THE EFFECTS OF DIAGENESIS ON THE HYDROLOGY OF THE SURFICIAL AQUIFER, BROWARD COUNTY, FLORIDA

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ABSTRACT

The Surficial Aquifer system of southeastern Florida supplies drinking water as a sole-source aquifer in Dade, Broward, and southernmost Palm Beach County. The aquifer consists primarily of marine to fresh water carbonates of Plio-Pleistocene age.

This study shows the relationships between diagenesis and the hydrology of the Surficial Aquifer in Broward County. Lithology and trace element concentrations were employed to determine zones of relatively high diagenesis. These zones are plotted on lithologic cross-sections and compared to geohydrologic cross-sections by Fish (1987). Zones of low hydraulic conductance (100 feet per day or less) correlate well with zones of high diagenetic trace element signatures. Lithologic and geochemical techniques of investigation used in this study can be helpful in the mapping of hydraulic conductance in similar carbonate terrains.

INTRODUCTION

Using petrologic and geochemical data this study establishes a relationship between diagenesis and existing hydrologic conditions within the Surficial Aquifer of eastern Broward county, Florida (Figure 1).

The lithologic sequences of the Surficial Aquifer in southeastern Florida (which includes the Biscayne Aquifer) have been previously described to represent essentially transgressive and regressive carbonate environments (Parker et.al.1955; Perkins 1977). Within formations, Perkins (1977) recognized many subaerial exposure surfaces (horizons) which are preserved as laminated crusts and as fresh water carbonate deposits. These surfaces indicate zones of relatively high diagenesis in many of the geologic formations of South Florida.

In addition, certain trace element associations also indicate high diagenesis in carbonate terrains. The trace elements studied were manganese (Mn), iron (Fe), strontium (Sr), and magnesium (Mg). These trace elements have different partition coefficients (Table 1), which during diagenesis will cause the trace elements to undergo differing amounts of dissolution and/or precipitation along with the carbonate material of the original sediments. The partition coefficient is the ratio of the molar concentrations of a substance dissolved in two immiscible liquids (Veizer,1974 ,1977 ,1982).

Influx of meteoric water into subaerialy exposed rocks creates disequilibrium in the original pore-water chemistry, initiating the mobilization of trace elements as well as furthering diagenesis (Veizer 1982).

Geochemical indications of increased diagenesis in marine limestones of the Surficial Aquifer are shown by an increase in the concentrations of Mn and Fe, along with a decrease in Sr concentrations, due to the influx of meteoric water during subaerial exposure (Veizer,1982).

A comparison between the geochemical and petrologic data obtained in this study with geohydrologic cross-sections previously completed in the study area by Fish (1987) show a correlation between zones of relatively low hydraulic conductance and zones which have undergone a relatively high degree of diagenesis (hydraulic conductance is approximately equal to effective permeability) .

METHODS

1) Core samples and thin sections from U.S.G.S. wells in Broward County were examined using both stereo (10x) and petrographic microscopes. This was done to determine texture, fabric, clast composition, bulk rock porosity, as well as diagenetic changes characterized by dissolution, recrystalization, and replacement. Cross-sections using the above mentioned data were constructed along transects connected by the wells used in the study (Figures 2 & 3).

2) Trace element data were derived from the same rocks. An inductively coupled plasma emission spectrometer (ICPES) was used to obtain concentrations of Mn, Fe, Mg, Ca, and Sr. Because trace element concentrations were highly variable in magnitude, and calcium concentrations were higher than all other elements, trace element concentrations were normalized to calcium concentrations to make plotting the data and calculations more manageable. These trace element concentrations in ppm are presented on Table 2 (Appendix) and on Figure 4.

3) Hydrologic data was obtained from a study completed by J. Fish (1987) in which pump tests were used to determine hydraulic conductance of the Surficial Aquifer.

The hydraulic conductivity values were determined in the field by the use of three different types of tests (Fish 1987) :

A) single well pumping tests, using only the pumped well for observations of response in the production zone. The single well pumping tests included step-drawdown tests, drawdown recovery tests, and specific capacity tests (Fish 1987).

B) multiple-well pumping tests, where an observation well in the pumped zone was monitored.

C) slug tests, which entail injecting a "slug" of water into an observation well and timing the water table's return to ambient pre-test conditions.

Depositional History

The Plio-Pleistocene geology of south Florida has been controlled by the fluctuation in sea level caused by changes in global climate, principally by several glaciations (Hoffmeister 1974). These climatic changes influenced the sequence of deposition of predominantly carbonate sediments in both fresh and salt water.

During the glacial stages, lowering of sea level caused erosion , deposition, and dissolution of sediments by meteoric water (Perkins 1977, Puri and Vernon 1965).

Laminated crusts, fresh water limestone, calcified roots of land plants, iron staining, and in some cases, loose terrigenous and carbonate sands above and within formational units are evidence for subaerial exposure. These occurred at various times in the Pliocene and the Pleistocene and cut across formational contacts (Perkins 1977). The fact that several subaerial horizons occur within some formations without showing facies changes indicates that many of the geologic formations are a record of multiple identical transgressive/regressive cycles (Perkins 1977).

Perkins believes that south Florida became a relatively flat shallow carbonate shelf of similar depositional energies and environments during each marine transgression since the late Pliocene (Perkins 1977).

In south Florida marine carbonate units deposited during the interglacial stages of the Pliocene and the Pleistocene include the Tamiami, Fort Thompson, Anastasia and Key Largo Formations as well as the Miami Limestone (Parker 1955). The geologic cross-sections (Figure 2) show the relationships of the geologic formations in the study area. Figure 3 shows the trace of the geologic cross-sections and the sample well locations.

STRATIGRAPHY

Tamiami Formation

In Broward County the Tamiami Formation is described by Parker (1955) as consisting of greenish clay marl, silty and shelly marl with calcareous marl (locally hardened to impure limestone), all of shallow marine origin and Pliocene in age. Maximum thickness is approximately 160 feet (Fish 1988). East of Collier County the formation begins to gently dip to the east and in Broward County is unconformably overlain by deposits of Pleistocene age.

Fort Thompson Formation

The Fort Thompson Formation is a wedge of late Pleistocene carbonate sediments that thins to the west. It is bounded by the Anastasia Formation north of Fort Lauderdale, and by the Key Largo Formation to the south (Parker 1955). The Lower portion of the Fort Thompson Formation is primarily an alternating sequence of marine and fresh water limestone of which the marine limestone has high permeability. The maximum thickness of the formation is approximately 100 feet near Hollywood, Florida.

Anastasia Formation

The Anastasia Formation contains coquina, quartz sand, calcareous quartz sandstone, and shelly marl of late Pleistocene age (Parker et.al. 1955). This unit occurs along the coast as a wedge that thins rapidly to the west and is equivalent in age to the marine portions of the Fort Thompson Formation and the Miami Limestone. The maximum thickness of the formation in the study area is 200 feet. These sediments are interpreted to be offshore bars and beach ridges (Parker 1955).

Miami Limestone

The Miami Limestone is a late Pleistocene deposit and includes both an oolitic and a bryozoan facies. The formation is present throughout the entire southeastern tip of Florida but only the bryozoan facies is present in the study area. The maximum thickness of the formation is 40 feet (Parker 1955). The Miami Limestone interfingers with the Key Largo Formation outside the study area.

Key Largo Formation

The Key Largo Formation is not found in the study area but is part of the Surficial Aquifer elsewhere in South Florida. This formation consists of coralline reef rock, calcarenite, and calcilutite of Pleistocene age. The formation interfingers with the Fort Thompson Formation and the Miami Limestone. The upper portion of the formation consists of cavernous coralline limestone that represents a relict coral reef system. The maximum thickness is 200 feet (Parker 1955).

PETROGRAPHIC ANALYSIS

Based on the following analyses and descriptions, the carbonate sediments that make up the rocks of the Surficial Aquifer of eastern Broward County are characterized as shallow water marine carbonates with only 2 occurrences of fresh water limestone. Samples from wells other than BRS-1 consisted of cuttings and/or core chips of low percent recovery.

The intergranular/bulk rock porosity and pore filling cements (sparry calcite) showed a high degree of variability within all the rocks examined with no systematic correlation between zones of low porosity and low hydraulic conductance or high porosity and high hydraulic conductance.

WELL BRS-1 A biomicritic fresh water limestone with thin shelled mollusks (*Heliosoma spp.* and *Planorbis spp.*) occurs from 0-10 feet. This fresh water limestone is underlain by approximately 17 feet (20-37 feet) of uncemented quartz sand, which becomes coarser downward. Minor carbonate skeletal fragments are present. Below 40 feet the rocks consist of alternating calcareous sandstone and biosparite. The thickness of these units varies from 3 feet thick for a bed of calcareous sandstone at 37-40 feet, to 170 feet thick for a sandy bryozoan/foraminiferal biosparite unit between 100 and 270 feet. Within the sandy biosparite units there are occurrences of biomicrite.

The fauna found in the marine deposits of well BRS-1 are thick shelled gastropods and pelecypods, echinoids, bryozoans, and benthic foraminifera. Calcareous algae are also present in these marine sediments. Occurrences of laminated crusts and iron staining were observed at depths of 37 feet, 110 feet, 145 feet, and 161 feet.

As mentioned earlier, Perkins determined that these sedimentary structures and deposits are evidence for the occurrence of subaerial exposure horizons of the past. Deposits overlying the subaerial horizons are composed of unconsolidated quartz sand at depths of 37 and 161 feet; however, the subaerial horizons at 110 feet (coquina) and 145 feet (sandy biosparite) are intercalated with rocks of similar lithology.

Well BRT-4 This well is characterized by alternating units of calcareous sandstone, molluscan biosparite/biomicrite, and uncemented carbonate sand, all of variable thickness. In addition there is a 3 foot thick layer of unlithified micritic ooze at approximately 136 feet.

Well BRT-15 This well is essentially the same as BRT-4 except that deposits of fresh water limestone are found from 9-23 feet.
The biomicritic fresh water limestone of well BRT-15 is similar to that found at a depth of 3-10 feet in well BRS-1.

Well BRT-22 This well is similar in lithology and fauna to BRT-4, but has no fresh water limestone .

General Geochemistry of Carbonate Systems

Calcite and aragonite are the predominant carbonate minerals found within the rocks of the Surficial Aquifer of South Florida.
Physical differences between calcite and aragonite cause them to have different environments of stability during deposition.
Among the differences between calcite and aragonite is density : aragonite = 2.9 g/cc , calcite = 2.7 g/cc, which is due to the differences in their trigonal and orthorhombic crystal structure .

The solubilities are also different for these two minerals.
When carbonate material is undergoing diagenetic alteration, trace elements with partition coefficients of less than one, such as - Sr, and Mg, will go into solution. Those with partition coefficients greater than one (Mn, Fe) will either remain undissolved or be precipitated from the pore water (Table 1). In short, concentrations of elements with partition coefficients less than 1 will decrease and those greater than one will increase in concentration during chemical reactions.

These changes in trace element concentrations enable the distinction of diagenesis in carbonate rocks, such as those of the Surficial Aquifer. Relative degrees of diagenesis can be revealed by analysis of trace element concentrations within carbonate materials. An increase in diagenesis is indicated by an increase in Mn and Fe concentrations and a a decrease in Sr concentrations (Veizer 1982).

GEOCHEMICAL ANALYSIS

Trace elements Mn, Fe, Sr and Mg were analyzed as well as Ca. Mg/Ca ratios were calculated in order to check that only the carbonate fraction of the rocks was entering the solute used in ICPES analysis. Only calcite and aragonite were observed. The graphs of trace element concentrations normalized to Ca can be seen in Figure 4. Values plotted are listed on Table 2. The Mn/Sr plots, at certain points, show that when Mn increases Sr decreases. Table 3 shows equipment drift for the ICPES during sample runs and samples used for quality control.

The points of the largest inverse relationships, as seen in well BRS-1, (Figure 4) are within 5 feet of the subaerial horizons determined by lithologic analysis. The samples from the other wells analyzed indicate that there are similar trace element relationships (Figure 5).

A plot of Sr versus Mn is shown on Figure 6. The present day concentrations of various forms of calcium carbonate in sea water are shown at the upper left portion of this diagram. The concentrations of all the analyzed samples (indicated by asterisks) fall below and to the right of the present day values. Samples that have not undergone diagenesis would be expected to plot at the upper left of the figure near the location of carbonate precipitated from present day sea water.

The location of the analyzed samples on the plot indicates that their concentrations have been affected by the diagenetic influence of meteoric water.

As mentioned, the increase of Mn with a decrease in Sr is geochemical evidence for diagenesis at zones where these relationships occur. When trace element values of all the wells are plotted on a geological cross-section of the study area, one can correlate fairly continuous horizons of these relatively high diagenetic zones (Figure 5). More significantly, the correlation shows that diagenetic zones cut across lithological boundaries and formational contacts. Such data infers that the diagenetic mechanisms which created these zones have acted on a regional scale rather than a local scale.

HYDROGEOLOGY

The geologic formations that make up the Surficial Aquifer system have a wide range of hydraulic conductivities that are not restricted to distinct lithologic units. Previous hydrologic investigations in South Florida show the presence of carbonate rocks with zones of similar hydraulic conductance crossing lithologic boundaries (Fish,1987). Hydraulic conductance in the Surficial Aquifer, therefore, is not influenced by lithologic boundaries or rock textures (Fish,1987).

Previous concepts led to the general acceptance of the Surficial Aquifer as an unconfined aquifer. However, there are a few scattered areas that appear semiconfined because of substantially lower relative permeability . Based on hydraulic conductance, Fish (1987) describes the base of the Surficial Aquifer system as being deepest at the coast and becoming shallower to the west. In eastern Broward county the aquifer reaches its maximum depth of approximately -373 feet near the city of Pompano Beach (Figure 7).

The top of this essentially unconfined aquifer follows the relatively flat topography of southeastern Florida. A cross-section of the generalized framework of the Surficial Aquifer is shown on Figure 8.

HYDROLOGIC ANALYSIS

When the lithologic and geochemical data are compared to pump test data (Fish 1987) an additional useful correlation becomes evident. As can be seen from Figure 9, the zones of the associated subaerial horizons, which also show trace element anomalies for Mn, Fe and Sr that are indicative of significant diagenetic effects, correspond to layers of the Surficial Aquifer with hydraulic conductance values of 100 feet per day or less. Although these values are not equivalent to those of conventional aquatards (less than 0.1 feet/day) they are relatively low in comparison to other hydraulic conductance values within the greater system, which are as high as 1000 feet per day within the Surficial Aquifer. The correlation of zones of high diagenesis and zones of low hydraulic conductance is well demonstrated in Figure 9.

Discussion

A distinct correlation can be made between the three types of data presented herein (lithologic, geochemical, and hydrologic). Zones of high diagenesis indicated by abnormal trace element concentrations and subaerial exposure surfaces correspond to zones of low hydraulic conductance (100 feet per day or less).

Occurrence of extensive recrystallization and secondary porosity were highly variable and were not found to correlate with either subaerial horizons, high diagenetic trace element zones, or zones of low hydraulic conductance. Discrepancies between these different parameters were expected. In the past petrographic data of this kind was often not effectual in determining zones of variable permeability or hydraulic conductance in the rocks of the Surficial Aquifer.

The lack of apparent correlation between petrographic evidence of diagenesis and geochemical indications of diagenesis may indicate that either the petrographic data from thin sections and core samples is incomplete due to the mode of sampling, or that the diagenetic changes indicated by porosity and recementation may need to be examined by methods that will evaluate these attributes on a regional scale, such as seismic surveys.

The data indicate that zones of low hydraulic conductance cut across lithologic boundaries in a similar fashion to that of the diagenetic trace element zones. This relationship suggests that diagenesis in the study area may be responsible for the development of both the existing low hydraulic conductance and trace element concentrations in the Surficial Aquifer.

The methods used in this study have demonstrated heterogeneity in the Surficial Aquifer in addition to that which was discussed in previous work (Fish 1987). In addition to the various zones of hydraulic conductance of Fish (1987), there is now evidence for a minimum of four zones of relatively high diagenesis, as demonstrated by trace element concentrations.

SUMMARY AND CONCLUSION

Lithologic, geochemical, and hydrologic investigations of the Surficial Aquifer in Broward County were conducted to better understand the relationship of diagenesis to the present hydrologic properties (specifically hydraulic conductance) of the Surficial Aquifer. The analyses revealed four zones that lie at four distinct depths vertically and over broad areas horizontally. These four zones are indicated by subaerial horizons, high diagenetic trace element values and relatively low hydraulic conductance of 100 feet per day or less.

The results of this study indicate that the diagenesis of the carbonate rocks of the Surficial Aquifer took place through subaerial exposure related to fluctuating sea levels in the past. This diagenetic process created zones of low hydraulic conductance in the present Surficial Aquifer.

The development of such zones within the Surficial Aquifer significantly alters its gross hydraulic conductance, effectively creating marked differences within the Surficial Aquifer, which, therefore, should be considered as heterogeneous with largely variable physical properties. These properties affect recharge, water quality, and water recovery.

The methods of investigation used in this study are useful for regional mapping of relative hydraulic conductance in similar carbonate terrains. In addition, the methods used in this study provide a new way of indicating zones of high relative productivity for ground water pumping purposes.

Relative hydraulic conductance of different levels in the Surficial Aquifer can be predicted on the basis of the vertical distribution pattern of certain trace element concentrations. Delineation of the different zones detected by the methods used in this study will allow pumping from strata that are not near zones of high diagenetic trace element values, thus, avoiding zones of low hydraulic conductivity.

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TABLE 1

Partition coefficients (After Veizer 1982)

Trace element In Calcite	Partition coefficients
Sr	.03-.13
Na	.00002-.00003
Mg	.013-.06
Fe	1.0-20.0
Mn	6-30
Zn	5-20

TABLE 2

Trace Element Concentrations for All Sampled Wells

[Sig is percent deviation of three consecutive measurements for each sample and is an indicator of short-term instrument stability; long-term reproducibility for all elements is 5% or better]

Sample depth (feet)	Mn	Sig (%)	Fe	Sig (%)	Mg	Sig (%)	Ca	Sig (%)	Sr	Sig (%)	Insoluble residue (%)
Concentration of Trace Elements in PPM of Soluble Fraction of BRS-1											
6-8	38.3	1.5	463.1	1.9	16,487	1.8	390,771	1.8	1,346	0.7	12.7
26-27	4.18	4.4	180.2	1.4	20,546	1.2	404,100	1.0	1,876	.02	12.2
37-38	33.8	.75	256.7	1.7	13,207	2.3	410,512	.84	397	.72	25.8
45	13.9	.70	226.0	1.8	15,130	.0	417,667	.10	1,008	.55	11.7
55-60	32.7	.50	883.5	.84	22,984	.82	418,392	.38	813	.71	31.5
80-83	5.85	2.4	134.9	.92	25,991	.34	379,388	.05	421	.22	38.5
90-95	14.3	1.3	145.6	2.2	31,858	1.4	413,519	1.2	1,748	.80	11.7
105-108	12.9	.4	169.1	1.6	35,569	.42	410,759	.71	1,156	1.0	13.4
110-120	25.6	1.1	374.7	.60	16,812	.0	419,273	.53	502	.69	8.58
125-128	8.53	2.1	139.8	1.6	39,438	1.6	417,858	1.2	853	1.1	6.26
145	18.0	1.9	307.3	.90	21,380	1.3	398,622	1.3	545	1.3	8.56
145-160	7.75	2.1	155.7	1.0	24,994	1.7	410,791	1.7	1,042	1.7	11.8
154-157	9.96	1.3	275.1	1.8	37,299	1.3	407,319	1.0	1,501	.94	7.64
167-168	31.7	1.2	202.7	1.5	23,480	.68	414,155	1.1	489	.80	19.0
171-173	13.2	2.4	146.7	1.5	17,373	1.0	349,695	1.2	357	.94	14.6
179-180	11.3	2.4	207.0	3.3	15,123	1.9	394,748	1.8	680	1.7	8.22
183-184	16.4	1.8	169.1	1.9	16,297	1.1	373,856	1.0	651	.94	16.9
199-200	34.8	1.2	504.0	.23	23,465	.32	362,116	.38	1,328	1.2	12.7
220-230	26.0	.90	199.0	1.0	23,858	.94	366,320	.89	1,882	1.1	15.3
255-260	3.84	6.4	159.0	.88	18,732	.87	381,040	1.1	974	.84	29.6
265-270	6.64	1.8	141.6	.59	22,494	.50	369,565	.63	3,779	.84	14.0
Concentration of Trace Elements in PPM of Soluble Fraction for BRT-4											
9-13	25.37	1.1	415.7	1.2	9,990	1.2	385,901	1.0	1,808	1.5	25.2
29-33	12.33	.69	247.4	.73	20,397	.82	391,477	.43	479.1	1.3	29.6
43-46	17.45	.85	380.7	.50	25,898	.73	369,151	.73	432.1	.68	26.4
59-63	13.17	1.4	285.0	1.1	37,227	1.0	377,051	.91	696.2	.90	33.0
76-79	5.03	2.1	97.5	1.8	28,318	.45	362,828	.75	437.0	.34	26.0
86-89	7.27	1.4	146.1	.46	312,39	.72	380,031	.94	468.0	1.0	23.0
99-103	10.13	1.8	270.3	1.2	29,868	1.0	362,641	1.2	391.7	.95	13.2
119-123	10.11	1.1	401.2	.66	44,760	.44	371,930	.69	494.0	1.1	30.0

TABLE 2 (continued)

Sample depth (feet)	Mn	Sig (%)	Fe	Sig (%)	Mg	Sig (%)	Ca	Sig (%)	Sr	Sig (%)	Insoluble residue (%)
Concentration of Trace Elements in PPM of Soluble Fraction of BRT-15											
6-9	19.57	1.4	718.9	1.1	172,418	0.01	372,029	0.70	1,220	0.45	12.5
9-13	123.8	1.8	1,319	1.5	54,199	1.1	395,751	1.9	661	1.1	18.6
24-30	22.26	.91	560.9	.69	62,183	.54	382,754	.81	1,992	.70	10.7
49-53	19.55	.71	569.6	.41	207,423	.20	360,700	.66	937	.79	37.8
73-76	14.22	1.2	468.5	1.1	206,626	.01	335,060	.70	1,396	.45	17.0
Concentration of Trace Elements in PPM of Soluble Fractin of BRT-22											
0-5	123.3	.59	1,658	.71	21,004	.62	400,033	.61	1,407	.75	40.7
19-25	59.49	.86	4,429	.83	31,733	.90	434,878	.88	719	.55	72.9
33-36	21.02	2.4	488.1	1.3	31,573	1.2	403,862	1.5	464	1.8	30.1
48-53	15.75	.90	282.0	.49	28,653	.45	378,529	.46	454	.17	10.8
68-72	6.11	2.5	132.5	1.0	28,685	1.4	399,226	1.5	1,229	1.5	22.4
82-84	11.13	.41	986.2	.55	61,694	.51	376,569	.25	798	.73	52.2
98-100	16.44	2.2	650.5	1.4	53,710	.90	420,671	1.8	935	.97	43.4
108-111	10.59	.56	607.4	.38	47,645	.05	411,028	.20	1,107	.23	46.5
129-132	29.5	1.1	1,865	1.6	218,637	.02	318,766	1.4	439	1.2	22.2
148-151	15.37	.57	806.2	.41	94,929	.54	407,968	.21	639	.32	39.3
158-161	13.93	.43	547.8	.25	85,012	.04	376,614	.09	538	.51	38.1

TABLE 3

RUN # 1 SAMPLE BRS-1 (6-8)

Mn	Fe	Mg	Ca	Sr
.3342	4.045	144	180.4	11.76
.3342	4.177	149	185.4	11.81

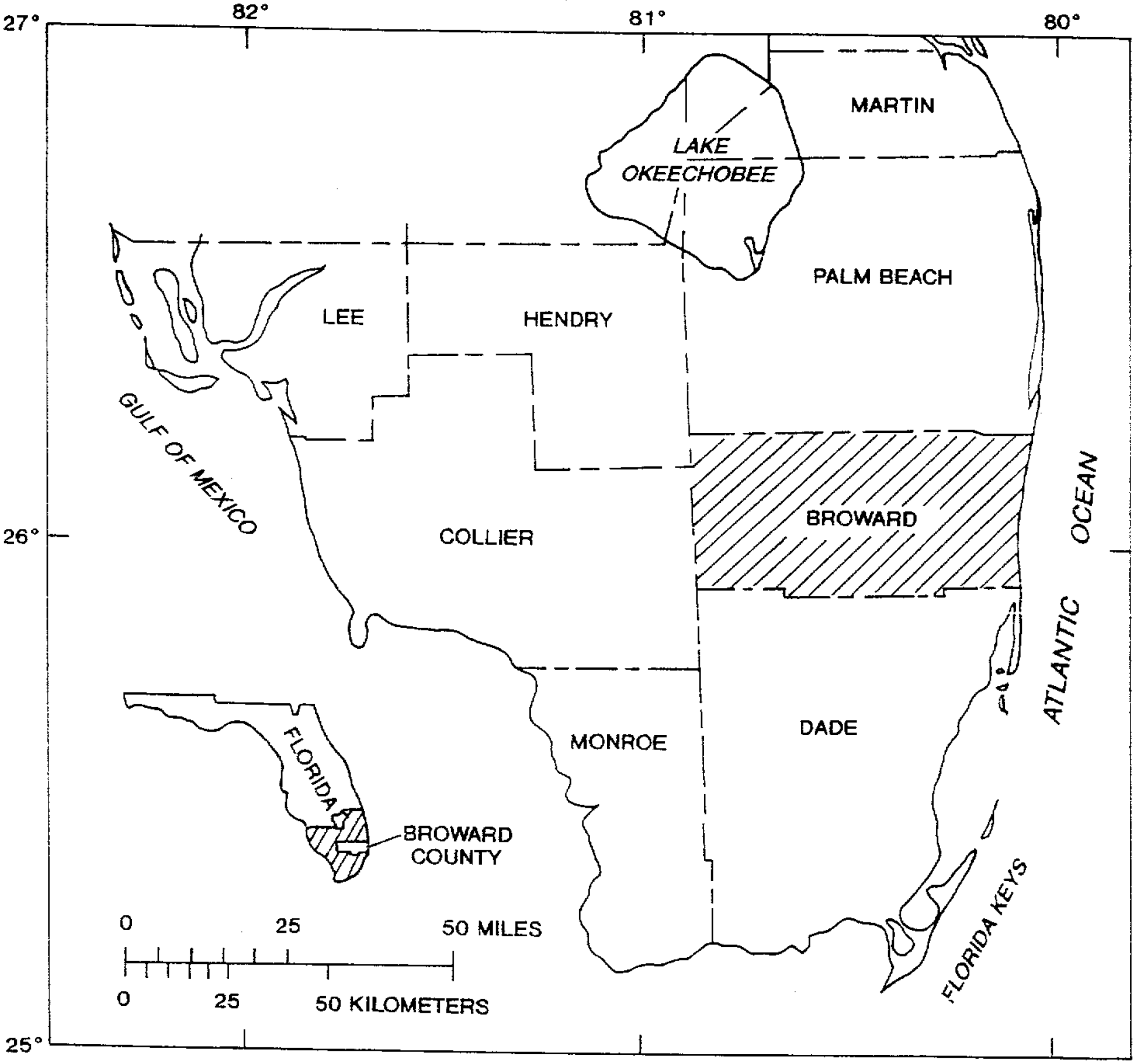
RUN # 2 SAMPLE BRS-1 (80-83)

Mn	Fe	Mg	Ca	Sr
0.03599	.830	159.9	2334	2.588
0.03780	.851	161.1	2396	2.600
0.03684	.845	159.4	2371	2.561

RUN # 3 SAMPLE BRS-1 (80-83)

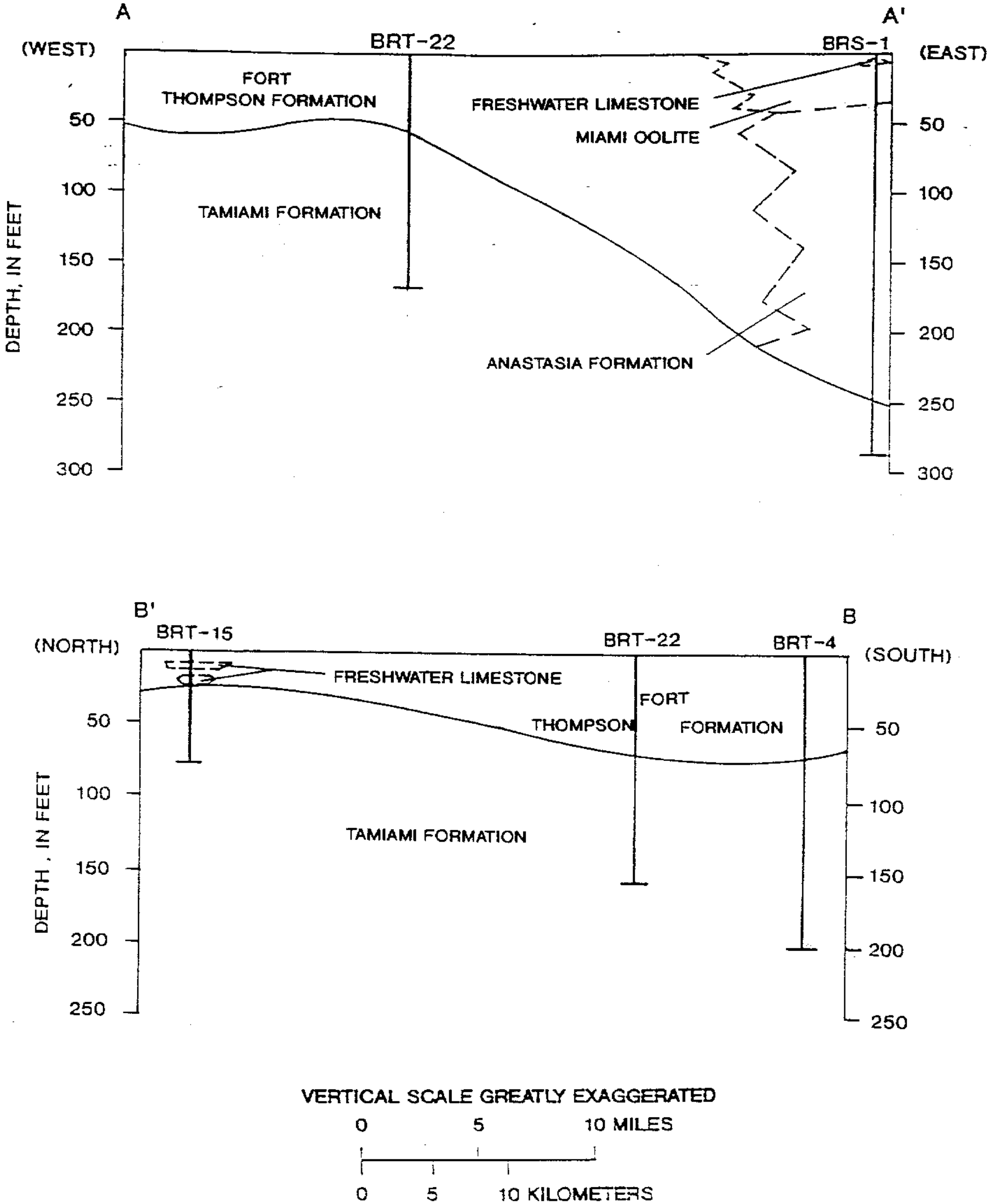
Mn	Fe	Mg	Ca	Sr
0.03827	.8508	161.2	2379	2.642
0.03979	.8891	166.2	2544	2.707
0.03747	.8749	160.2	2386	2.585
0.03844	.9133	164.1	2457	2.629

Quality control samples, concentrations in ppm of samples used for every tenth measurement in ICPES to detect equipment drift over time for samples from all wells. Each run is one day of analysis. Samples from BRS-1 were used as control for all runs, as indicated.



Location of Broward County, Florida

Fig. 1



E-W Geologic Cross-section A-A' and N-S Geologic Cross-section B-B'

Fig. 2

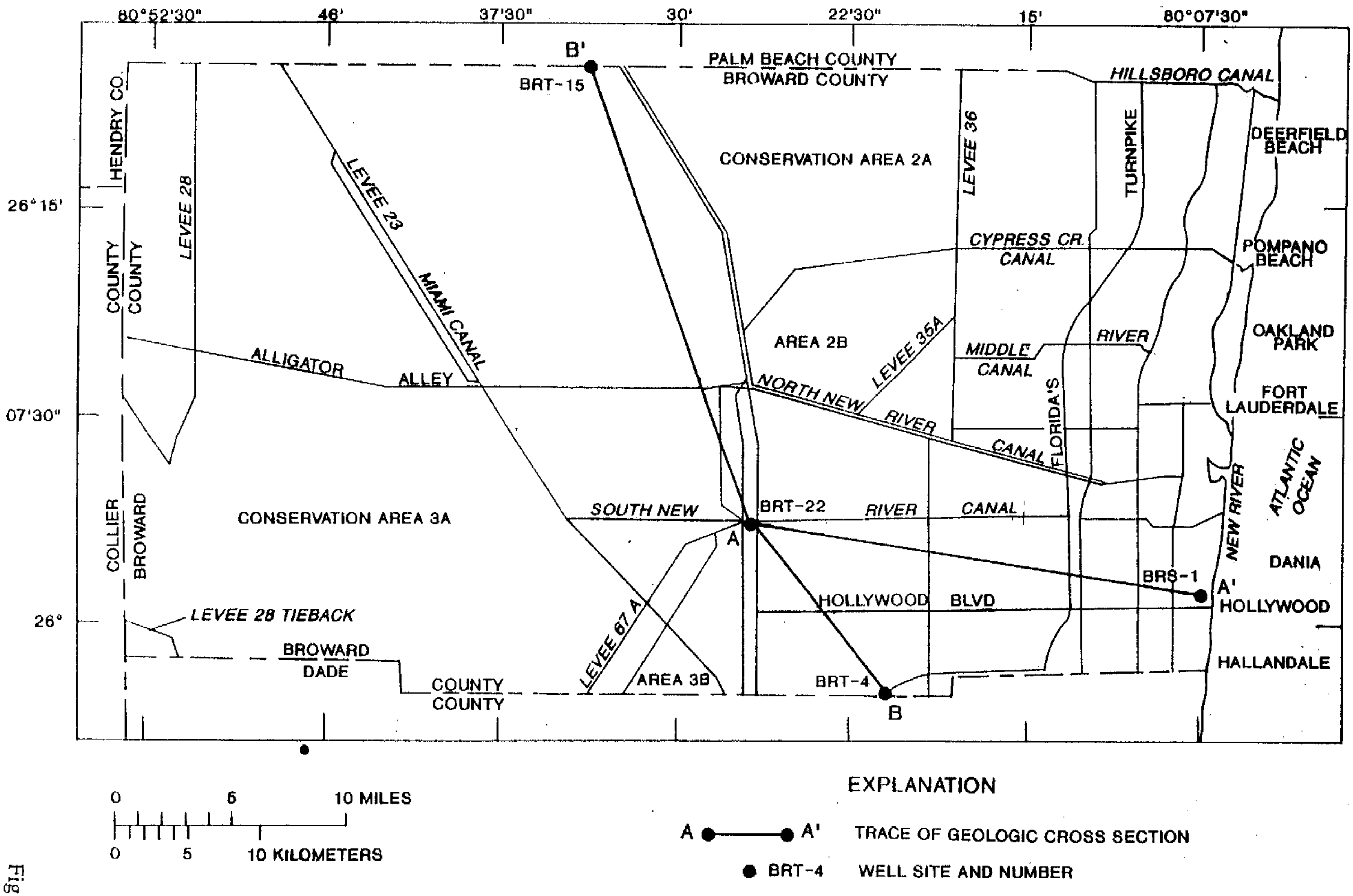
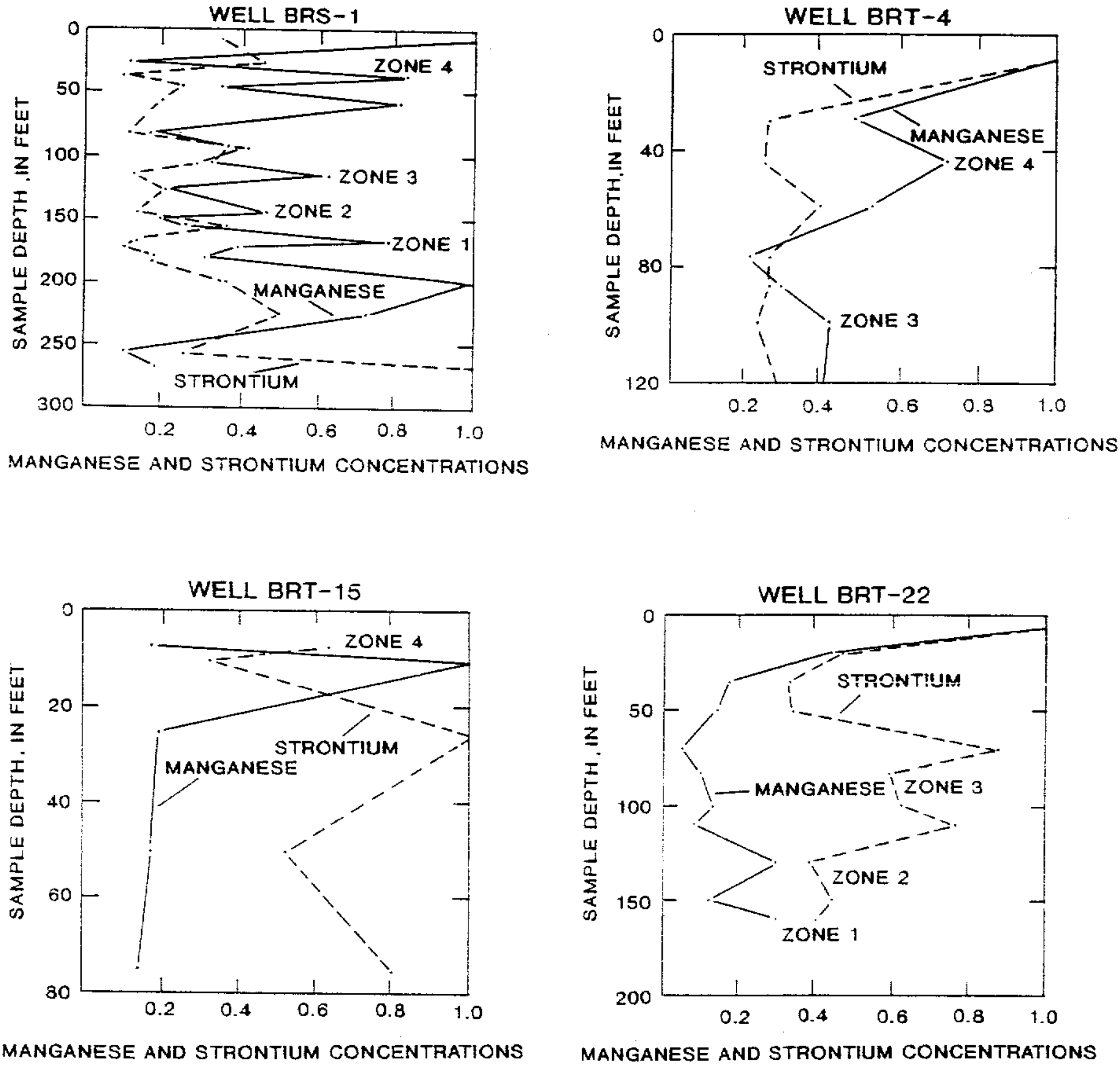


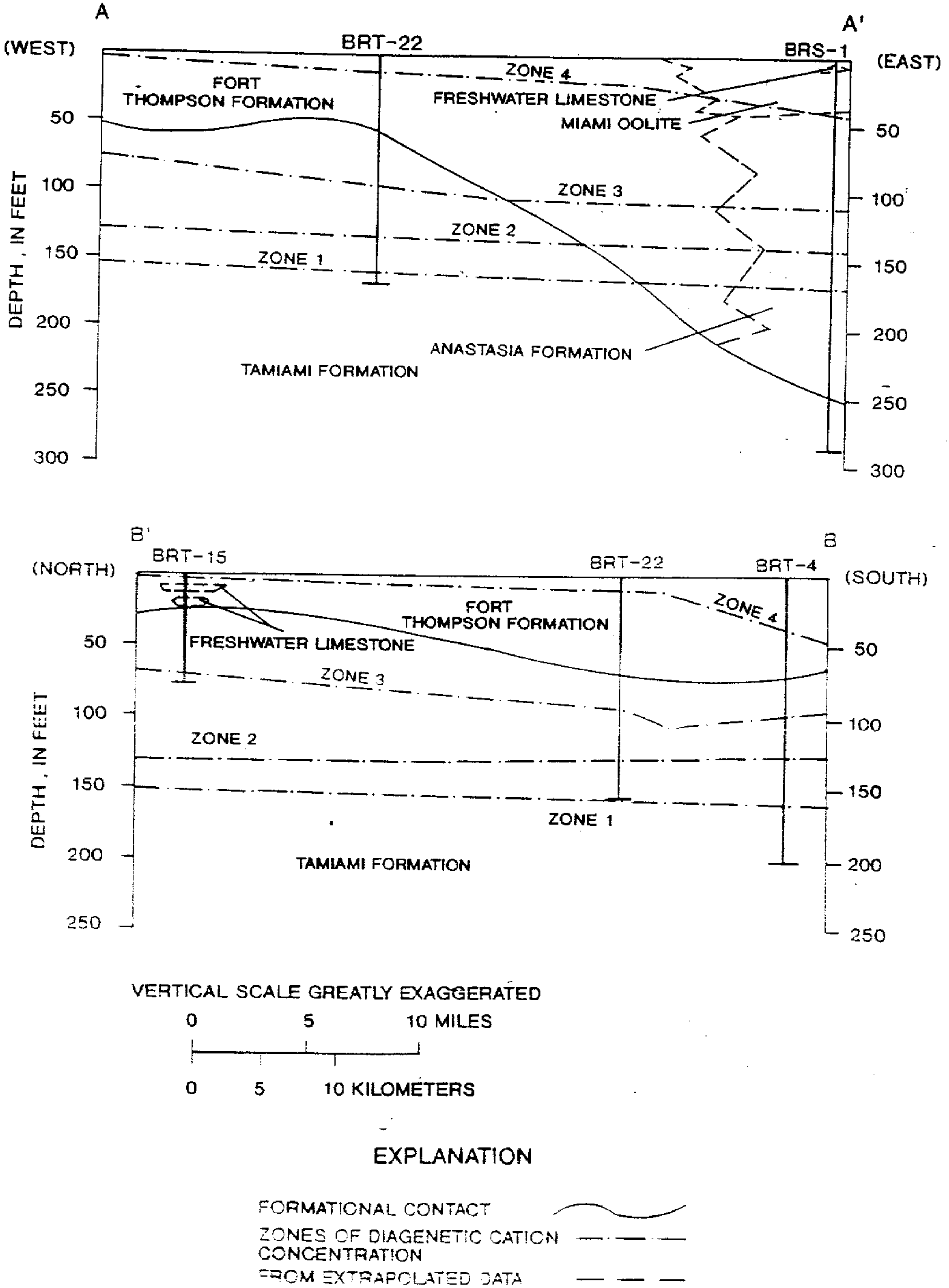
Fig. 3

Location of Well Sites and Cross-sections

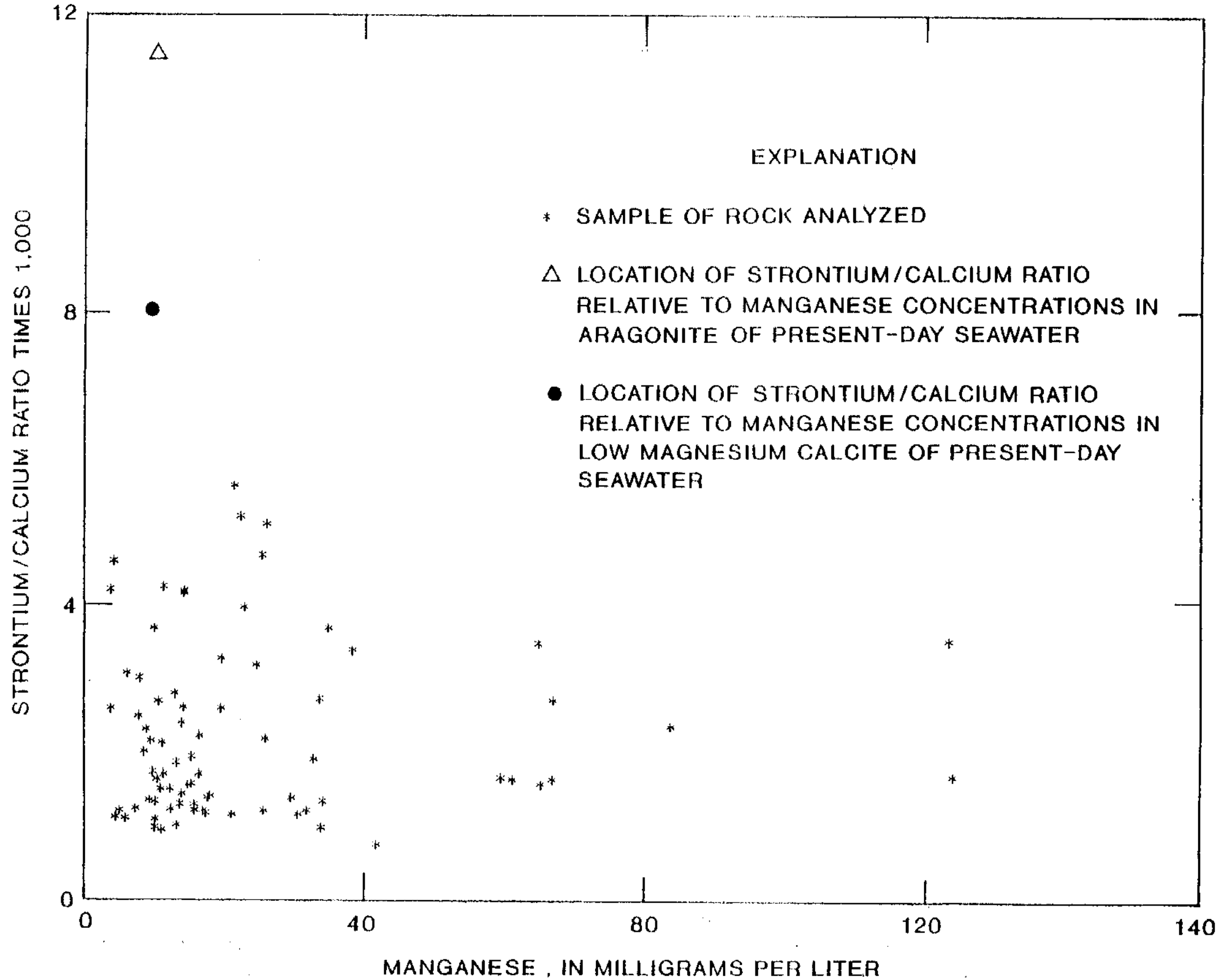


Trace Element Concentrations

Fig. 4



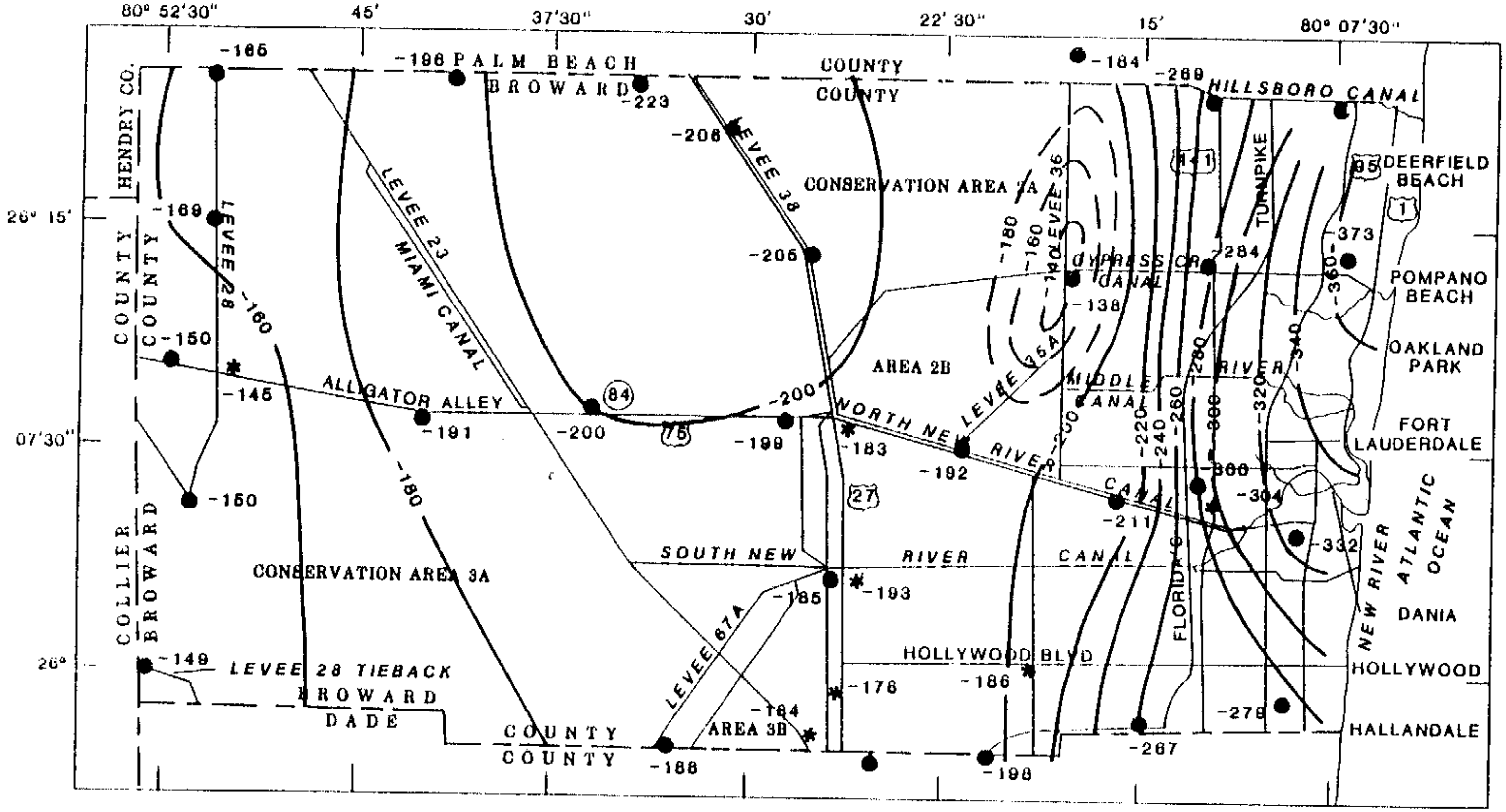
Cross-section A-A' and B-B' with Zones of High Diagenesis Fig. 5



Concentrations of Sr/Ca vs. Mn

Fig. 6

Fig. 7



0 5 10 MILES

0 5 10 KILOMETERS

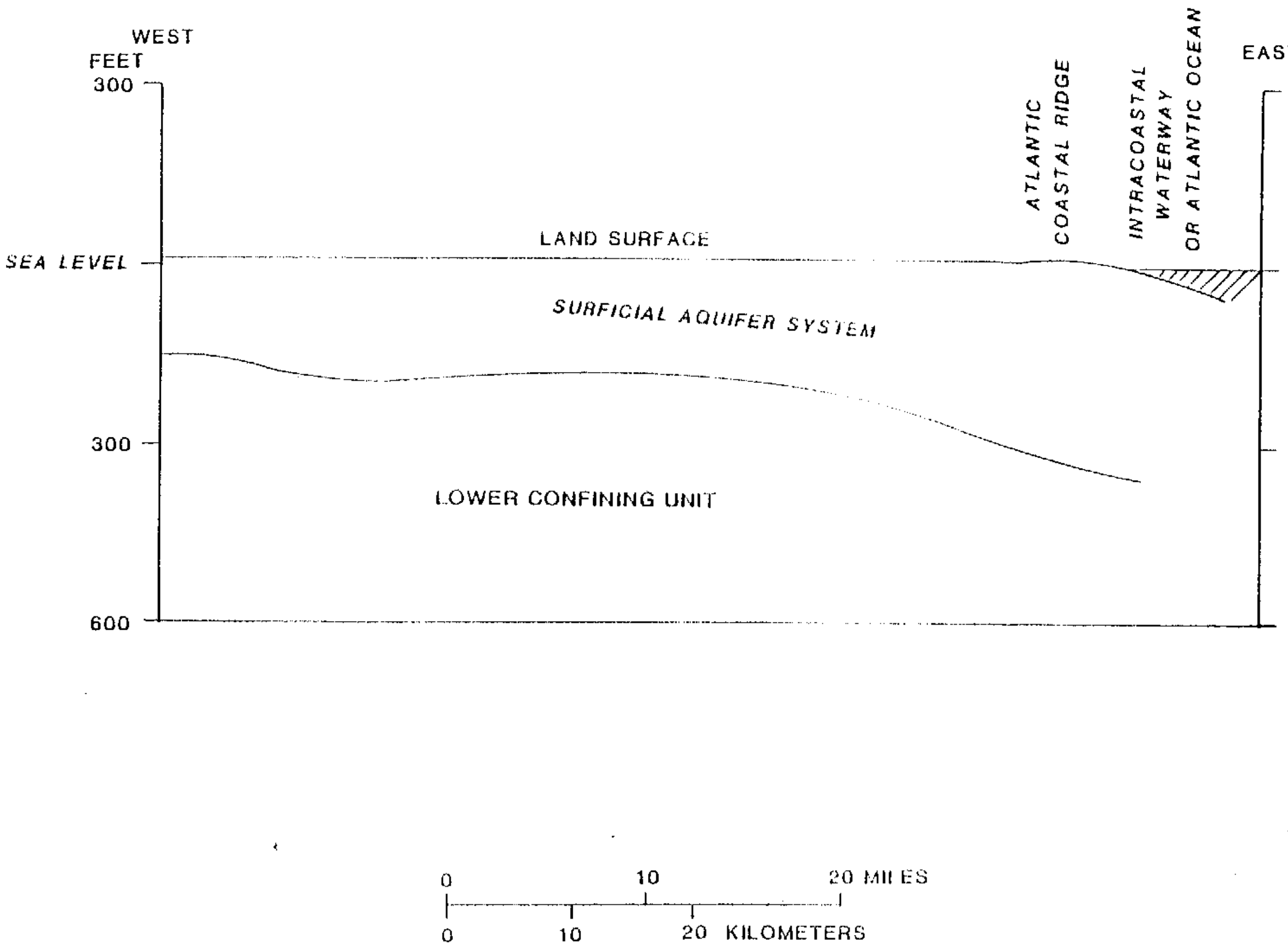
EXPLANATION

——200—— STRUCTURE CONTOUR--Shows altitude below Sea Level of base of surficial aquifer system. Dashed where approximately located. Contour interval 20 feet

● -198 TEST HOLE, THIS STUDY--Number is altitude of base of surficial aquifer system, in feet below Sea Level

✱ -184 TEST HOLE, LOG FROM U.S.GEOLOGICAL SURVEY FILES --Number is altitude of base of surficial aquifer system, in feet below Sea Level

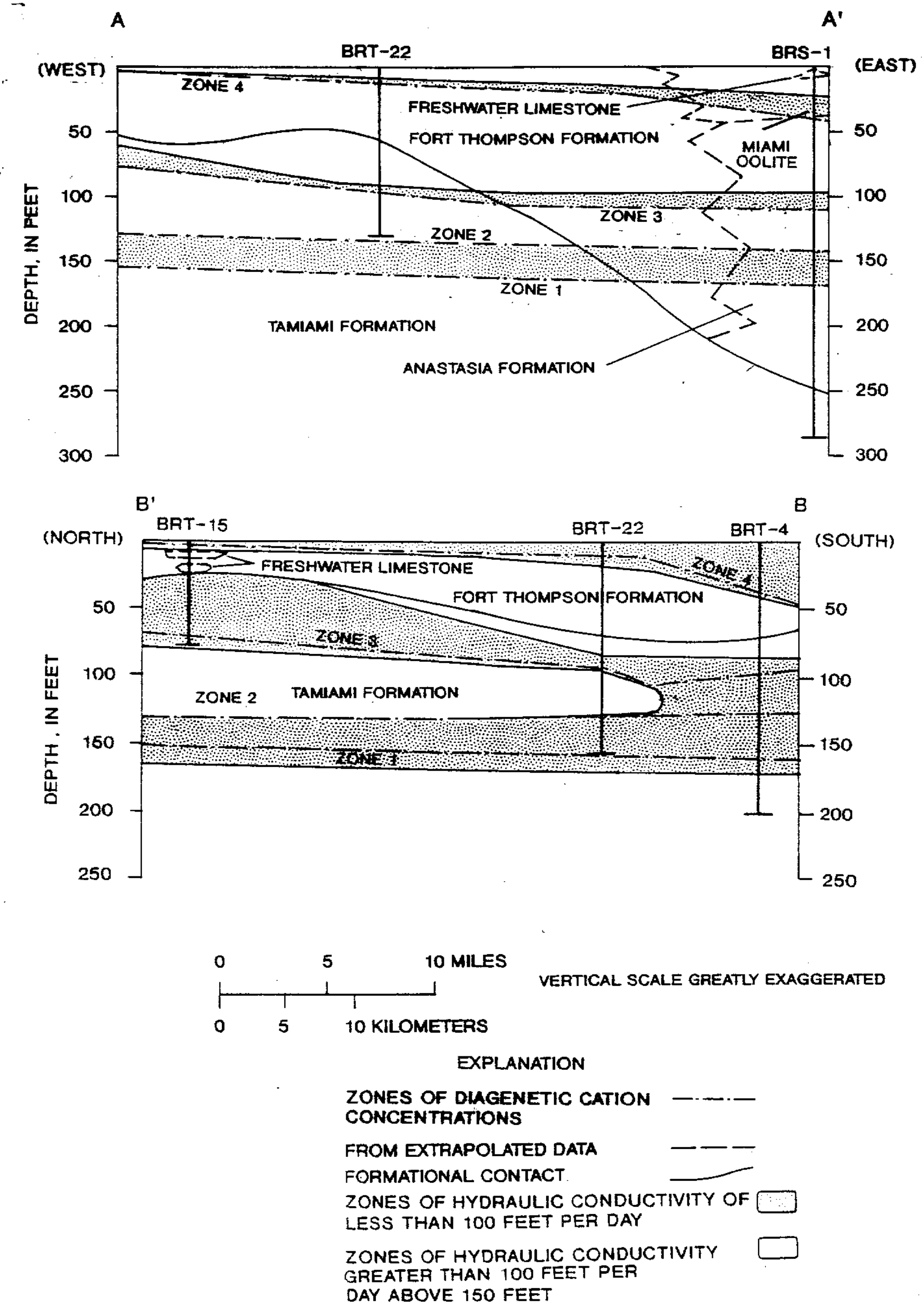
Base of the Surficial Aquifer System in Broward County



SCALE APPROXIMATE
VERTICAL SCALE GREATLY EXAGGERATED

Fig. 8

Generalized Hydrogeologic Profile



Cross-section A-A' and B-B' Showing Hydraulic Conductance and Trace Element Zones Fig. 9