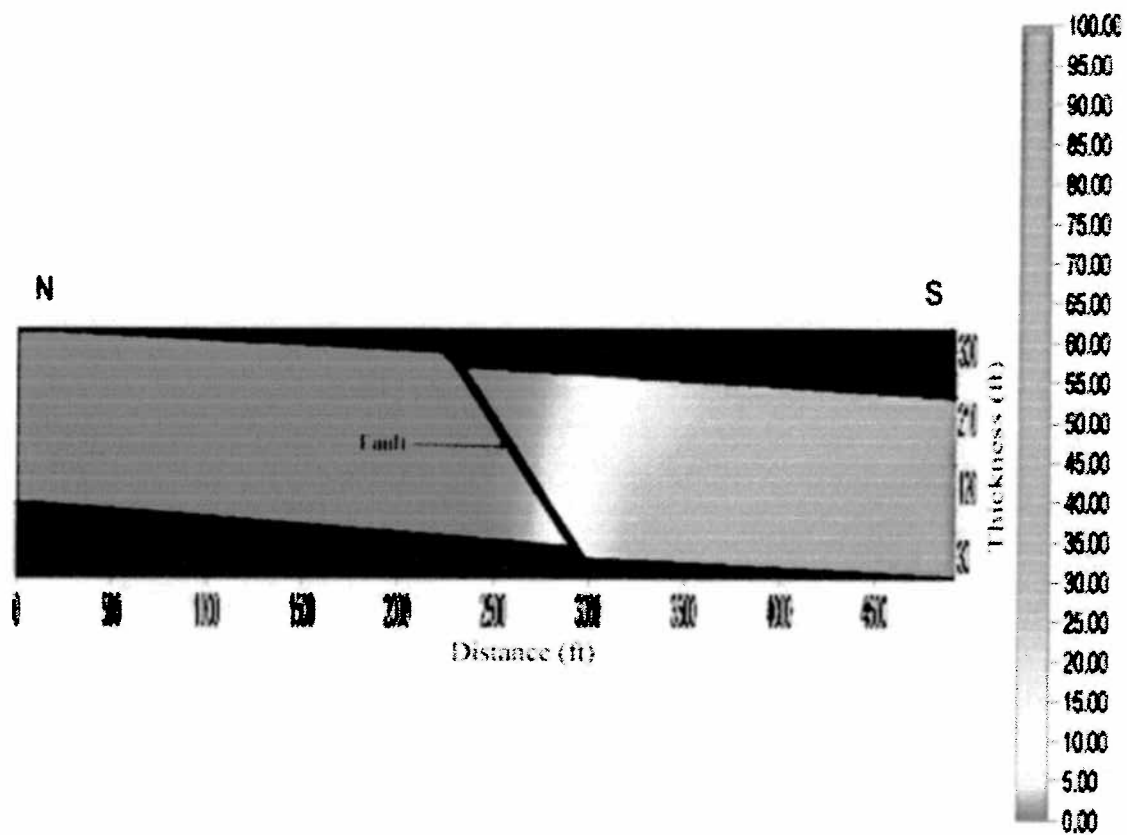


Figure 25 (scenario 3): Effect of pumping on ground water distribution (The right side bar shows the colors representing each concentration of seawater in percentage).

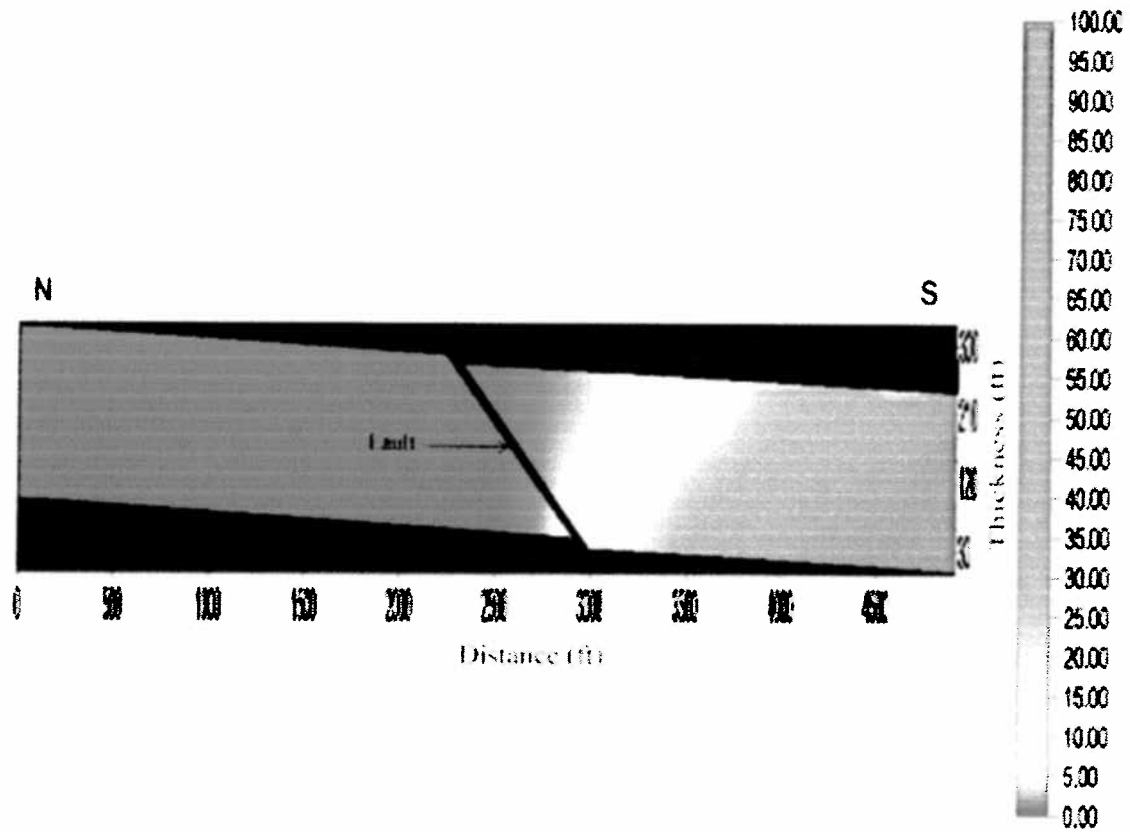


Figure 26 (scenario 4): Effect of conduit flow on ground water distribution (The right side bar shows the colors representing each concentration of seawater in percentage).

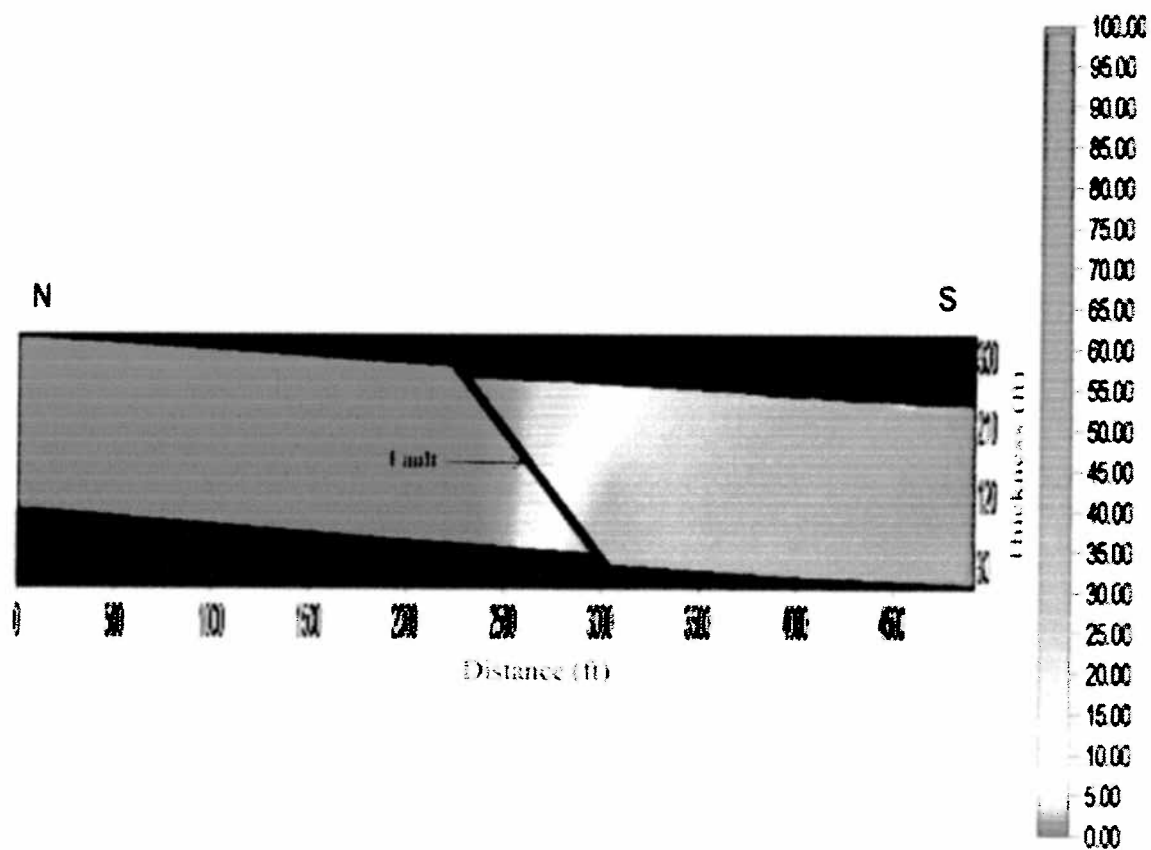


Figure 27 (scenario 5): Effect of conduit flow on ground water distribution (The right side bar shows the colors representing each concentration of seawater in percentage).

(Figure 26) as was modeled in scenario 3. In the scenario 5, the amount of saline water injected was increased by 90% over scenario 4, yielding an area of high salinity north the fault (Figure 27). This produced output similar to data from Whiteman (1979; Figure 28).

Chemical analysis data (Figure 22) shows two different views: one is related with seawater and the other is halite dissolution water. Data from a few of the wells, such as EB-781 (observation well in the “2,000-foot” sand), EB- 780B (observation well in the “1,500-foot” sand south of the fault), and EB- 280 (plugged well in the “1,500-foot” sand) fall on the molar Na:Cl ratio corresponding to sea water dissolution and data from the rest of the wells fall on the molar Na:Cl ratio corresponding to halite dissolution.

CHAPTER V: DISCUSSION

The only source of drinking water in the Baton Rouge area is ground water. Industries are also dependent on ground water. The demand for fresh ground water results in withdrawal of huge amounts of ground water by pumping. The pumping may increase saline water intrusion into the fresh water aquifers in some areas north of the Baton Rouge fault. Saline water intrusion leads to the need for expensive replacement of groundwater sources. Pumping might also change the hydraulic behavior of the fault system. Therefore, we need to better understand how the saline water is moving either across or along the fault and how pumping effects the movement. To achieve this goal, four models were developed, and available water chemistry data were analyzed.

Previous studies offer alternate explanations of the presence of saline water north of the BRFS. It has been found in most of the previous studies (such as Cardwell et al., 1967; Rollo, 1969; Smith, 1976; Whiteman, 1979; Torak and Whiteman, 1982; and Tomaszewski, 1996) that the Baton Rouge Fault is acting as a leaky barrier. But in 2002 two abstracts proposed deeper sources (Stoessell, 2002 and Miller, 2002) through conduit flow. Stoessell (2002) showed that saline water is moving up through the Goose Point fault that is a part of the BRFS. Stoessell (2003, Unpublished data) also studied data from well EB-782A, completed in the “1,000-foot” aquifer in the East Baton Rouge area. His chemical study for this well also indicates a deeper source for the saline water. Until 2000, the only mechanism used for explaining the intrusion of saline water into

freshwater aquifers were lateral flow across the fault. In another recent study, Kuecher and Roberts (2000) proposed a mechanism of conduit flow and how it is possible to get more saline water on one side of the fault than by flow across the fault. In his previous study, Whiteman (1979) mentioned a plume of high salinity water north of the fault compared to the adjacent well south of the fault. He observed high salinity water in well EB-123 north of the fault in the “600-foot” sand, whereas the adjacent well EB-818 in the “400-foot” sand south of the fault had a lower chloride concentration. He reported that the well EB-123 showed chloride concentration of 3,680 mg/L in 1962 (Figure 28); whereas, the well EB-818 showed concentration of 2,380 mg/L in 1968. The well EB-869 in the “600-foot” sand yielded chloride concentration of 3,380 mg/L and a production well EB- 876 in the same aquifer showed a concentration of 4,120 mg/L in 1971(Whiteman, 1979). The wells EB-871 and EB-868 in the “400-foot” aquifer showed chloride concentration of 3,820 mg/L and 469 mg/L respectively in 1971. Whiteman (1979) assumed that the chloride concentration at the base of the “400-foot” aquifer south of the fault probably is more than 5,000 mg/L.

It has been determined in previous studies that subsidence occurred as a result of pumping and natural causes especially on the northern side of the fault in the Baton Rouge area. It has been observed that this subsidence caused compaction of the aquifer sediments, resulting in reduction of porosity and permeability. In addition, the hydraulic behavior of the fault zone may have changed over time due to pumping. As it has been known that the BRFS is active, the permeability of the fault zone and damage zone might have refractured and reopened, helping to increase movement of the fluid through the fault zone, thus increasing fluid migration along the fault plane.

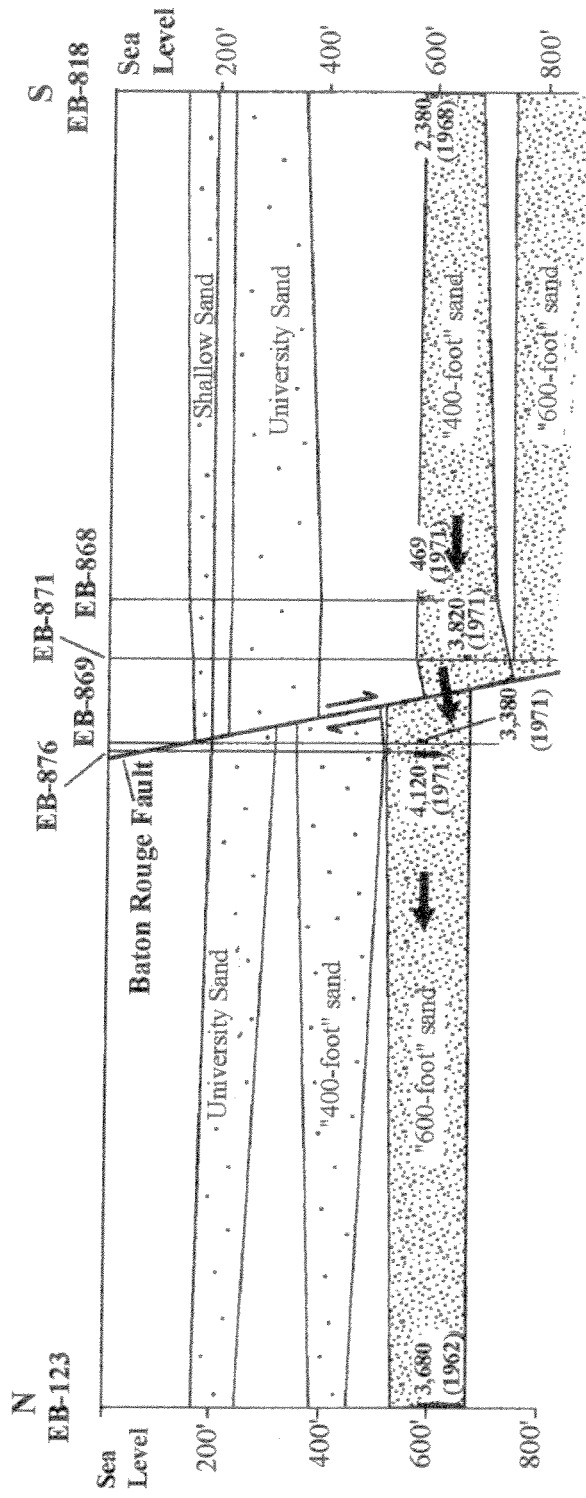


Figure 28: Chloride concentration closure to the Baton Rouge Fault (modified from Whiteman, 1979).

On the other hand, in some places different ages of sand layers are juxtaposed on both sides of the fault and they are interconnected in some places. This might allow the fluid to move laterally across it.

Literature on growth faults indicates a fault can serve as both a barrier and a conduit. The geological modeling in this study supports the findings in the literature. They are discussed in the literature review section.

Modeling suggests that either lateral flow or conduit flow can explain observed distribution of saline water. In this study, scenario 1 (Figure 23) shows the ground water conditions within an inclined aquifer in the Baton Rouge area when it is unaffected by a fault. In scenario 2 (Figure 24), ground water is affected by fault and shows that saline water remains behind the fault although the input of fresh water was same as it was in scenario 1. So the fault is acting as a barrier.

In scenario 3 (Figure 25), the aquifers are affected by pumping and as a result the model shows that the saline water is leaking laterally across the fault. The fourth model shows that the saline water is moving along the fault. The fifth model (Figure 27) shows that saline water moved across the fault but a plume of higher saline water remains on the northern side of the fault.

The output from scenarios 3 and 4 produce virtually identical results while postulating different causes. Therefore, either explanation---leaky barrier or conduit--- is consistent with the observed salinity distribution. Geochemical analysis indicates that at least some of the time conduit flow better explains the available water chemistry data. The chemical analysis (Figure 22) data (from 1942-97 in the East Baton Rouge area) of molar Na:Cl ratio shows two different scenarios. Only a few of the wells show that saline

water is coming across the fault because of dilution of seawater and some others data show that the saline water is coming up the fault as a result of halite dissolution. Thus, the geochemical data indicates that this Baton Rouge fault is probably acting in a dual role as both barrier and conduit. In figure 22 only data from a few wells in the “400-foot” and “600-foot” sand in the East Baton Rouge area show that the saline water is coming from the seawater dilution. The remainder of the data showed saline water is coming from halite dissolution.

Current data and models are not sufficiently precise to distinguish between conduit and lateral flow. During this study no literature was found on fault zone analysis regarding the Baton Rouge fault zone, such as permeability of the fault zone, width of the fault zone, mineralization of the fault zone etc.

The number of wells whose data indicate halite dissolution (Figure 22) are few, such as EB-781 (observation well in the “2,000-foot” sand), EB- 780B (observation well in the “1,500-foot” sand south of the fault), EB- 280 (plugged well in the “1,500-foot” sand). This is despite including all types of well data, such as from observation wells, pumping wells, public supply wells, industrial wells, destroyed wells, and plugged wells etc. In addition, there is no way of determining how representative the data are of the aquifers, given potential problems, such as casing leakage. Data that would help refine the distinction between conduit and lateral flow are not yet available. Necessary for further analysis are chemical data such as, chloride, sodium and bromide concentration data. In addition, the Baton Rouge fault zone needs to be studied in detail.

Sensitivity of the model:

In the models, the fault zone was designated by 164.0 ft wide cells but ideally the grid would be much more refined. Similarly, fault throw is 16.4 ft but greater throw would be a useful extension of the model. Marler and Ge (2003), in their model for the Elkhorn fault zone, South Park, Colorado, considered thick (400ft) and thin (10ft) fault zones with low permeability in both cases. Both of the models gave reasonable fits to the expected head distribution, with the fault is acting as a barrier.

The models in this study are very much sensitive to fault permeability, aquifer permeability, amount of fresh water input in the left side of the grid area, amount of saline water considered coming from below. The models are also very sensitive to the grid length and width. In this study, the fault permeability used, was the lowest number (6ft/day) that was accepted by the program without it's failing to converge to a solution. This is a limitation of the program, not nature. Though the program was limited in the allowable permeability contrast between the aquifer material and the fault zone, MOCDENSE was chosen because of its superior reduction in numerical dispersion as compared to SUTRA and HST3D.

CHAPTER VI: CONCLUSIONS

This study found the following:

- i. The Baton Rouge Fault System slows or prevents the migration of saline water north of the fault.
- ii. Modeling supports either hypothesis of the fault acting as a conduit or leaky barrier for saline water intrusion into the fresh water aquifer.
- iii. Modeling also supports the conduit hypothesis for higher salinity water in the aquifers north of the fault than the adjacent aquifers in the south. However, alternate explanations based on sampling depth are possible.
- iv. The chemical analysis supports both hypotheses, depending on which data is examined, indicating the fault serves a dual role.

The results of chemical analysis by Stoessell (Unpublished, 2003) from “1,000-foot” aquifer in the East Baton Rouge area and the analysis done during this project from the USGS report for the same aquifer show that the water in well (EB-782A) is coming from halite dissolution. The only known source is the Luann salt that was deposited during the Jurassic time far below the aquifers. This supports the hypothesis of conduit flow. However, previous analyses of water chemistry have been used to support the leaky-barrier hypothesis. The findings of this thesis indicate that the fault serves a dual role-leaky barrier and conduit. Due to pumping, the fault’s behavior may change through time, helping to create the dual role.

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