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STRATIGRAPHIC ANALYSIS OF GEOPHYSICAL LOGS FROM WATER WELLS IN PENINSULAR FLORIDA

By

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ABSTRACT

Geophysical well logs are widely utilized in peninsular Florida. Such logs are often the only reliable geologic information obtainable for formations which exist in the subsurface in any given area. The stratigraphic interpretation of such logs is thus important in accurately determining the regional geology and stratigraphy of the state.

Gamma ray and electric log characteristics of the nine Paleocene age to Pliocene age geologic formations typically present in peninsular Florida are considered. Primary emphasis is placed upon stratigraphic interpretation of gamma ray logs, with electric logs serving as a supplementary source of information.

Most of the formations considered can be divided into two gamma ray log zones: an upper zone of lesser intensity and a lower zone of greater intensity. The lower zones of the Suwannee, Ocala (locally), Avon Park, Lake City and Oldsmar Limestones generally consist of hard, thick dolostone zones. Average gamma ray intensity decreases downward through the stratigraphic section as the Hawthorn Formation, Tampa, Suwannee and Ocala Limestones are penetrated. The Ocala is recorded as the lowest gamma ray intensity on logs run in water wells in the region. The Hawthorn Formation displays the highest intensity due to the presence of relatively high concentrations of phosphate. Avon Park and Lake City gamma ray intensities can also be relatively high because of the presence of peat and clay as discrete beds and as disseminated material in carbonate beds.

Where it exists, the Tamiami Limestone can sometimes be distinguished on gamma ray logs as a somewhat variable three-zone series of characteristics.

INTRODUCTION

Borehole geophysical logging techniques in water wells have become increasingly important and widely utilized in Florida. Several state and federal agencies as well as many private consulting firms currently operate well logging equipment. As a result, a large number of water wells, test holes and observation wells are being logged state-wide and much of that information is available for public inspection. This paper was written as an aid to geologists, hydrologists and engineers in their interpretaion of these logs: specifically with regard to natural gamma ray and electric (Normal resistivity or single point resistance) logs as they can be applied to stratigraphic identification and correlation.

The information presented herein is summarized from the logging of 938 wells located in 32 counties (Figure 1). Most of the wells logged are located inside the 19 counties comprising the St. Johns River Water Management District, however additional wells were logged in southwest Florida (28 - Manatee, Sarasota, Charlotte and Lee counties) in southeast Florida (8 - St. Lucie, Martin and Palm Beach counties), northwest peninsular Florida (8 - Hamilton, Taylor, Columbia, Madison and Gilchrist counties) and in the Florida Keys (3 - Monroe County).

Wells ranged in depth between 44 and 3,482 feet. Logging was accomplished with the borehole geophysical equipment of the Florida Department of Natural Resources, Bureau of Water Resources (now part of the Department of Environmental Regulation) and the St. Johns River Water Management District over the period of 1974 through 1984. All logs are on file at the Florida Bureau of Geology, Tallahassee and the logs run by the St. Johns River Water Management District are also on file at the Palatka, Florida, office of the District.

In each well, at least one complete gamma ray log was obtained. In most of

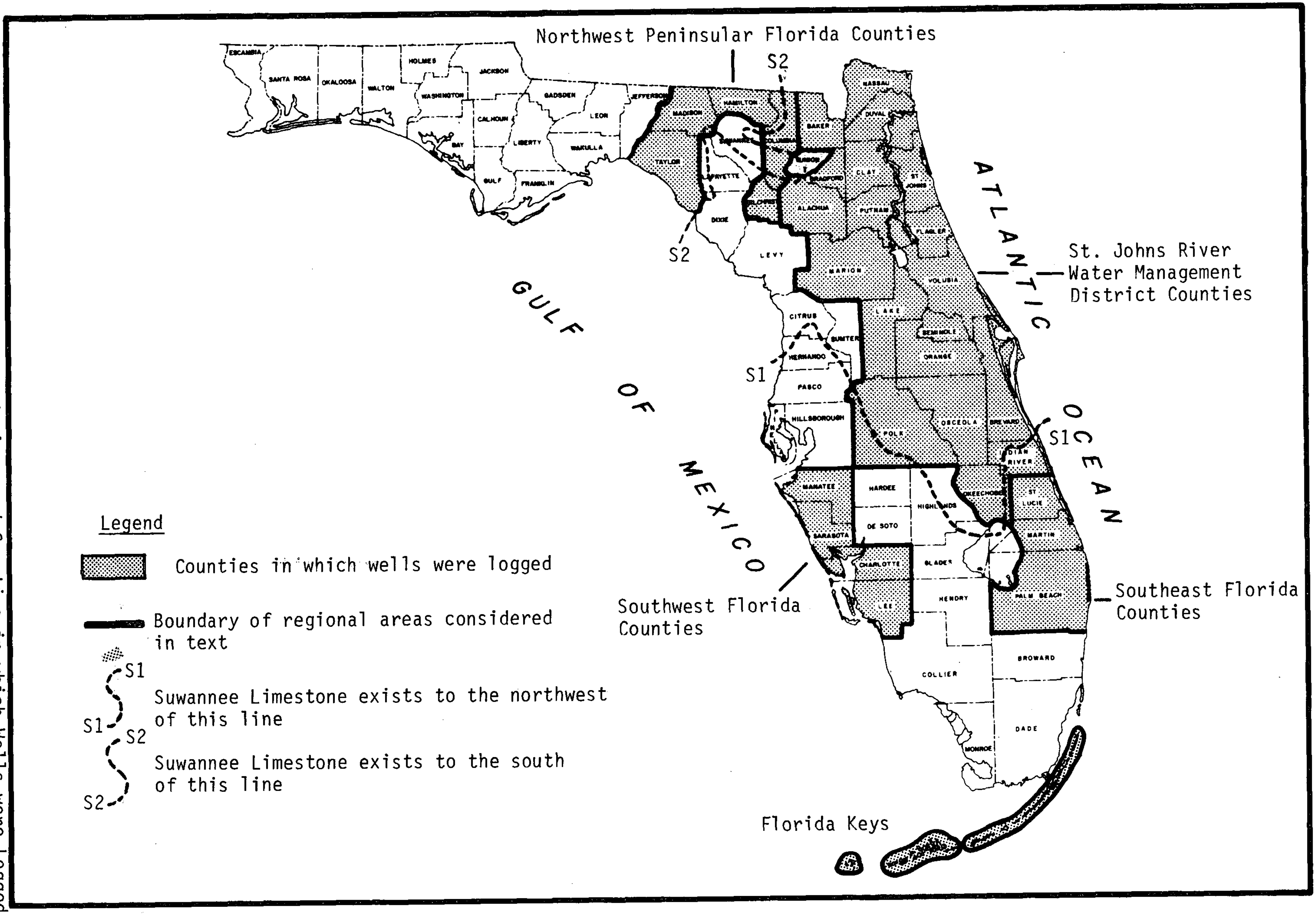

Figure 1. Location Map Showing Study Area and Counties in which Wells were Logged.

the wells, a suite of logs, consisting of caliper, gamma ray and electric, was obtained. Emphasis is placed upon the gamma ray log in this paper because it is not significantly affected by enlargements in borehole diameter and because it can be run inside casing, thus obtaining lithologic information from the entire length of a well. The gamma ray log is included in the standard suite of logs run by most well logging organizations and is generally accepted as a proven stratigraphic tool. Additional logs such as temperature, flowmeter (spinner) and borehole fluid resistivity were obtained in some of the wells.

The gamma ray probes utilized for this report were of three different types. A gross count probe, containing a relatively small-sized (3/4 inch by 3 inches) sodium iodide scintillation crystal was used primarily outside of the counties comprising the St. Johns River Water Management District. A lithology probe containing a large 1 inch by 4 inches sodium iodide scintillation crystal was utilized within the St. Johns River Water Management District and occasionally in other selected wells. Both gross count and lithology probes have an outside diameter of one and eleven-sixteenths inches. A slimline probe, one and one-quarter inches in outside diameter, was also used. This probe contains a 3/4 inch by 1 1/2 inch sodium iodide scintillation crystal and was used for logging very small diameter wells. This slimline probe was utilized primarily in counties included within the St. Johns River Water Management District. The most important difference between these probes is sensitivity, which is related to crystal size and outside diameter of the probe (Keys and MacCary, 1971). Since the gamma ray logs are used only qualitatively, logs from all three probes can be easily correlated and no interpretive difficulties are encountered in matching logs from different probes. Many wells logged originally with a small crystal size probe were later relogged with the lithology probe. Additionally, all three probes were run in one well using identical scales and electronic settings, allowing exact sensitivity comparisons. Chart values are given on each log in counts per second (cps). All logs were recorded with a scale of zero to two hundred counts per second deflection full scale, and no other recorder, pen or electronics settings were changed between wells logged. Since the three probes differ only with regard to crystal size and diameter, three distinct sets of logs result, with the members of each set recorded at identical sensitivity and scale. Most gamma ray probes have a radius of investigation of approximately one to two feet (Keys and MacCary, 1971).

Two types of electric logs were run. In both types, the spontaneous potential (sp) curve, usually recorded by commercial logging companies on the left hand side of the chart paper, was found to be a mirror image of the resistivity curves in the water-filled, predominantly carbonate-lithology boreholes characteristic of peninsular Florida and hence, only the resistivity or resistance curves are considered.

In wells logged with the Bureau of Water Resources equipment, the single point resistance curve was recorded. This type of probe is estimated to have a radius of investigation equal to approximately ten times its outside diameter (Keys and MacCary, 1971). This probe is approximately one and one-half inches in outside diameter, thus the radius of investigation is approximately fifteen inches. Chart values (recorded in ohms) are relative and variable from well to well. With the St. Johns River Water Mangement District equipment, 16- and 64-inch Normal resistivity (double point) curves were obtained. The sixteen-inch curve appears to be best for correlation of the relatively thin marker beds characteristic of the region. The sixteen-inch curve also allows detection of thin lithologic zones or beds in the continuous carbonate section of the wells (such as thin interbedded limestone and dolostone). On these logs, measurements are in ohm-meters. The sixteen-inch Normal has a radius of investigation of sixteen inches (Keys and MacCary, 1971), and because of a different arrangement of electronics, is much more accurate and reproducible (repeatable) than the single point resistance curve.

In the process of stratigraphic interpretation, these logs were correlated with corehole data, drillers' cuttings and descriptions and all available published geologic information. Geologists currently working in the state were also consulted in order to obtain their interpretations and opinions. The Florida Bureau of Geology graciously allowed access to many of their coreholes for geophysical logging and comparison of the geophysical logs with the cores. Also, the statewide masterfile of geophysical logs maintained by the Bureau of Geology was consulted for counties in which no logs were run by the author and the geophysical characteristics of the formations as deduced from wells logged in the counties shown in Figure 1 were found to be generally applicable throughout the entire peninsula.

The geophysical characteristics of formations ranging in age from Paleocene to Pliocene are considered (Figure 2). The formations are: Cedar Keys Formation (Paleocene), Oldsmar Limestone (Early Eocene), Lake City Limestone (Middle Eocene), Avon Park Limestone (Middle Eocene), Ocala Limestone (Late Eocene), Suwannee Limestone (Oligocene), Tampa Limestone (Early Miocene) and Hawthorn Formation (Miocene to Pliocene). In addition, the Tamiami Limestone (Pliocene) and possibly equivalent Jacksonville Limestone are considered in two local areas in Appendix A.

While there exist several formations recognized statewide that are younger than the Hawthorn Formation, they are relatively difficult to identify in the subsurface by means of geophysical logs, particularly since they are almost always cased off in water wells and hence, only the gamma ray log is available.

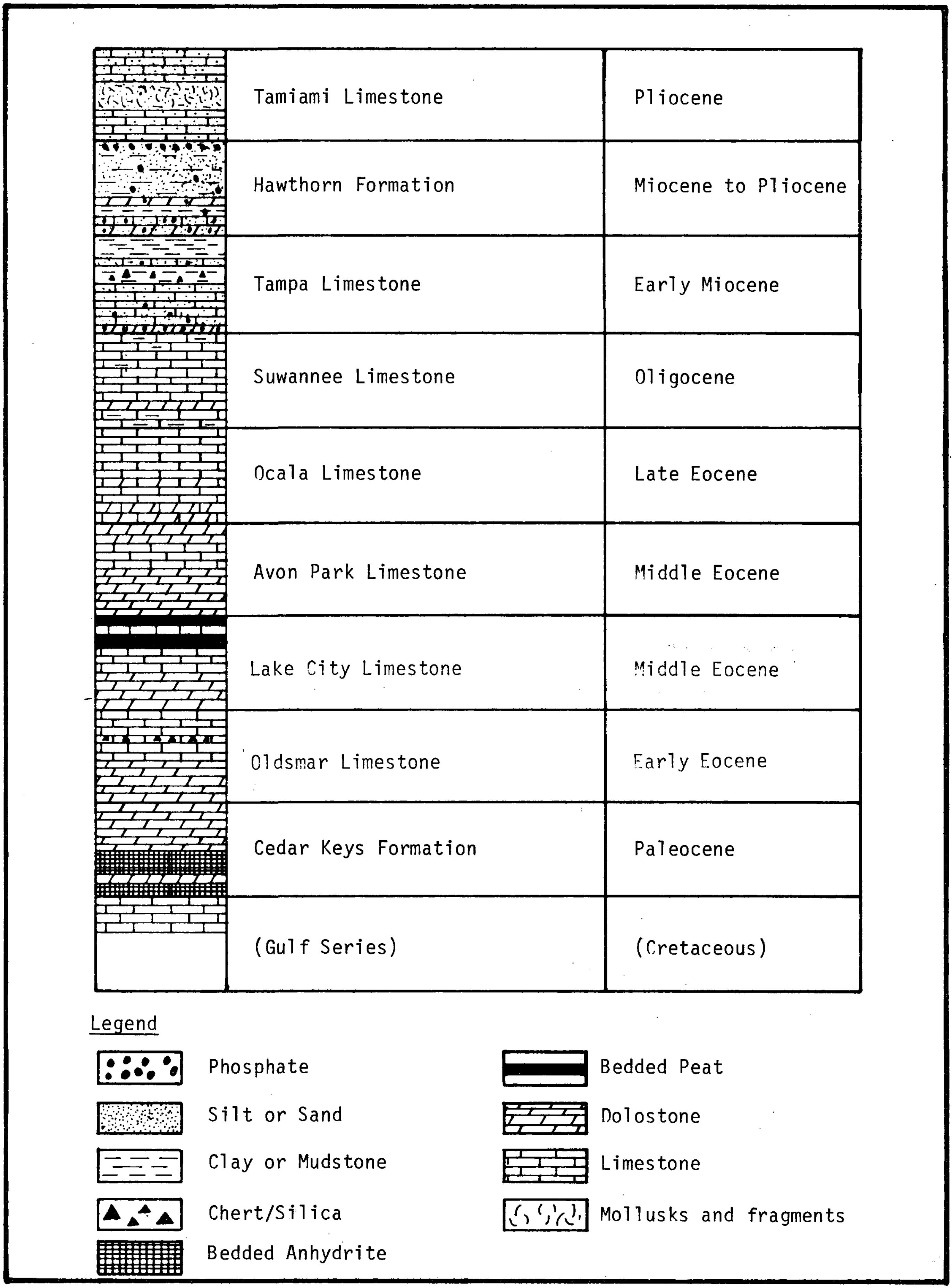

Figure 2. Stratigraphic Column

Gamma ray characteristics in these formations are usually extremely variable and cannot be regionally traced.

The format of this report follows the geology and geophysical characteristics of each formation in descending order, as they are penetrated by the drill. On the figures depicting gamma ray logs, low-intensity is considered to be 0 to 30 counts per second (cps), medium-intensity is considered to be 30-170 cps and high-intensity is considered to be 170 cps or greater. This numerical (cps) scale is strictly relative and varies considerably with equipment used, various pen, recorder and electronic settings, hole size and several other physical variables. It is used in this report only as a general indicator of relative intensity. Similar considerations apply to electric logs, although double-point resistivity logs are generally more standardized and less variable-influenced than other logs. Appendix B gives a tabulation of selected deep wells logged showing depths of formation contacts. Appendix C shows graphical representations of complete gamma ray logs from selected deep wells along the Atlantic and Gulf coasts of Florida.

HAWTHORN FORMATION

The Hawthorn Formation consists of interbedded and intermixed sand, silt, clay, dolostone and limestone, with much dolomite (Scott and MacGill, 1981), silica and phosphate present. Generally, individual units or beds within the Hawthorn are only traceable locally within a single county. However, the formation can be regionally divided on the basis of geophysical logs into an upper clay, silt and sand zone and a lower carbonate and clay zone, both zones containing phosphate in varying proportions.

Typically, the upper zone of the formation is recorded on gamma ray logs as a relatively uniform medium-intensity gamma ray trace with widely-spaced to absent high-intensity peaks, or as a zone of broad, widely-spaced, medium-intensity peaks corresponding to the upper clastic unit. The lower zone is recorded on gamma ray logs as a series of very-high-intensity phosphate peaks alternating with thin, medium to low intensity valleys (Figure 3).

In most areas of peninsular Florida, the top and bottom of the formation are shown characteristically as high-intensity phosphate peaks. The basal Hawthorn bed typically shows the highest-intensity and thickest gamma ray peak, especially where the lower contact marks an unconformity. In this case, the basal beds usually consist of a rubble zone of sandy, very phosphatic dolostone and limestone (most of northeast and central Florida). In some areas, well-lithified, phosphatic mudstone and clay beds are found at the unconformity (Indian River County, for example). The lower contact is always an unconformity unless the fully-developed Tampa Limestone is present below the Hawthorn, as is apparently the case in some areas along the southwest coast of Florida (portions of Manatee and Sarasota counties). In some portions of Alachua and Columbia counties, the uppermost Hawthorn bed records as the thickest and highest-intensity gamma ray peak.

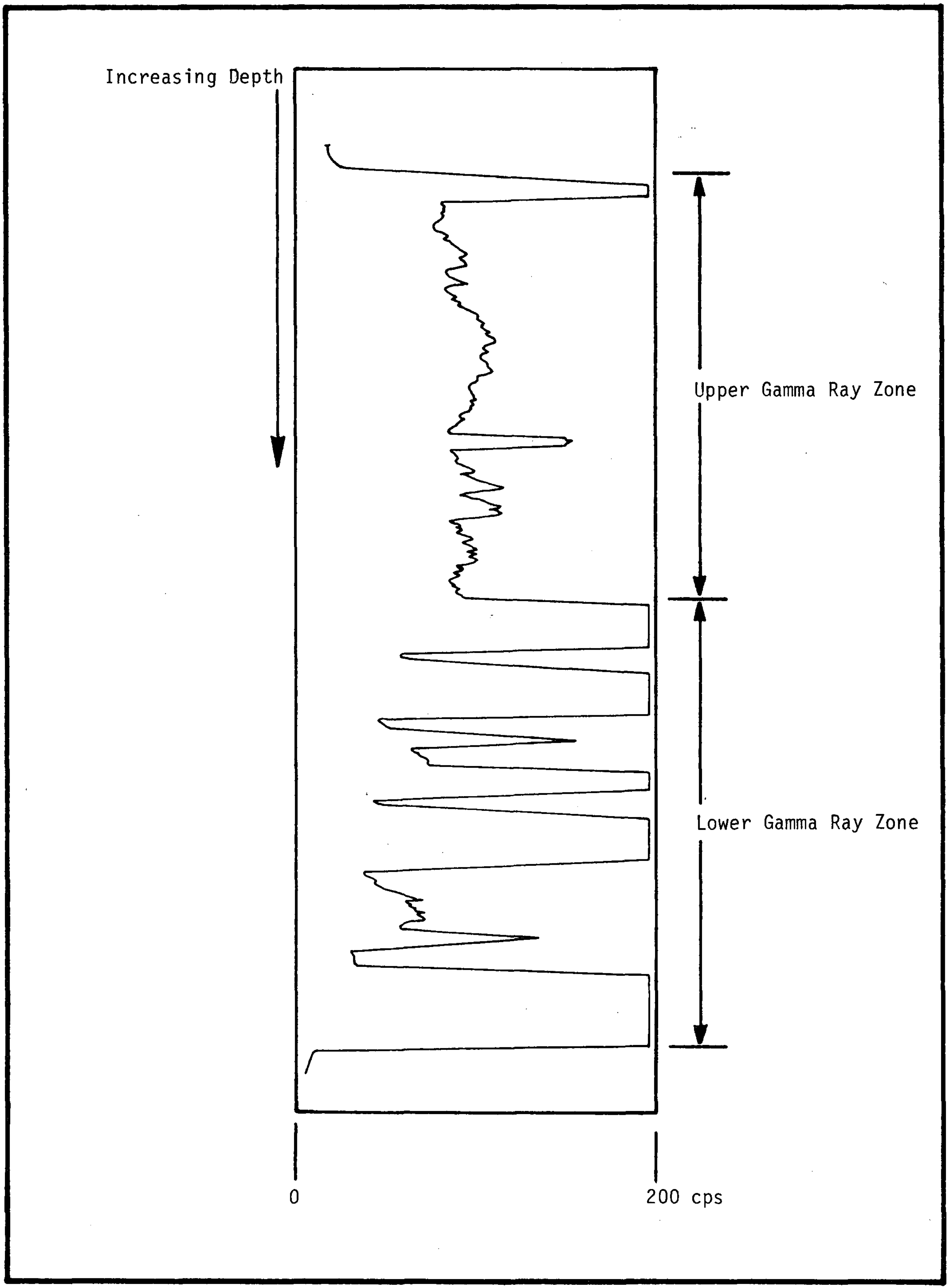

Figure 3. Hawthorn Formation Gamma Ray Log

In some areas along the southeast and southwest coasts of the state, the Hawthorn contains very little or no phosphate and the gamma ray log records relatively uniform medium-intensity characteristic of clay, silt and sand mixtures with interbedded impure carbonates. This occurs in the east part of Palm Beach County, the Florida Keys, the southeast portion of Lee County and on the barrier island south of Sebastian Inlet, Brevard County. Here, the logs show no high-intensity phosphate peaks within the formation, however the basal very-high-intensity peak is always present, albeit somewhat reduced in intensity (Appendix C-5 and C-6).

From Palm Beach County south on the east coast (Appendix C-5) and Collier County and south on the west coast, the Hawthorn can be divided into five gamma ray zones. These zones can be easily correlated into the Florida Keys (Appendix C-6). The zones in descending order are: 1.) an upper medium-intensity zone, 2.) a lower-intensity zone with a high intensity peak marking a regional unconformity (T. Scott, Florida Bureau of Geology, oral communication, 1983) at mid zone, 3.) a middle-Hawthorn medium-intensity zone which sometimes shows a series of distinct medium-high-intensity peaks, 4.) another lower-intensity zone and 5.) a lower zone consisting of the basal high-intensity peak with or without several medium-intensity peaks located immediately above the basal peak. The uppermost medium-intensity zone always records as an intensity conspicuously higher than that recorded by the surficial materials overlying the Hawthorn. The top of the formation in this area is generally 100 to 250 feet below land surface.

In central Brevard and south Flagler counties (immediately adjacent to areas in Volusia County and portions of north Brevard County where the formation is absent) the Hawthorn is relatively thin (5 to 50 feet). In this area, it is composed exclusively of the lower zone. Here, the zone is divided into one two, or occasionally three high-intensity phosphate peaks which are typical of basal Hawthorn Formation, but here make up the entire formation. In central Marion and south Lake counties, the formation is similarly recorded as a single, thin (less than 20 feet), very-high-intensity gamma ray peak. The Hawthorn is absent along the top of the Ocala Uplift.

In the central Florida region, central Lake County, Orange County and southwest Seminole County, the formation is composed almost exclusively of the lower zone, showing very high-intensity throughout. Here, the Hawthorn is relatively thick (generally over 100 feet). In the Type area of Alachua County, north-central Florida, the Hawthorn also consists of only the lower, high-intensity zone.

Southwest of the central Florida area, in western portions of Manatee, Sarasota, Charlotte and Lee counties, the lower high-intensity zone of the Hawthorn continues to dominate on gamma ray logs run in the formation. Here, the zone represents a thick sequence of competent (non-caving) dolomite clays and silts (Scott and MacGill, 1981) and carbonate beds containing very little unconsolidated material. The entire formation is recorded on gamma ray logs as closely-spaced, high-intensity, phosphate peaks (Appendix C-8). Wells in the eastern (inland) portions of these counties record both upper and lower zones well-developed on gamma ray logs (with the exception of southeast Lee County, as mentioned above).

Southeast of the central Florida area, in western St. Lucie and Martin counties and to the northeast in Duval and Nassau counties, where the formation is typically and fully developed, the upper medium-intensity gamma ray zone is relatively thicker and constitutes greater than one-half the total formation thickness on gamma ray logs. The log is characterized by widely-spaced, medium-intensity peaks and thick sections of low-medium to medium-intensity.

In Duval and Nassau counties, the top of the lower gamma ray zone is marked by a single, thin, high-intensity gamma ray peak which records a hard, brown, sandy, phosphatic, dolostone bed (Appendix C-1, C-2).

On electric logs, the formation is also divisible into two zones. The upper zone typically shows uniform medium- to low-resistivity characteristic of sand and silt or clay, sometimes in the form of hard, lithified, phosphatic sandstone cemented by calcium carbonate (Figure 4). This sandstone lithology can also be found in the section represented by the lower gamma ray zone in some areas. In interbedded and sometimes thick clayey sections, the resistivity dips to very low values. The lower zone of the formation records as very-low-resistivity characteristic of clay and mudstone, interspaced with occasional to many, broad, high-resistivity carbonate or sandstone peaks.

In portions of northeast Florida (Flagler, Putnam and St. Johns counties), the basal Hawthorn bed of very phosphatic, hard, sandy dolostone records on electric logs as a very-high-resistivity peak. In southwest coastal Florida (western Sarasota County), the lower Hawthorn appears on electric logs as medium-high-resistance peaks alternating with lower-resistance valleys, exhibiting a very rough signature and high relief on the log (Figure 5). This is characteristic of alternating carbonate and clay beds or high porosity carbonate beds. The upper portion (zone) of the formation here also shows the uniform medium- to medium-high-resistance characteristic of sand and silt beds.

The Hawthorn Formation is absent in portions of north Seminole, north Brevard, south Putnam, south Flagler, south Columbia, west Alachua, west Marion, north Polk and most of Volusia and Taylor counties. It is also absent in Pasco, Hernando, Sumter, Citrus, Levy, Dixie, Gilchrist and Lafayette counties and portions of Suwannee and Madison counties (Sweeney and Windham, 1979, and Vernon, 1951).

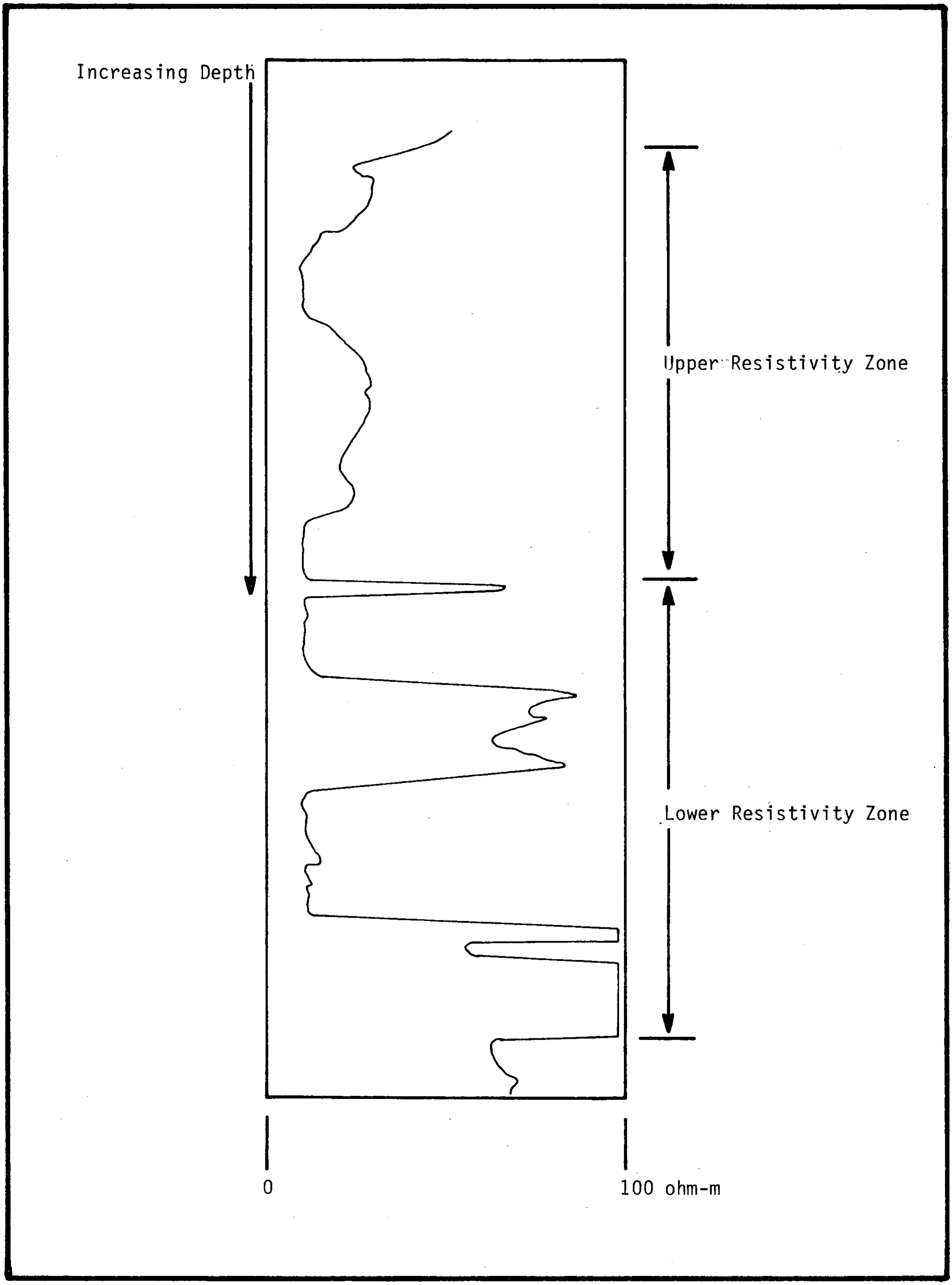

Figure 4. Hawthorn Formation Resistivity Log

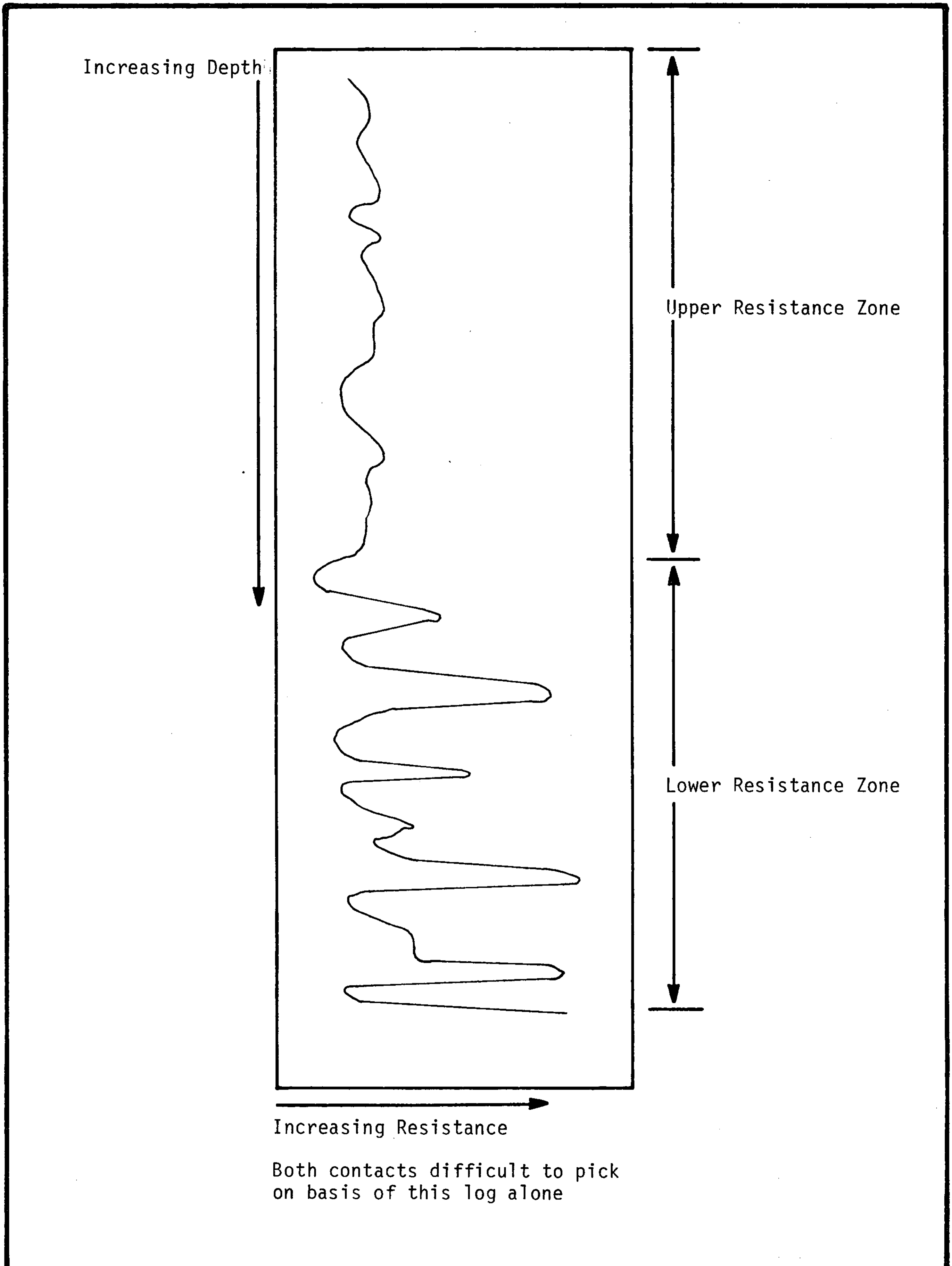

Figure 5. Hawthorn Formation Resistance Log, Southwest Florida

TAMPA LIMESTONE

The Tampa Limestone consists of arenaceous and argillaceous, slightly phosphatic, occasionally hard and well-lithified, brown to white limestone and dolostone, sometimes interbedded with thin, green to variously colored, clay beds. It can also contain chert. Phosphate content is conspicuously less than that of the overlying Hawthorn Formation. The unconformity which sometimes separates the two formations is shown on gamma ray logs as a high-intensity peak marking the base of the Hawthorn.

Typically, the contact between the two formations is picked on gamma ray logs by the occurance of a definite reduction in intensity to a continuous medium- to low-intensity in the upper zone of the Tampa (Figure 6). This lower intensity continues downward for approximately one-third to one-half of the total formation thickness. This section is sometimes cased off with a liner in deep wells, probably because of the presence of soft carbonate or clastic beds. The lower one-half of the formation is characterized by showing continuous low-medium-intensity on gamma ray logs and low, rounded, gamma ray peaks, with occasional high-intensity phosphate peaks. The unconformity at the base of the formation is typically marked by a medium- to high-intensity phosphate peak. This peak is usually the highest-intensity recorded in the formation.

In some wells, the entire formation records as a continuous low-medium-intensity gamma ray trace with low, rounded closely-spaced peaks, often lacking the basal high-intensity peak (Figure 7).

The Tampa Limestone is typically developed in southwest Florida, where it attains a thickness of 250 to 300 feet (Manatee, Sarasota and Charlotte counties, Appendix C-7, C-8). It also exists in a much thinner and less characteristic form along the southeast coast, south of St. Lucie County. Here it records on gamma ray logs as a relatively thin (70 feet) zone of medium-

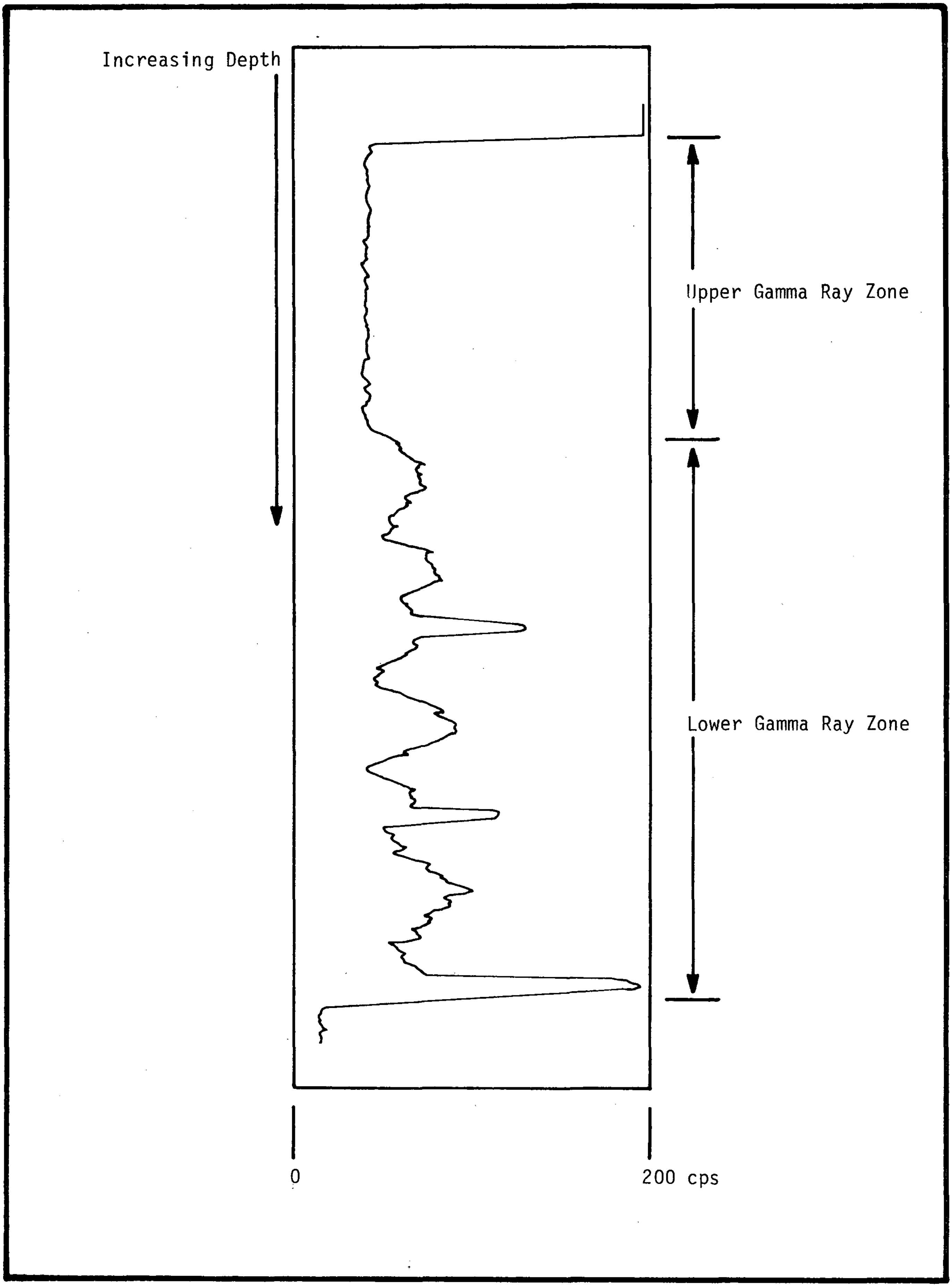

Figure 6. Tampa Limestone Gamma Ray Log

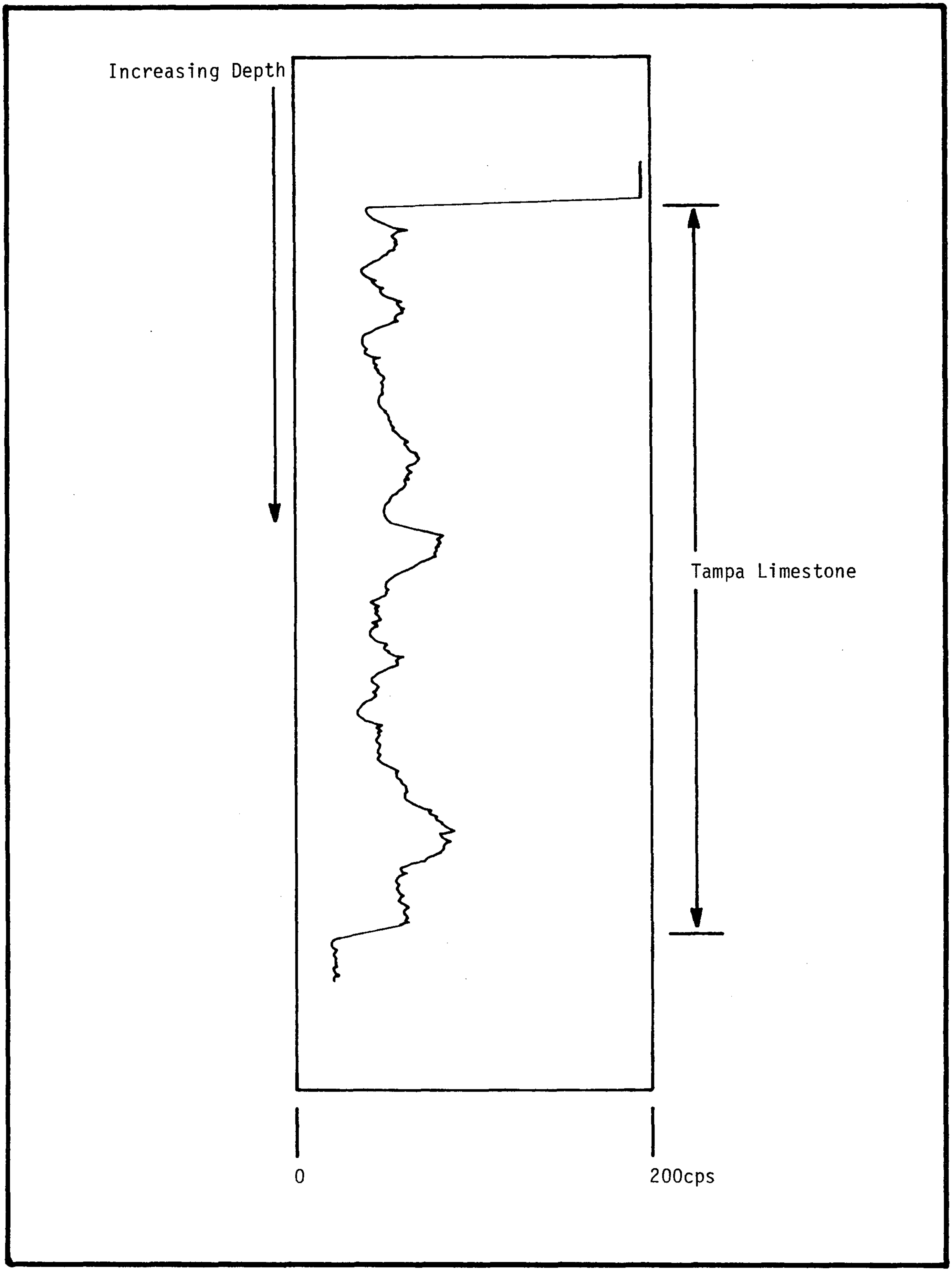

Figure 7. Second Tampa Limestone Gamma Ray Log

intensity peaks (east Palm Beach County, Appendix C-5), although this material might not be referable to the formation (T. Scott, Florida Bureau of Geology, personal communication, 1984). In the Florida Keys, development of the formation most closely resembles the thick and complete section found on the southwest coast, being about 200 feet thick: the formation is recorded on gamma ray logs as a series of medium, rounded, closely-spaced peaks, lacking high-intensity peaks (Appendix C-6) and is usually divisible in to the two typical gamma ray zones.

A very thin section also occurs in some portions of northwest peninsular Florida. In northwest Hamilton County, for example, the formation is represented by a dolostone bed that is twenty to thirty feet thick that contains no phosphate: Gamma ray intensity is uniform and medium-low (distinctly lower intensity than recorded in the Hawthorn), and lacks phosphate peaks. Again, this material might not be referable to Tampa Limestone (T. Scott, Florida Bureau of Geology, personal communication, 1984).

In some widely spaced wells in Volusia and north Brevard counties in northeast Florida, a low-medium-intensity gamma ray peak occurs between the overlying clastic-and-coquina section and the underlying Ocala Limestone. This thin, low-medium-intensity peak records a three to fifteen feet thick, sandy, slightly- to non-phosphatic limestone or dolostone bed that could be Tampa Limestone (H. K. Brooks, Earth Resources Consultants, oral communication, 1980). The characteristic peak is found sporadically throughout Volusia and north Brevard counties where the Hawthorn Formation is absent. However, this peak could represent a very thin outlier of Hawthorn Formation. Not enough lithologic or paleontologic information is available from the bed to definitely assign it to either formation.

On electric logs in southwest Florida (Sarasota, Manatee and Charlotte counties), the Tampa Limestone records as relatively high-resistance peaks (characteristic of hard low-porosity carbonates) separated by lower-resistance valleys (characteristic of clay beds), as shown on Figure 8. The resistance trace within the Tampa is characteristically less rough and exhibits less relief on the logs than the resistance trace typically recorded within the Hawthorn Formation because the Tampa is generally characterized by thinner and less numerous clay beds (very low resistance) between the more numerous higher-resistance carbonate beds.

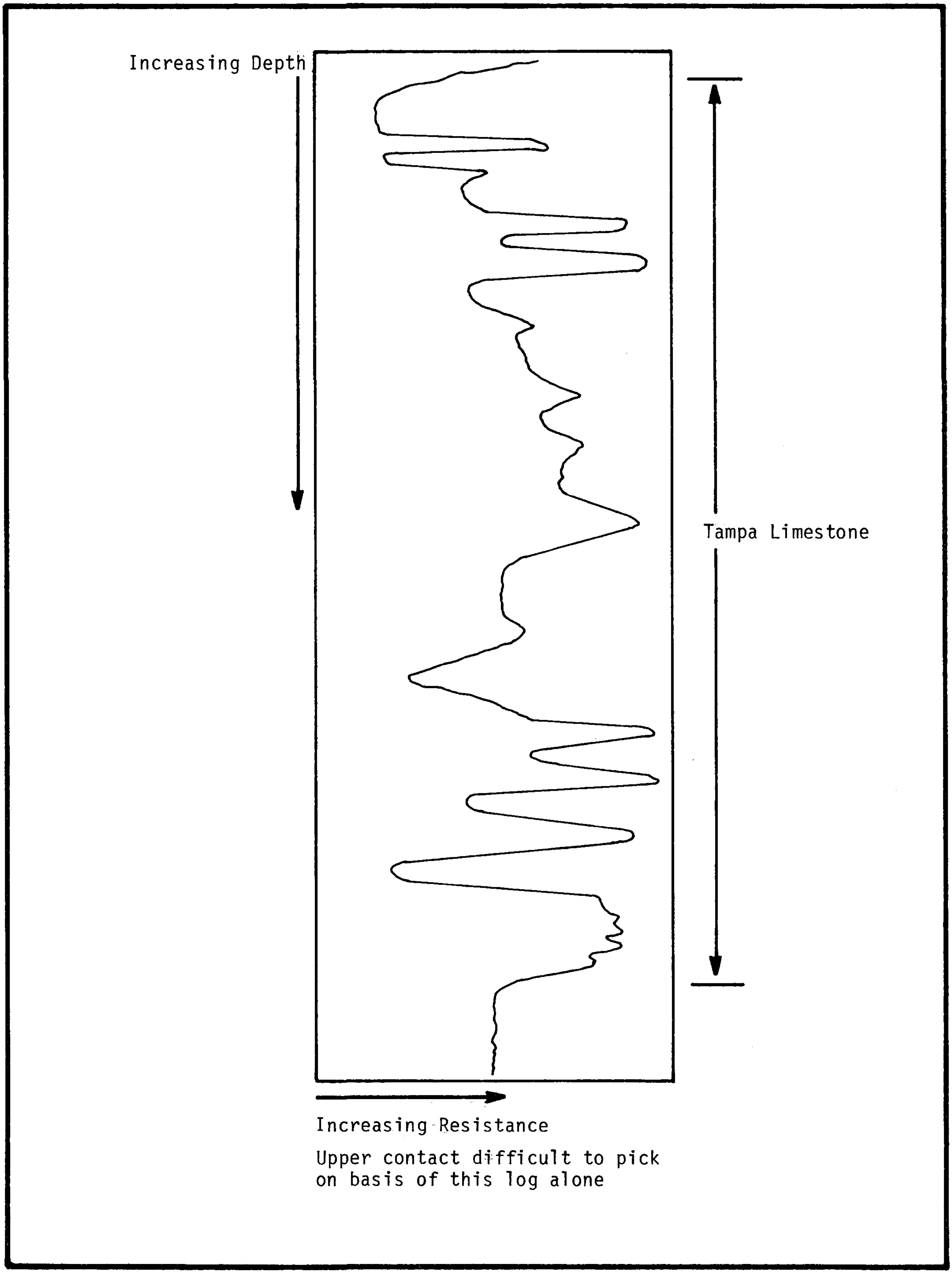

Figure 8. Tampa Limestone Resistance Log

SUWANNEE LIMESTONE

The Suwannee Limestone consists of white to tan, pure to slightly argillaceous and arenaceous, coquinoid (coarse to fine biological debris) to chalky limestone, with some dolostone and dolomitic limestone present. Generally, the formation contains no phosphatic material however traces of silt-size phosphate have been reported from southeast Florida (Brown and Reese, 1979).

Where typically developed and relatively thick (southwest Florida), the formation is as much as 300 to 400 feet in thickness and is divisible into two distinct zones on the basis of gamma ray logs (Figure 9). The upper zone (which is usually the thinner of the two) is characterized by an even, relatively low-intensity trace but is usually not as low in intensity as is the trace in the Ocala Limestone as discussed in the next section. The lower (and usually thicker) zone is recorded as low- to low-medium-intensity, relatively thick, gamma ray peaks probably indicating hard dolostone beds.

Generally, gamma ray intensities within the Suwannee are markedly less than the intensities characteristic of the Tampa. The upper Suwannee gamma ray zone is easily distinguishable from the basal Tampa zone, even when the contact is not an obvious unconformity that records as a medium- to high-intensity gamma ray peak.

In southwest Florida (Sarasota and Manatee counties), the formation is typically developed and attains 300 feet in thickness (Appendix C-8). In Charlotte County, it is much thicker and most of the formation consists of the basal, uneven intensity gamma ray zone, with the low, thick gamma ray peaks reaching medium-intensity (Appendix C-7). In all three counties, the base of the Suwannee is usually recorded on gamma ray logs as a low- to medium-intensity peak declining sharply into the very-low-intensity characteristic of the Ocala.

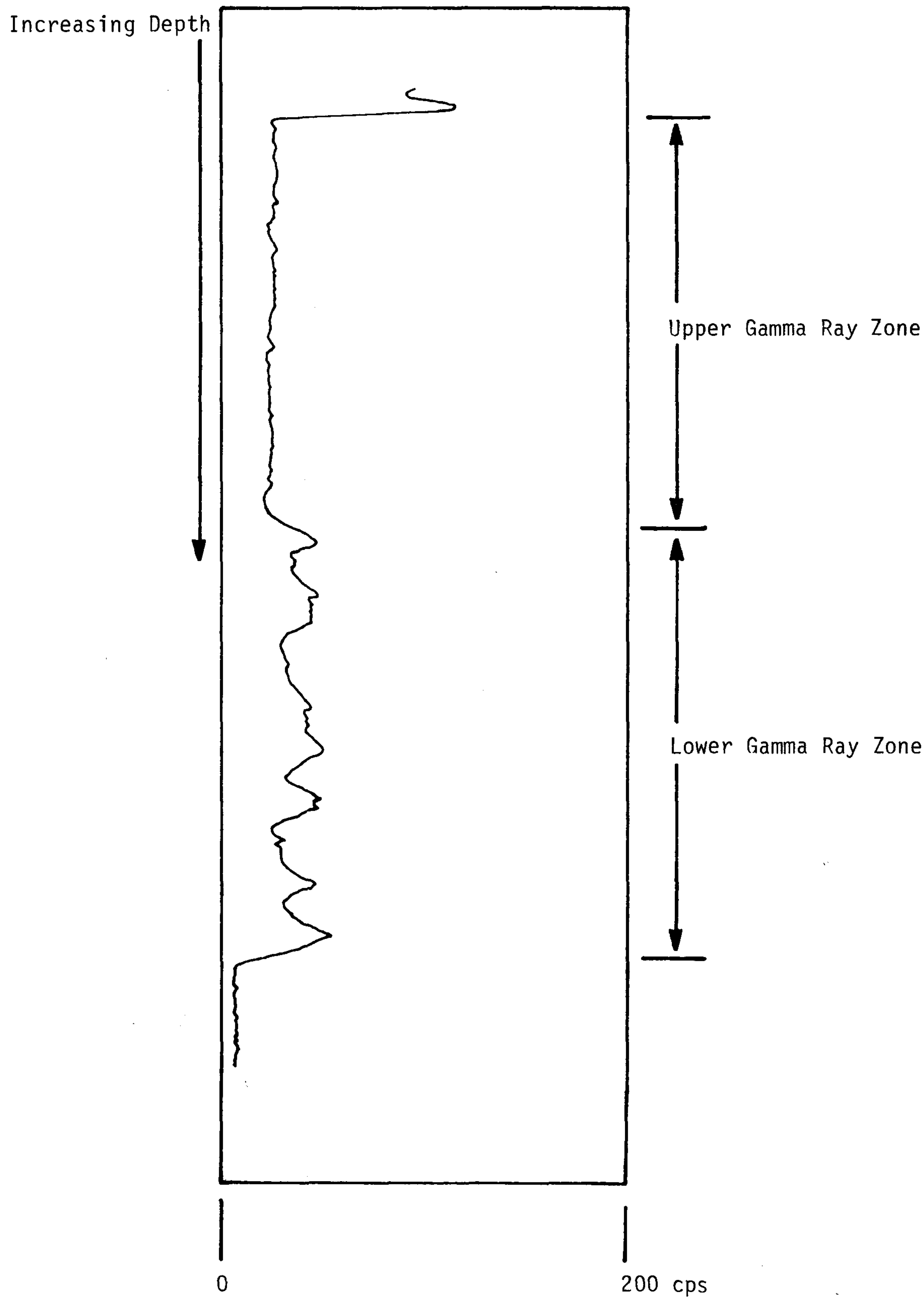

Figure 9. Suwannee Limestone Gamma Ray Log

In a few wells, the contact is apparently unconformable, showing a medium-intensity gamma ray peak that very sharply contrasts with the low-intensity in the Ocala. Thus, logs from some wells show well-defined gamma ray peaks at the bases of the Hawthorn Formation, the Tampa Limestone and the Suwannee Limestone.

In southeast Florida (west Martin and east Palm Beach counties, Appendix C-5), the formation is very thin (20 to 50 feet) where present, and records as a low- to medium-low-intensity, rather uniform gamma ray trace, with occasional medium-intensity peaks. Here, it is usually positioned between the very thin, medium-intensity gamma ray peaks denoting the thin Tampa (?) Limestone and the also rather thin (where present) very-low-intensity gamma ray trace of the Ocala Limestone. In portions of Indian River, St. Lucie, Okeechobee, Osceola and south Brevard counties, the formation attains a thickness of over 180 feet. Here portions of the Suwannee are apparently Early Miocene in age (T. Scott, Florida Bureau of Geology, personal communication, 1984). In most of this area, the Suwannee can be divided into three gamma ray and electric zones (Figure 10). The upper and basal zones are characterized by low-medium- to medium-intensity (less intensity than is recorded in the Hawthorn Formation) gamma ray trace and low-resistivity (higher than typical in the Hawthorn). These portions of the logs record a chalky, argillaceous, white limestone which contains little, if any, porosity. The middle zone is recorded as low-intensity on gamma ray logs and shows, typically, two high-resistivity peaks on electric logs with medium- (limestone) resistivity overall. This array of characteristics marks a hard, tan, recrystallized, biological-debris limestone possessing medium to high moldic porosity. Most water production in wells in this area originates in this middle zone.

In this Indian River County area, the base of the Suwannee (top of the Ocala) is marked by a sharp decrease from the medium- or medium-low-intensity

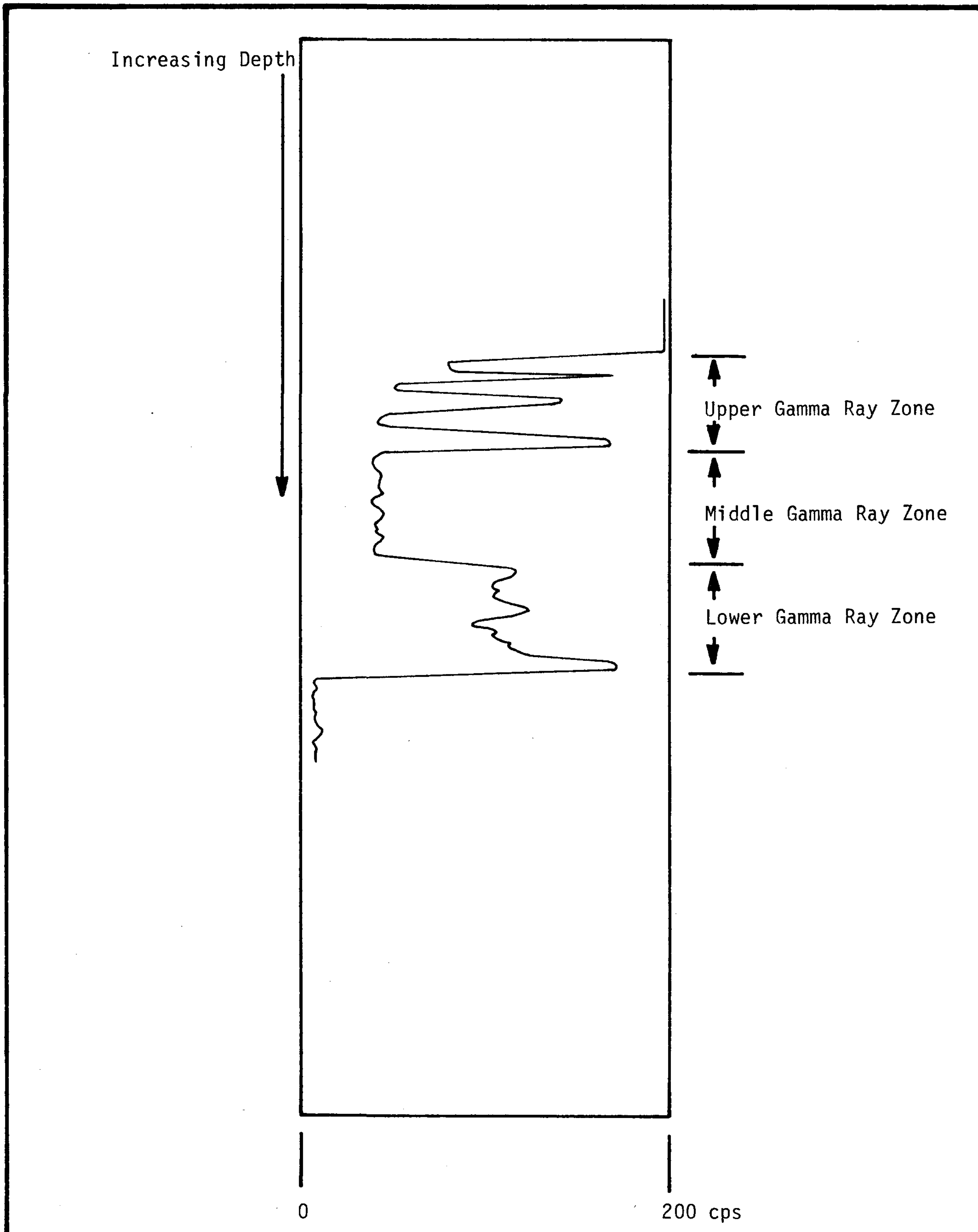

Figure 10. Suwannee Limestone Gamma Ray Log, Southeast Florida

gamma ray trace characteristic of the basal zone of the Suwannee into a very pure, hard and recrystallized limestone bed at the top of the Ocala. This limestone bed is recorded as very low gamma ray intensity (lowest in the entire limestone section) and as a very-high-resistivity peak. In southeast Indian River and northeast St. Lucie counties, the basal gamma ray zone of the Suwannee is apparently missing and the contact with the Ocala is marked by a low-intensity, broad, gamma ray peak, the base of which descends into the still-lower-intensity gamma ray trace characteristic of the very pure limestone bed at the top of the Ocala.

The Suwannee Limestone in the area of Indian River, St. Lucie, Brevard, Osceola and Okeechobee counties apparently reaches its thickest extent in two wells on the barrier island directly east and southeast of Vero Beach, Indian River County, where 170 to 180 feet of Suwannee is found. Both gamma ray zones of the typical southwest coastal Florida Suwannee are well-developed and clearly defined. The gamma ray pattern in the Oligocene limestone recorded in this well (and in four other wells nearby) are identical with the gamma ray trace obtained from wells in southwest Florida in the section well-established and generally acknowledged as Suwannee Limestone. This concurrance forms the basis of the present author's assignment of the Oligocene limestone found in this area to the Suwannee Limestone. The base of the formation in this well is marked by a sharp drop from a uniform, low-medium-intensity series of gamma ray peaks into the very-low-intensity of the Ocala Limestone gamma ray trace. This well is located in a rather deep anomaly in which all formations are very thick and complete, and the top of the Floridan aquifer is anomalously deep (approximately 600 feet).

The Suwannee is also recorded in wells in northwest peninsular Florida: its Type Section is described from exposures along the Suwannee River in this area. In the subsurface, the Suwannee appears to be no more than 100 feet in thickness (central Taylor County), and to consist of the lower zone only on gamma ray logs. Gamma ray intensity is very-low to low-medium and is generally very uniform, showing only occasional sharp peaks (especially at its base). In northwest Hamilton County, very-low-intensity (Ocala-like) portions alternate with low-intensity, broad, rounded peaks. In Madison County, the Suwannee Limestone is recorded on gamma ray logs as a very low (Ocala-like) even intensity trace with a sharp low-medium-intensity peak at its base. At the base of the Suwannee in this area, the gamma ray trace sometimes slowly declines in intensity into the very-low-intensity trace of the Ocala Limestone, lacking the more abrupt contact characteristic elsewhere.

The Suwannee Limestone is questionably present in a few wells drilled in the deepest portion of the Jacksonville (Duval County) basin. Up to 20 feet of Suwannee records as medium-low-intensity on gamma ray logs. This characteristic signature is positioned between the basal Hawthorn high-intensity peak and the very-low-intensity Ocala gamma ray trace. It records white, sandy, slightly phosphatic calcirudite. On the basis of the presence of silica sand and phosphate, this thin bed could also be Tampa Limestone.

On electric logs in southwest Florida (Manatee, Sarasota and Charlotte counties), the Suwannee is characterized by an almost-smooth resistance trace with very low relief shown on the log (Figure 11). The upper contact with the Tampa is well-defined and consists of an abrupt change from high-relief peaks and valleys into the much-smoother Suwannee trace.

Elsewhere, typically the upper gamma ray zone exhibits low, smooth resistivity curves (but with resistivity values higher than those typical in clay) and the lower gamma ray zone shows higher uneven resistivity with two or more broad, medium-resistivity peaks (typical of well-lithified and

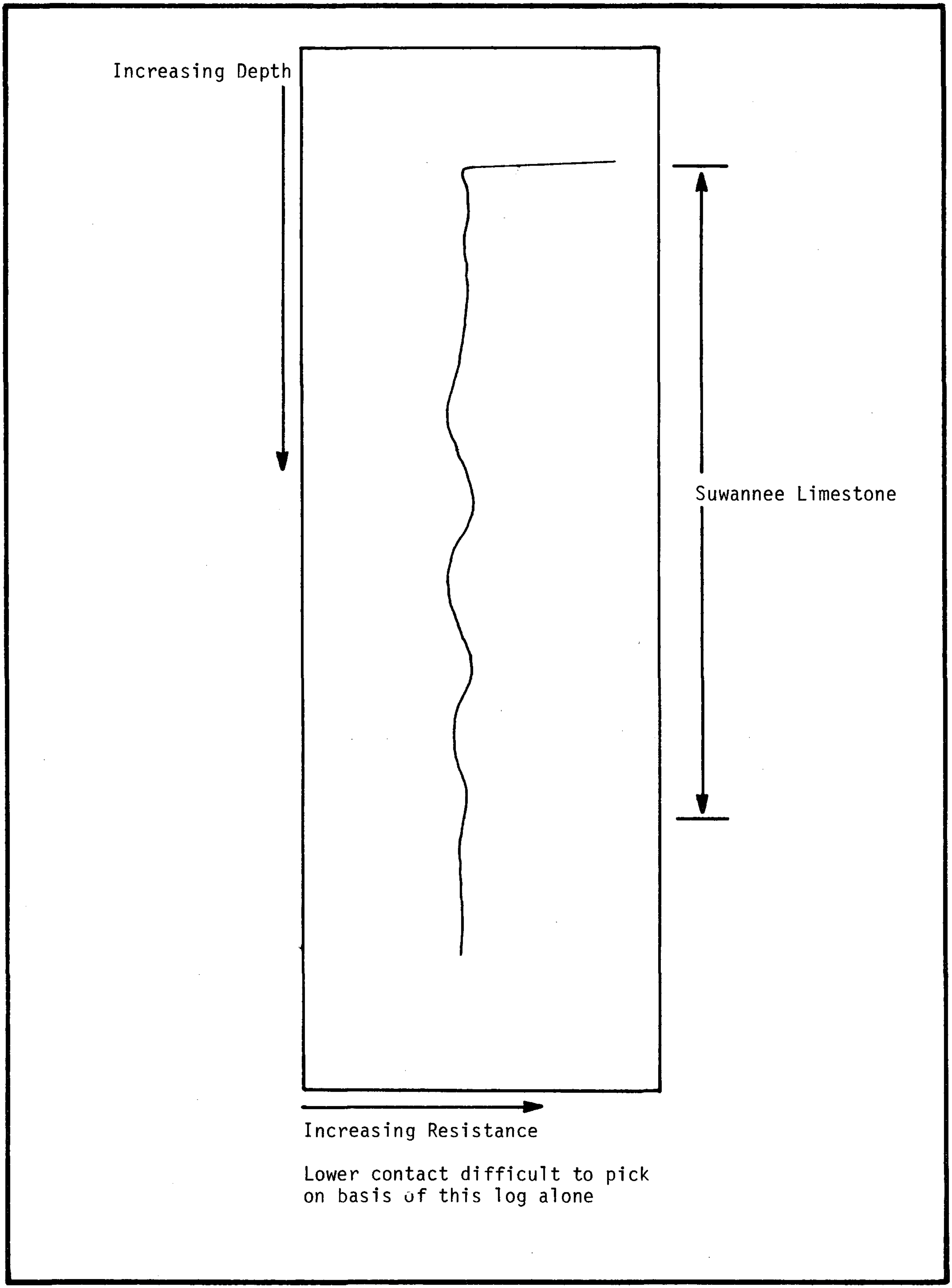

Figure 11. Suwannee Limestone Resistance Log, Southwest Florida

recrystallized carbonates). In St. Lucie, Indian River, Okeechobee, Osceola and south Brevard counties, the base of the Suwannee is well-marked and is picked at the top of the very-high-resistivity peak associated with the uppermost, recrystallized very pure limestone bed of the Ocala (Appendix C-4). The extent of the Suwannee in the study area is shown in Figure 1: the Suwannee is present to the south of line S_1 and to the northwest of line S_2 (Bishop, 1956; Klein, et al., 1964; Knapp, 1979; Stewart 1966; Vernon, 1951; Yon and Hendry, 1972).

OCALA LIMESTONE

The Ocala Limestone consists of white to light tan, hard and recrystallized to very soft and friable, foraminiferal, coquinoid limestone, with some intermixed echinoid, bryozoan, and other biological debris. It is typically the purest calcium carbonate limestone penetrated in water wells and hence, shows the lowest gamma ray intensity in the section. The formation can be divided into two zones on the basis of gamma ray logs: an upper zone of very pure carbonates showing very low gamma ray intensity and a lower zone recording slightly higher-intensity (Figure 12). The lower zone sometimes contains dolomitic limestone or, in some areas, thin, interbedded dolostone, a "lower Ocala dolostone zone" (Sarasota and Manatee counties, southwest Florida). This paper agrees with Cole and Applin (1964) wherein the basal "Inglis Formation" of the "Ocala Group" of Puri (1957) is included in the Avon Park Limestone. Thus, the Ocala Limestone of present usage is approximately divided into an upper member (gamma ray log zone): the "Crystal River Limestone" of Puri (1957) and a lower member (gamma ray log zone): the "Williston Limestone" of Puri (1957).

The upper gamma ray zone occurs north of a line extending west-northwest and east-southeast through north Putnam and south St. Johns counties on the east coast of Florida and south of central Brevard County, although the two gamma ray zones are often difficult to distinguish in this southern east coast area. Some wells in south Brevard County on the barrier island and in southeastern to southcentral Indian River County show a well-differentiated Ocala on gamma ray logs.

The formation thins south of St. Lucie County on the east coast to as little as 30 feet in a well in southwest Martin County. In a well near Jupiter, northeast Palm Beach County, about 80 feet of Ocala is recorded as a very low and even intensity gamma ray trace (Appendix C-5). In both of these wells,

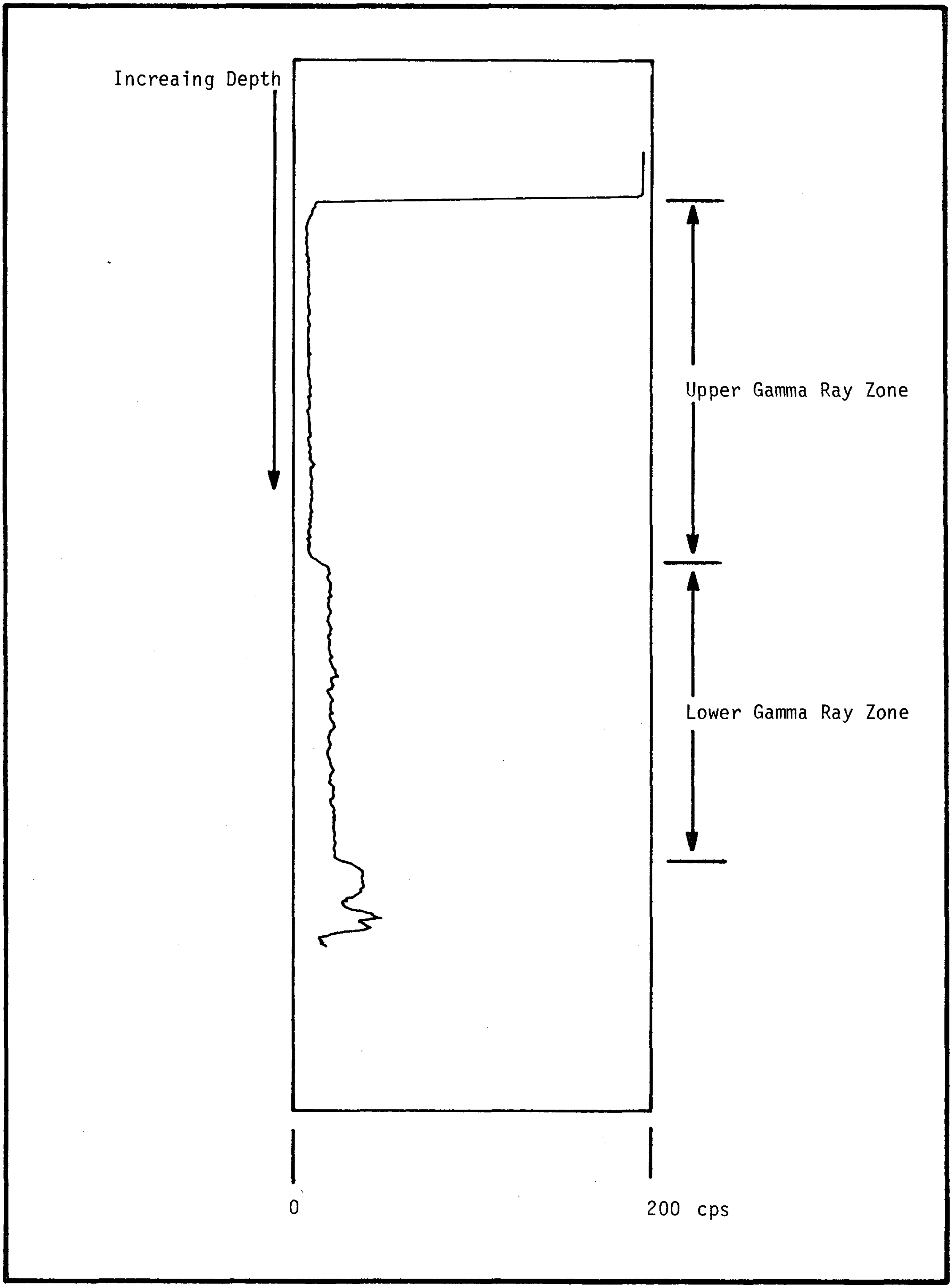

Figure 12. Ocala Limestone Gamma Ray Log

differentiation into upper and lower gamma ray zones is not possible.

Elsewhere, the formation is recorded as a less-uniform gamma ray trace, with broad, very-low-intensity peaks spaced between zones of a very uniform, very-low-intensity trace. This is typical in some areas of Indian River, St. Lucie and south Brevard counties and in portions of northwest peninsular Florida, specifically, Taylor and Columbia counties.

In the interior portion of the state, the formation sometimes cannot be divided into upper and lower gamma ray zones. It nevertheless characteristically shows the lowest and most uniform gamma ray intensity in the carbonate section of logged wells.

In Sarasota and Manatee counties (southwest Florida), the formation is recorded as a very low gamma ray intensity trace only in its middle section (Appendix C-8). Its basal and upper one-third portions characteristically are recorded as broad, very slowly increasing and decreasing curves (relatively low-intensity). The formation equals or exceeds 300 feet in thickness in southwest Florida.

In the Jacksonville basin (Duval and Nassau counties), the Ocala thickens to approximately 250 feet and shows an extremely well developed two-gamma-ray zone differentiation (Appendix C-1, C-2). Typically, the upper zone is thickest, comprising about two-thirds of the formation.

In portions of Alachua and Columbia counties, logs from several wells show the presence of a 3 to 10 foot thick dolostone bed located stratigraphically in the upper portion of the Ocala Limestone. The bed is recorded on gamma ray logs as a very characteristic low-medium-intensity peak positioned between a typical very-low-intensity (pure calcium carbonate limestone) Ocala gamma ray trace. This bed has been referred to informally as the "Steinhatchee dolomite bed" (Puri, et al., 1967).

On electric logs, the Ocala usually records as a series of relatively-high- to very-high-resistivity peaks interspaced with portions of resistivity trace showing flat, medium-resistivity (northeast Florida to east-central Florida). This is illustrated on Figure 13. Two to three peaks are typical, but as many as six to eight are recorded where thick Ocala sections occur. The stratigraphically lowest high-resistivity peak is invariably present on electric logs. The contact with the Avon Park Limestone occurs at or near the base of this usually thick (10 feet) very-well-defined peak. In east-central to southeast Florida (south of Brevard County) and in some wells in central Florida (Marion County), the contact becomes slightly deeper stratigraphically, separated from this lower high-resistivity peak by as much as 30 to 40 feet. This interval of carbonate beds records as straight-line, very uniform resistivity (typical limestone) trace. In southeast Florida (Indian River and St. Lucie counties), the uppermost bed in the Ocala consists of very pure, recrystallized, very-high-resistivity limestone, which is recorded on gamma ray logs as very-low-intensity and on electric logs as very-high-resistivity. In portions of north Putnam and north St. Johns counties and to the north along the east coast of Florida into Duval County, the typical Ocala resistivity trace characterized by high-resistivity peaks is confined to the upper portion of the Ocala. Here, a lower-Ocala resistivity zone occurs and is characterized by broad, low-resistivity peaks separated by straight-line (limestone) resistivity trace. The two resistivity log zones and the two gamma ray log zones in northeast Florida in the Ocala Limestone section are not correlative.

In southwest Florida (Manatee and Sarasota counties), the Ocala can also be divided into two resistance zones (Figure 14). The upper zone is recorded as almost-flat, zero-relief trace showing no peaks or valleys and the lower zone is recorded as very-high- (dolostone) resistance peaks separated by rather thin

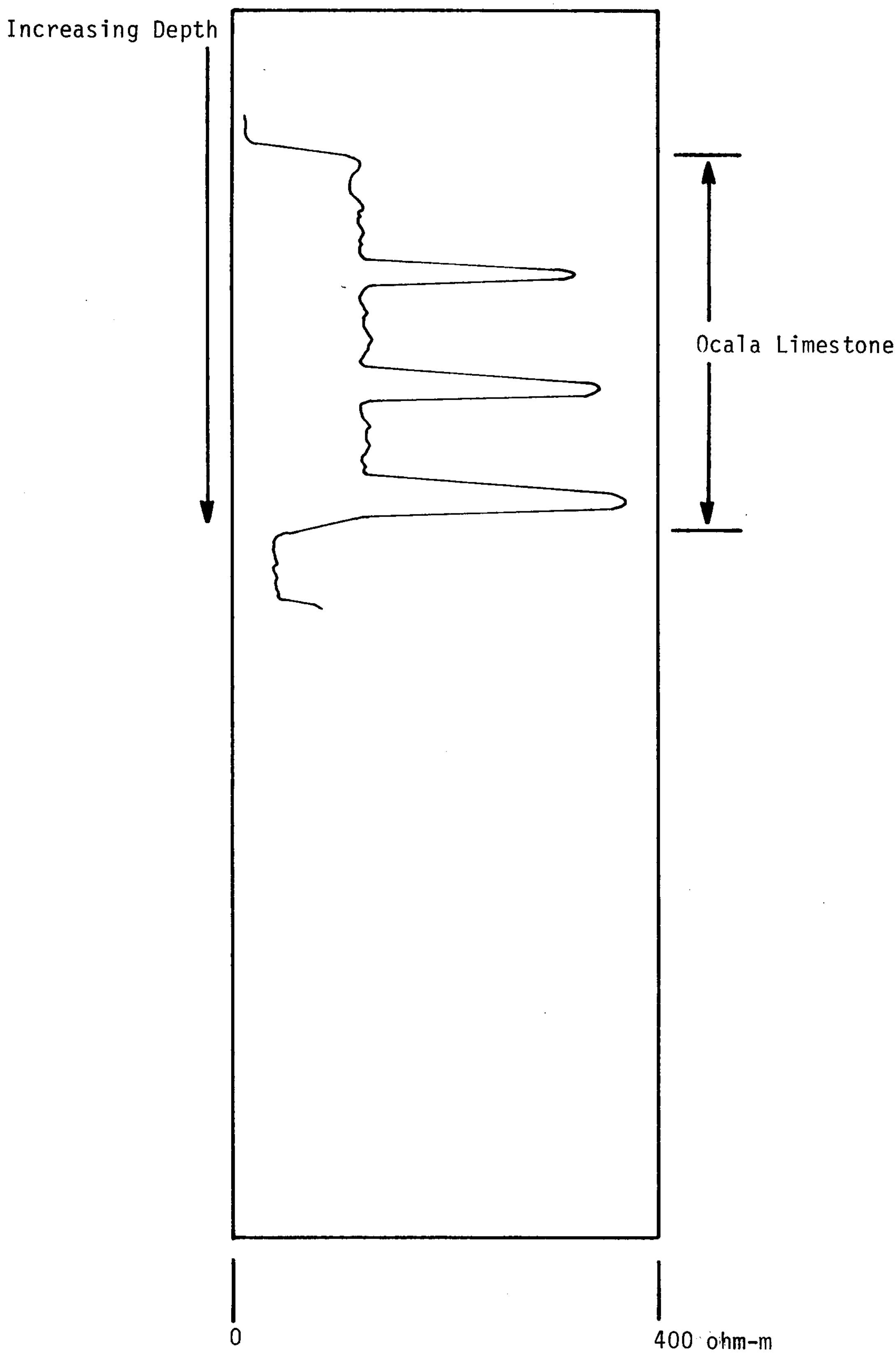

Figure 13. Ocala Limestone Resistivity Log

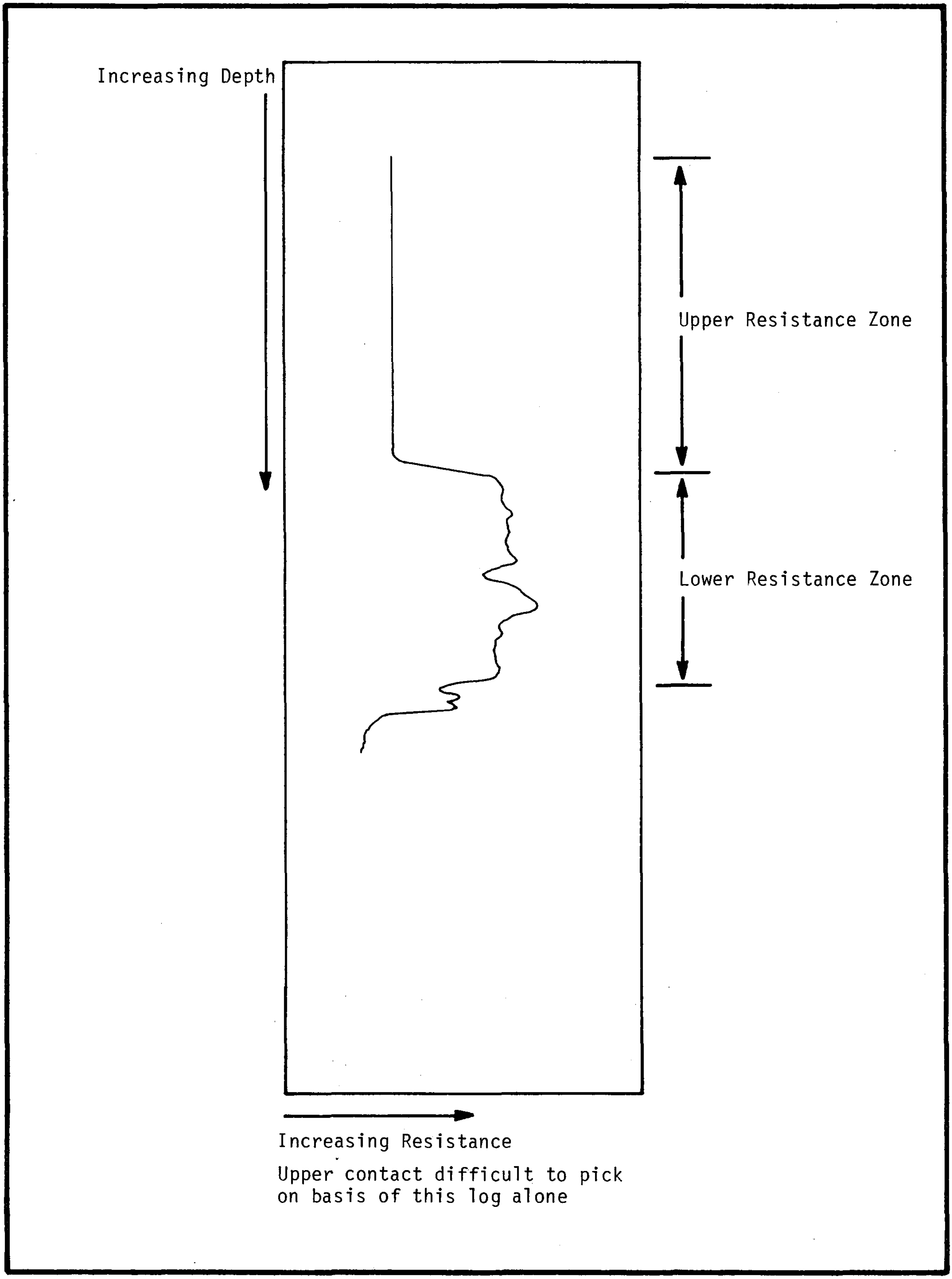

Figure 14. Ocala Limestone Resistance Log, Southwest Florida

(2 feet) to medium-thin (10 feet) resistance valleys. The lower zone consists of less than or equal to one-half the total formation thickness. Thus, in southwest Florida, the electric resistance trace becomes progressively smoother and shows less relief on the log downward with each successive formation, i.e., the upper Ocala shows less relief on resistance logs than does the Suwannee, which shows less than the Tampa, etc.

The Ocala Limestone is absent in most of Dade and Broward counties (R. Sproul, Ch_2M Hill, oral communication, 1982) and in the Florida Keys (Monroe County). The formation is also absent in portions of southwest Volusia County (Deland and DeBary) and west-central (southwest of Leesburg) and south (Clermont) Lake County, in the south central part of Orange County and northwest part of Osceola County, as well as in the Avon Park outcrop area of Levy, Citrus and southwest Marion counties (Puri and Vernon, 1964).

AVON PARK LIMESTONE

The Avon Park Limestone consists of interbedded dolostone, dolomitic limestone and limestone, ranging from a foraminiferal calcarenitic limestone, weakly cemented and partially dolomitic, to a very fine-grained chalky dolomitic limestone, to a pure dolostone (completely recrystallized, hard, brown dolostone composed of minute dolomite rhombs). Peat and carbonaceous films are common, especially in the upper part of the formation. The peat is in the form of discrete, relatively thick (5 feet) beds interbedded with carbonates (predominantly dolostone), very thin carbon-film plant fossils scattered in dolostone, and scattered coarse- to very-fine-sand-size flecks of peat within dolostone beds.

At the top, the contact with the overlying Ocala is usually marked by an unconformity characterized by peat and/or clay beds, or peaty dolostone or limestone beds. This impure carbonate zone is sometimes 50 feet or more in thickness as shown on the logs.

Statewide, the Avon Park is divisible into two distinct, correlative gamma ray and electric log zones (Figures 15 and 16).

The upper zone is marked on gamma ray logs by a definite and well-marked increase in intensity from the very-low-intensity of the Ocala. In Marion and Lake counties, this intensity-increase is very prominant and thick and medium- to high-intensity gamma ray peaks are characteristic. Elsewhere this intensity increase is usually continued uniformly throughout the entire upper zone, or can be in the form of discrete low-medium-intensity peaks denoting dolostone or dolomitic limestone and carbon films interbedded with limestone. In some areas, only a single sharp peak occurs at the top of the Avon Park, marking the contact (Martin and Palm Beach counties, southeast Florida, Appendix C-5, and Sarasota and Manatee counties, southwest Florida, Appendix C-8). This signature also

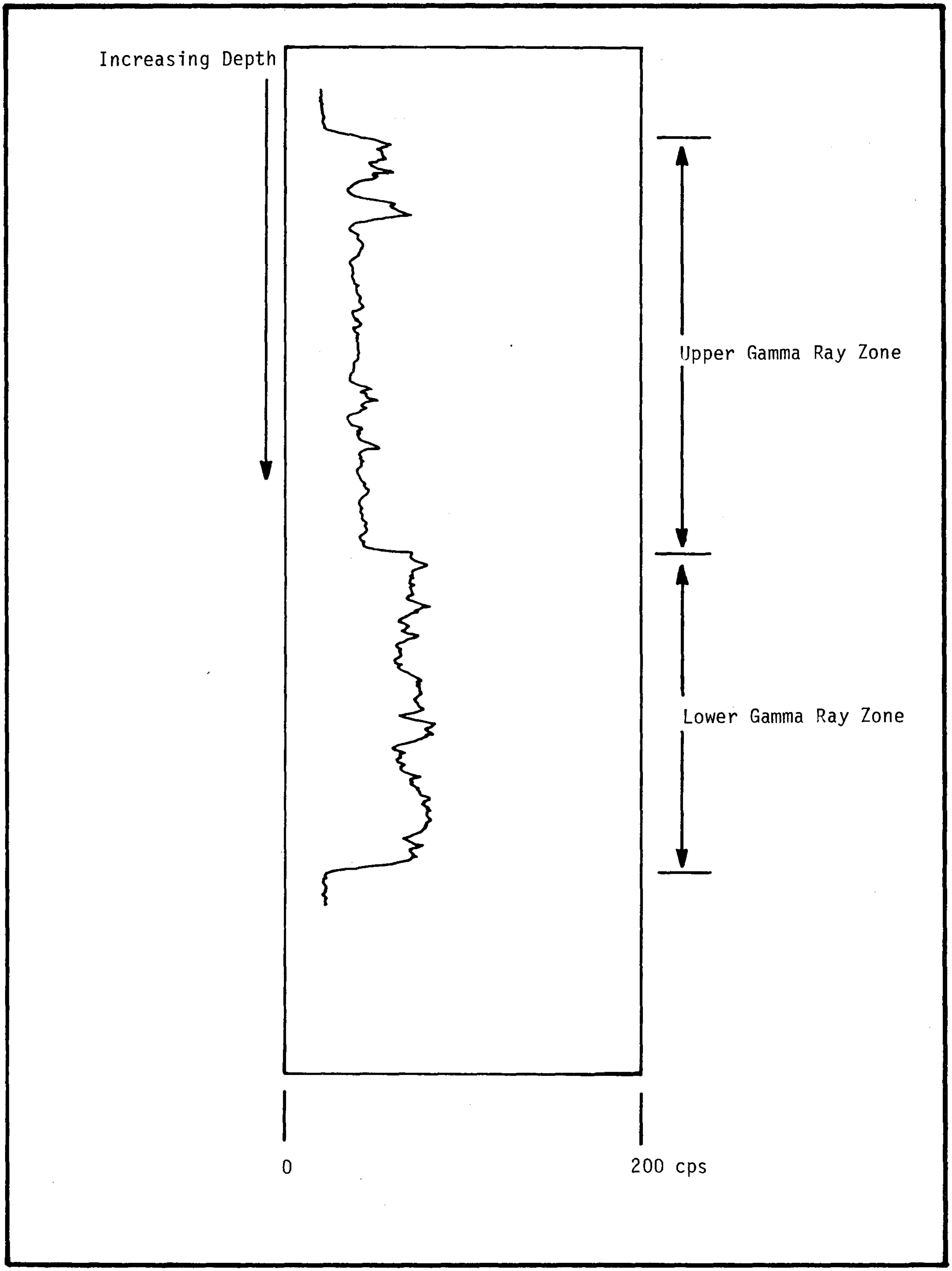

Figure 15. Avon Park Limestone Gamma Ray Log

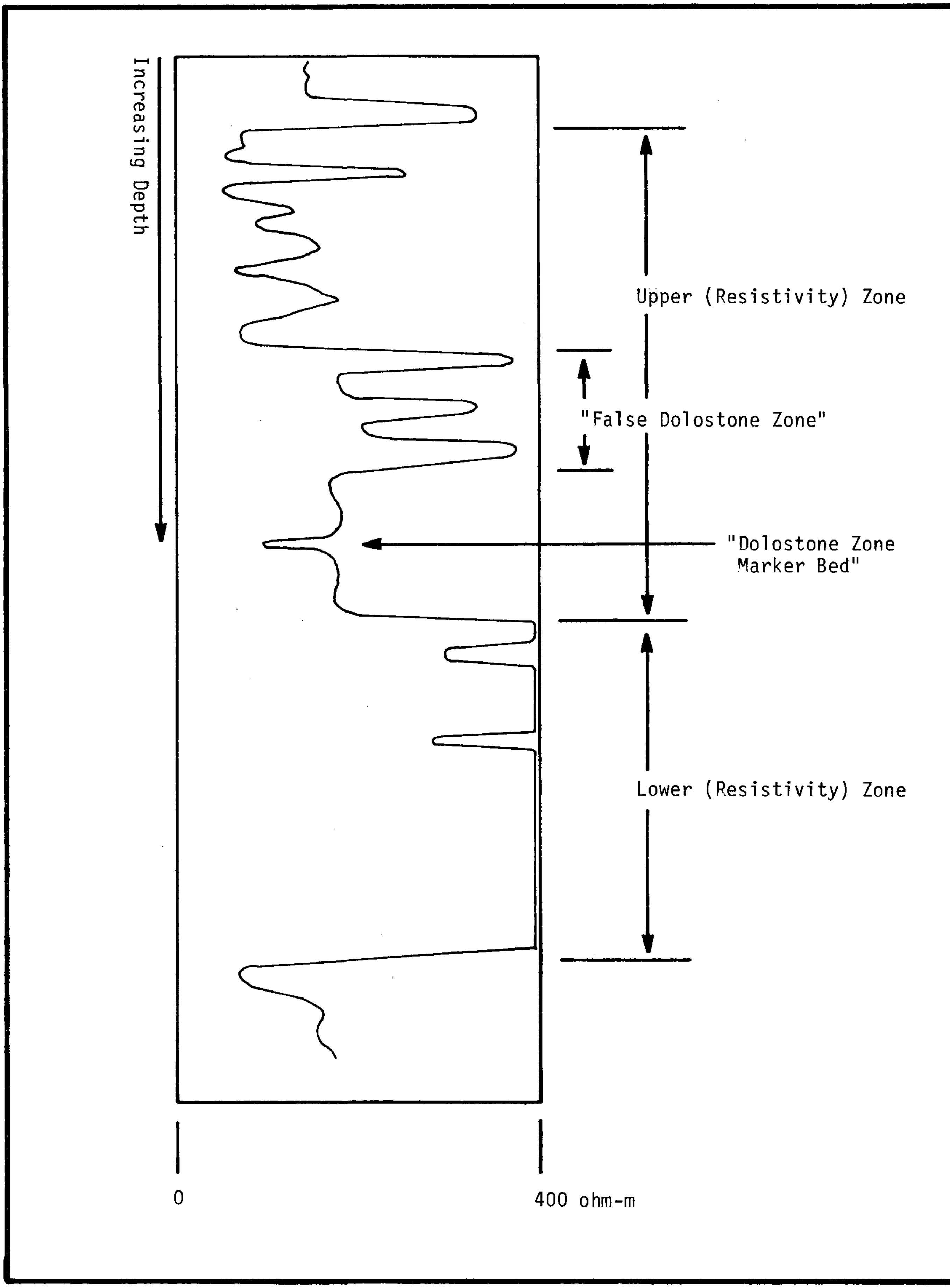

Figure 16. Avon Park Limestone Resistivity Log

occurs on logs from wells elsewhere in peninsular Florida, i.e., several wells north of Palatka, Putnam County. Characteristically however, the upper portion of the upper zone is recorded on gamma ray logs as a series of low- to medium-intensity gamma ray peaks continuing downward to approximately one-half of the upper zone thickness. The remainder of the upper zone thickness is recorded as slightly lower gamma ray intensity, usually with scattered, broad, low-medium-intensity peaks.

On electric logs, the upper zone consists of a very characteristic series of resistivity peaks and valleys. The upper contact is marked by a relatively low-resistivity, thick series of valleys (Lake and Marion counties), sometimes showing a well-developed, high-resistivity, dolostone peak between the uppermost and next downward peat or clay bed valley (Volusia, Flagler, south Putnam, north Seminole counties). This upper portion of the upper zone low-resistivity trace consists of one to three resistivity valleys in southeast Florida (Indian River County and south) with the remainder of the zone recorded as low peaks and a generally straight-line resistivity trace characteristic of a uniform series of thick, relatively porous, carbonate beds.

In the central peninsula upland area (Marion, Lake and Polk counties), the middle portion of the upper Avon Park zone is characterized by a thin (30 to 80 feet) series of medium-high-resistivity peaks interspaced with thin resistivity valleys. This portion is herein referred to as the "false dolostone (low porosity) zone". This portion is also well-developed along the north peninsular Florida Atlantic coast, for example at Daytona Beach and at New Smyrna Beach, Volusia County. This characteristic trace becomes indistinguishable southeast of Volusia County and to the north in Alachua, Putnam and St. Johns counties.

In the central peninsula area, the portion of the upper Avon Park zone below the base of the "false dolostone (low porosity) zone" and the top of the lower Avon Park zone generally consists of even-resistivity, high-porosity limestone trace showing no high-resistivity peaks. A single very-low-resistivity valley denoting a peat or clay bed occurs in this portion of the log and is referred to by the present author as the "dolostone (low porosity) zone marker bed". This resistivity valley is well-developed in Marion, Lake and Polk counties and also exists sporadically in southeast Florida (Indian River and Brevard counties), albeit in a less typically developed form. In this southeast area, there exits no "false dolostone (low porosity) zone" and the resistivity valley is approximately 100 feet below the top of the Avon Park. The total thickness of the upper Avon Park zone varies from 0 feet (Duval and Baker counties, northeast Florida) to less than 100 feet (Marion County, central Florida) to over 300 feet (Sarasota County, southwest Florida).

The lower zone is referred to herein as the "dolostone (low porosity) zone". It consists of thick beds of dark brown, very hard, dense dolostone interbedded with very thin to absent limestone or dolomitic limestone. Large caverns and fractures (which produce prodigious amounts of water in wells) are characteristic. Bedded and disseminated peat is also common.

On gamma ray logs, the zone is characteristically shown as a series of peaks slightly to significantly higher in intensity than the upper Avon Park zone or as a continuous higher-intensity trace devoid of peaks. On electric logs, it records as a series of very-high-resistivity peaks interspaced with thin low-resistivity valleys or as a thick zone of uniformly high resistivity. The lower zone is well-developed under the entire Florida peninsula, including the Florida Keys where both lower and upper zones are clearly differentiated on gamma ray logs (Appendix C-6).

In portions of Duval, Nassau and Baker counties, northeast Florida, the Avon Park is very thin, consisting of only the lower portion of the lower zone

(Appendix C-1, C-2).

The base of the lower zone is usually considered to be the contact between the Avon Park Limestone and the Lake City Limestone (Chen 1965). The Avon Park is everywhere present in the Florida peninsula (Applin and Applin, 1944; Chen, 1965; Meyer, 1962).

LAKE CITY LIMESTONE

The Lake City Limestone consists of interbedded limestone and dolostone with much recrystallization. Throughout the peninsula, the top of the formation consists of a series of rather pure limestone beds composed of loosely cemented small foraminiferal tests, biological debris and some recrystallized limestone. This lithology contrasts with the thick dolostone beds of the lower Avon Park zone (Chen, 1965). In the southern one-third of the peninsula, the entire formation contains much gypsum, both disseminated and as discrete (but very thin) beds. In most of the northern one-third of the peninsula, discrete peat beds (mainly in the top one-half of the formation) and some disseminated peat occur in the formation.

On gamma ray logs, relatively low and even intensity is typical of the top of the Lake City. The intensity is markedly lower than the intensity characteristic of the lower Avon Park zone. In south Florida (Florida Keys), the top of the formation is also marked by a low-intensity gamma ray trace (Figure 17). Here, the middle portion of the formation is marked by a change in lithology from the pure limestone of the uppermost Lake City into very gypsiferous limestone beds interbedded with occasional gypsum beds in the middle part of the formation. Thus, below the uppermost low-intensity portion of the upper gamma ray zone, the remainder of the upper gamma ray zone consists of a low-medium-intensity, very uniform trace containing sharp thin evaporite valleys typical of gypsiferous carbonate beds. Over-all formation intensity on gamma ray logs is much more uniform and even when compared to that recorded in the Avon Park.

On gamma ray logs, in the northern portion of the peninsula (Duval, Baker, Putnam, St. Johns, Alachua and Lake counties), the upper zone of the formation is characterized by relatively low and uniform intensity characteristic of

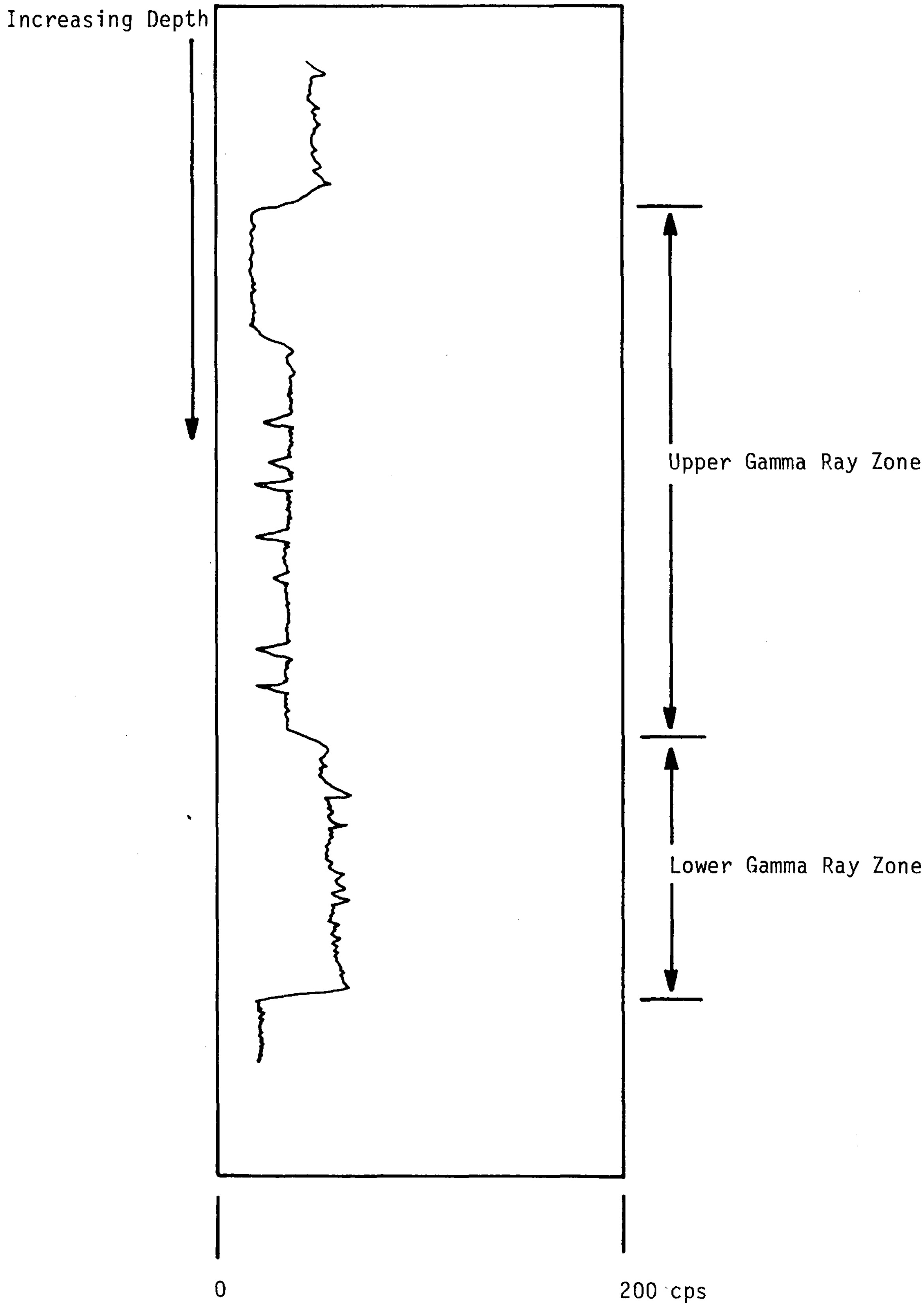

Figure 17. Lake City Limestone Gamma Ray Log, South Florida

relatively pure limestone beds, separated by one to four medium- to very-high-intensity gamma ray peaks marking discrete peat beds (Figure 18). These peat beds are considered to be marker beds for the top of the Lake City Limestone (Chen, 1965). Peaks such as these are sometimes found on logs recorded in the lower portion of the formation as well (Duval County).

In the central one-third of the peninsula (south Lake, Orange, Seminole and south Volusia counties) and also in southeast Florida (Indian River County) and in Nassau County (northeast Florida), the peat beds at the top of the formation are very thin to absent and the upper contact of the formation is marked on gamma ray logs as a very-low-intensity trace immediately below the higher-intensity of the basal Avon Park lower zone (Figure 19). Here, the upper gamma ray zone is relatively less than one-half the total formation thickness. The formation is characterized on electric logs as a series of high-resistivity peaks gradually increasing in resistivity stratigraphically downward. The peaks are generally higher in resistivity than the lower Avon Park zone peaks. A thin to thick (40 to several hundred feet) interval of low-resistivity (high-porosity limestone) is located between the high-resistivity of the lower Avon Park zone and the high-resistivity peak series in the Lake City. This is the stratigraphic location of the peat marker beds found in the northern one-third of the peninsula (Figure 18).

Everywhere in the peninsula, the base of the formation is marked by a thick (greater than 100 feet) to thin (30 feet) lower Lake City gamma ray zone of slightly higher-intensity when compared to the remainder of the formation, denoting a basal section of dolostone beds (which records on electric logs as high-resistivity peaks or as a thick uniformly high-resistivity trace). The base of the formation is thus indicated in southwest Florida (Sarasota County) as well as in most of central and northern Florida. The base of the Lake City

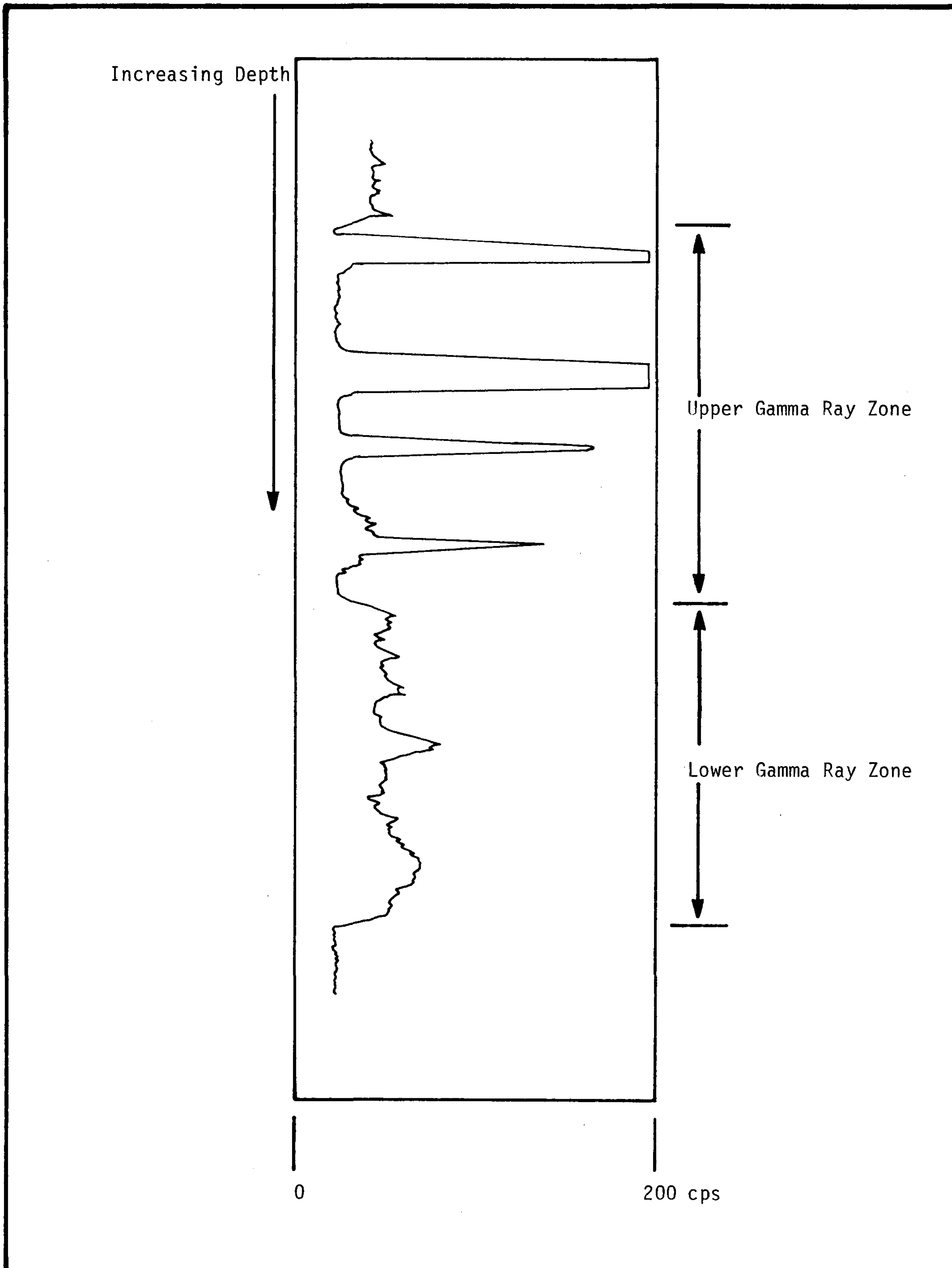

Figure 18. Lake City Limestone Gamma Ray Log, North Florida

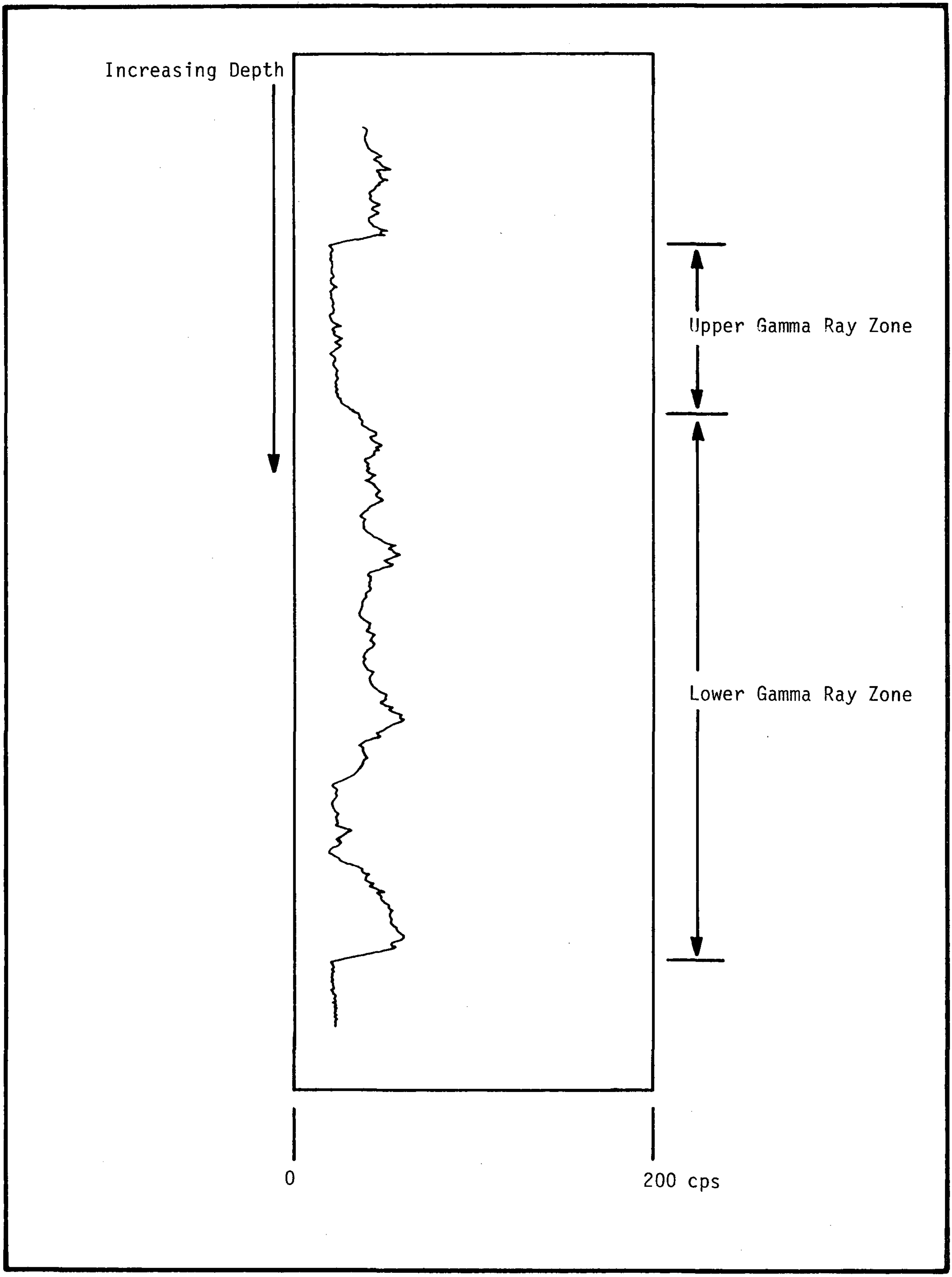

Figure 19. Lake City Limestone Gamma Ray Log, Central Florida

is described from well cuttings obtained from wells in Duval County, northeast Florida, as a zone of glauconite (dark green potassium mica) disseminated in the carbonate beds immediately above the carbonate beds of the Oldsmar Limestone, which lack glauconite. The presence of this mineral is often associated with unconformities (Mason and Berry, 1968) and in part explains the slightly higher gamma ray intensity recorded in the lower portion of the Lake City in Duval and Nassau counties. In Nassau County, the high-resistivity dolostone section at the base of the formation in the peninsula is recorded as very-low-intensity on gamma ray logs. The Lake City is everywhere present in the Florida peninsula (Applin and Applin, 1944).

OLDSMAR LIMESTONE

The Oldsmar Limestone consists of interbedded dolostone and limestone, with both lithologies generally very recrystallized. The dolostone is very hard and pure, dark brown to dark gray in color and is mainly sucrosic, composed of minute dolomite rhombs. Some beds of massive microcrystalline dolostone are present, particularly in the lower one-half to two-thirds of the formation, which consists of thick beds of very hard dolostone (Chen, 1965). This lower Oldsmar dolostone (low porosity) zone is composed specifically of dark brown to very dark brown (almost black in hand specimen appearance), very hard microcrystalline dolostone, generally 100 to several hundred feet in thickness. This section has been referred to as the "D. H. Zone" by oil well drillers (Maher and Applin, 1968).

The limestone is mainly a recrystallized, hard, low-porosity, biological-material, foraminiferal, coquinoid (calcarenite) to chalky limestone, existing predominantly in the upper one-half of the formation. The so-called "boulder zone" (Puri and Winston, 1974) of high transmissivity and high potential for the injection of liquid wastes appears to be located stratigraphically within the Oldsmar Limestone. This "boulder zone" is situated within the lower one-half (dolostone zone) of the formation. High-resistivity dolostone zones such as this mark the bases of the Avon Park, Lake City and Oldsmar Limestones (Chen, 1965). Characteristic low-porosity (high-resistivity) as recorded on electric logs is misleading in that very high permeability (due to thin interconnected caverns, cavities and fractures) is actually present.

The uppermost portion of the upper half of the formation consists of dolomitic limestone (with scattered original-material foraminifera recognizable) and limestone (very recrystallized and hard). This section contains a lesser number of dolostone beds when compared to the remainder of the formation and hence, records on gamma ray logs (Figure 20) as a low-intensity trace immediately below the slightly to markedly higher-intensity characteristic of the basal Lake City.

Below this uppermost low-intensity gamma ray trace (but still within the upper one-half of the formation) is a thin (less than 100 feet) section of silica-rich minerals and other impurities included in carbonate beds: predominantly dark brown to dark gray chert along with small euhedral quartz crystals and interbedded impure (argillaceous) limestone and dolomitic limestone (Sarasota, Duval and Nassau counties). Scattered peat flecks and glauconite are also present (Duval County). This silicic and impure limestone section is shown in gamma ray logs as a trace of low-medium-intensity to medium-intensity peaks separated by a sustained low-medium-intensity trace (Duval, Nassau, Putnam and Sarasota counties).

In coastal northeast Florida (east Duval and east Nassau counties), immediately below this low-medium-intensity gamma ray trace there exists a second low-intensity portion which is located stratigraphically above the lower Oldsmar (dolostone) zone. In some portions of the peninsula however, the low-medium-intensity of the silicic trace continues downward without interruption into the yet higher-intensity characteristic of the basal one-half (dolostone zone) of the Oldsmar (Figure 20). This latter arrangement is characteristic on logs from deep wells in northwest Putnam County and in west Sarasota County.

Generally, electric log characteristics vary considerably from well to well. However, the two-fold division into an upper low-resistivity, low-intensity gamma ray zone (with scattered to common high-resistivity peaks) and a basal, thicker, much higher-resistivity, higher-intensity gamma ray zone occurs across the entire Florida peninsula (Chen, 1965). The Oldsmar is everywhere present in the Florida peninsula (Chen, 1965).

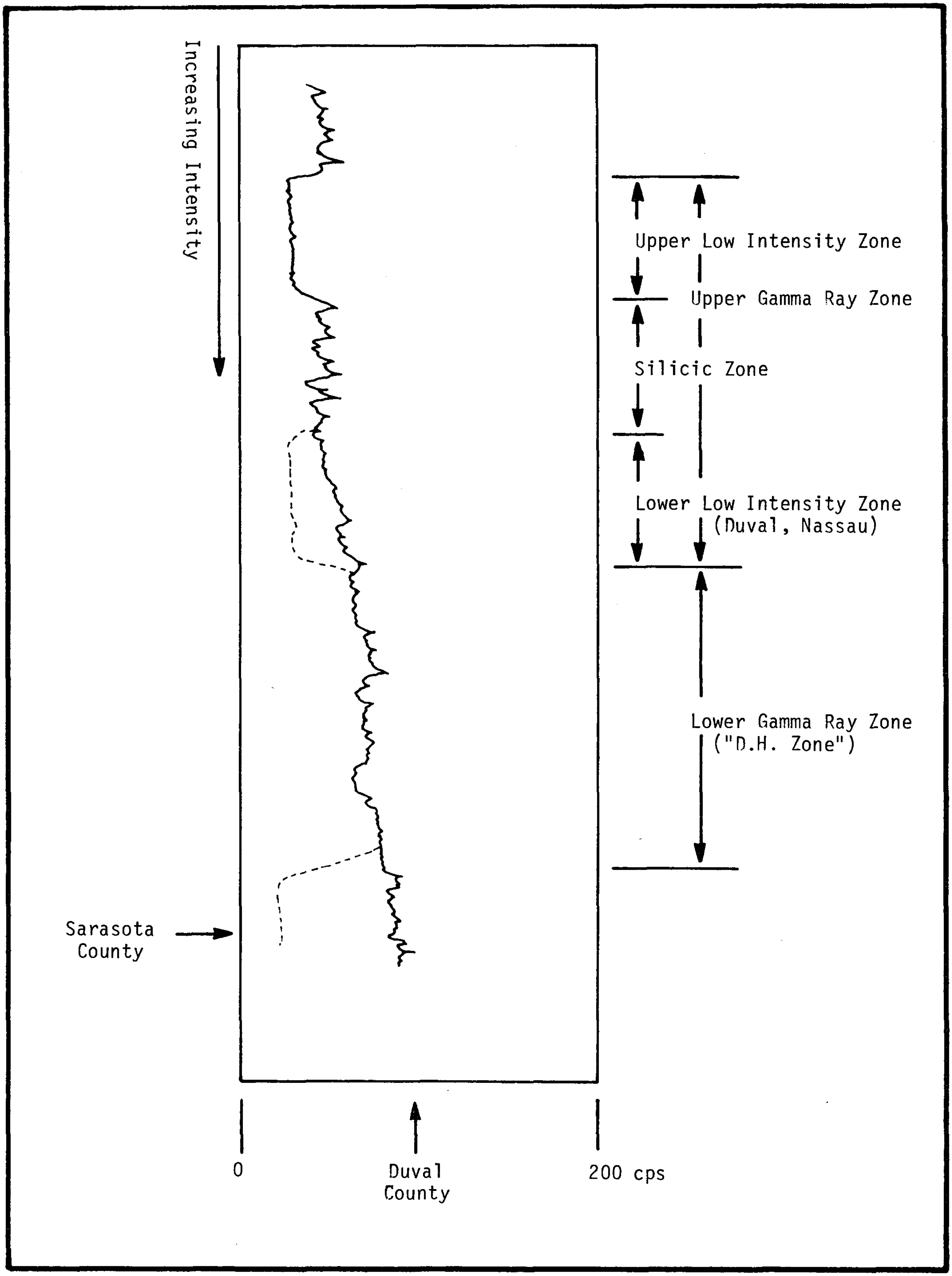

Figure 20. Oldsmar Limestone Gamma Ray Log

CEDAR KEYS FORMATION

The Cedar Keys Formation consists of dolostone and evaporites (predominantly gypsum and anhydrite) with some limestone. The gypsum occurs mainly as veins and porosity-fillings whereas the anhydrite can be found in discrete beds, particularly in southwest Florida and primarily in the middle section of the formation (Chen, 1965).

In Florida, very few water wells are drilled deeply enough to penetrate Cedar Keys, hence there is a paucity of information concerning the formation. Generally, oil test wells penetrate the Cedar Keys, however most commercial oil-well gamma ray logs are not as sensitive as water well gamma ray logs limiting interpretive capabilities. Also, since it is generally acknowledged that no hydrocarbons will be found in the Cedar Keys, most commercial operators are not particularly concerned with it and the formation is usually cased off in oil tests, further reducing the sensitivity of gamma ray logs.

This author has logged only three wells which penetrate the Cedar Keys (in an open hole section) and this section of the paper is focused on characteristics shown in these three wells.

The first well is located in west Duval County, northeast Florida. The top of the formation is picked at approximately 2,000 feet below land surface, where the resistivity trace descends from the very-high-resistivity characteristic of the lower Oldsmar (dolostone) zone into a very low, even and uniform, straight-line resistivity (Chen, 1965). Gamma ray intensity is relatively high, characterized by broad, medium-intensity peaks continuing downward from the lower Oldsmar zone and gradually increasing in average intensity. The contact between the Oldsmar Limestone and the Cedar Keys Formation cannot be picked in this well on the basis of the gamma ray log alone.

At approximately 2,150 feet below land surface, the uppermost anhydrite bed of the middle section of the Cedar Keys is seen on the electric log as a medium-high-resistivity peak and on the gamma ray log as a very-low-intensity valley between thick zones of medium-high-intensity.

The second well is located in west Sarasota County (Southwest Florida). Here, approximately 250 feet of Cedar Keys is penetrated and is recorded on the gamma ray log as a low-intensity trace with thin, well-defined, very-low-intensity valleys characteristic of anhydrite beds (confirmed from the driller's log). The top of the formation is indicated by a well-defined and abrupt drop in gamma ray intensity from the lower Oldsmar (dolostone) zone into the even, much lower gamma ray intensity of the Cedar Keys (at a depth of about 3,230 feet below land surface). The overall lower-intensity of the formation on gamma ray logs in south Florida is probably due to the presence of much disseminated anhydrite. No electric log is available.

The third well is located on Merritt Island, central Brevard County. The top of the Cedar Keys is marked on the neutron log (roughly equivalent to the electric short-normal curve) where the apparent porosity increases abruptly at about 2,485 feet and remains at a relatively high value downward. This is the equivalent of the low, even, straight-line resistivity zone which marks the top of the Cedar Keys (Chen, 1965). Again, the contact between the Oldsmar Limestone and the Cedar Keys Formation cannot be picked from the gamma ray log.

At approximately 2,680 feet an anhydrite bed similar to the one detected in west central Duval County was shown on the gamma ray and neutron logs. The Cedar Keys is everywhere present across the Florida peninsula (Chen, 1965).

SUMMARY

This paper summarizes gamma ray and electric log characteristics of the Paleocene through Pliocene formations typically present in peninsular Florida. Interpretation was developed from the logging and log interpretation of 938 wells in 32 counties. The stratigraphic interpretation of gamma ray logs is emphasized and electric log characteristics are used to further refine gamma ray log interpretation.

All formations considered (except the Cedar Keys) can be divided into two gamma ray log zones: an upper zone of lesser average intensity and a lower zone of greater average intensity. The Suwannee Limestone, in the Indian River County area, can additionally be divided into three gamma ray and electric zones: upper and basal zones of higher average gamma ray intensity and lower resistivity, and a middle zone of lower average gamma ray intensity and higher-resistivity. The Suwannee, Ocala (in some areas), Avon Park, Lake City and Oldsmar Limestones all exhibit lower "dolostone zones" which generally correlate to the higher gamma ray intensity zones and higher electric log resistivity zones shown on the logs. The Hawthorn Formation, Tampa, Suwannee, Ocala, Avon Park and sometimes the Lake City, are usually separated by unconformities which are often recorded on gamma ray logs as a low-medium to high-intensity peak or series of peaks.

Average gamma ray intensities recorded become markedly lower with each successively deeper formation through the sequence of: Hawthorn, Tampa, Suwannee, and Ocala. The Ocala characteristically shows the lowest gamma ray intensity encountered on logs from water wells in the region. Gamma ray intensity is highest in the Hawthorn Formation, primarily due to the presence of relatively large amounts of intermixed phosphate. Gamma ray intensity in the Avon Park and Lake City can also be locally very high, recording peaks

resembling Hawthorn Formation phosphate peaks. These high-intensity peaks are due to the presence of discrete beds of peat, argillaceous peat and peaty, argillaceous dolostone.

Since only three wells were logged into the Cedar Keys Formation, generalized geophysical characteristics cannot be inferred, however from other sources (Chen, 1965) a triple division can be detected, primarily on electric logs. The middle zone of high-resistivity peaks corresponds to very dense, hard, anhydrite beds interbedded with dolostone. The upper and lower zones generally lack anhydrite as discrete beds and thus show lower, more uniform resistivity.

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APPENDIX A

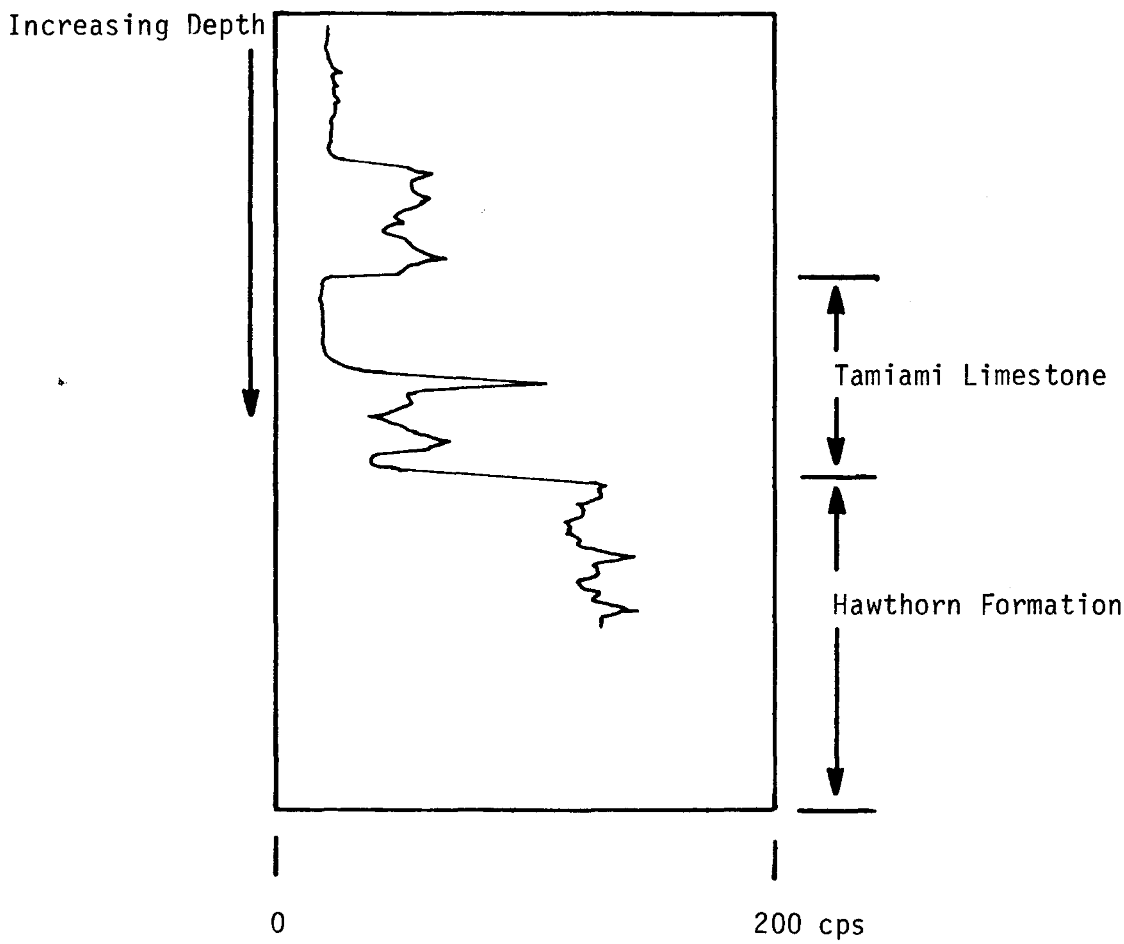
The Tamiami Limestone and Jacksonville Limestone in Two Local Areas in Peninsular Florida

TAMIAMI LIMESTONE/JACKSONVILLE LIMESTONE

In the local area of Brevard, Indian River and St. Lucie counties (southeast Florida), the Tamiami Limestone consists of light to very dark gray, silty, sandy, slightly phosphatic limestone composed of a generally well-cemented and hard biological debris of (primarily) mollusc fragments which are unaltered to completely recrystallized. High moldic porosity is common in the recrystallized limestone beds. Thickness varies from 0 to 90 feet. The base of the formation is its contact with the very phosphatic green silt, sand or carbonate of the upper Hawthorn Formation. Age is thought to be Pliocene (T. Scott, Florida Bureau of Geology, oral communication, 1982).

The Tamiami Limestone as defined above is found in the subsurface in wells in the Atlantic coastal area from north Brevard County (Titusville) south to at least St. Lucie County. Generally, the formation is present on the barrier island and pinches out inland to the west: it becomes a sequence of unlithified, unrecrystallized beds (of similar lithology) in wells more than about 15 miles west of the Atlantic shoreline.

On gamma ray logs in this area (where the formation is typically developed in its hard recrystallized limestone form), the Tamiami Limestone can be divided into three zones (See Figure). The uppermost zone consists of a low-intensity valley representing a bed of relatively pure, very hard and well-cemented, high porosity limestone varying in thickness from 5 feet to approximately 40 feet. The middle zone consists of a medium-low-intensity peak or series of peaks representing a bed of very silty or sandy, impure, moderately- to poorly-consolidated limestone ("marl"). Phosphate content is typically higher than in the upper zone. The basal gamma ray zone records as one to three low-intensity valleys between slightly higher-intensity peaks (of average intensity greater than the upper zone but less than the middle zone), representing either



Tamiami Limestone Gamma Ray Log from the East Coast of Florida relatively pure, chalky and moderately well-cemented limestone or a "coquina" in the classic sense. Both lithologies contain very fine, black, phosphate grains (which are the probable cause of the moderately high gamma ray intensity recorded in these beds). The basal contact is well-defined as a sharp increase in intensity associated with the top of the very phosphatic Hawthorn Formation.

In most of Indian River and St. Lucie counties where the formation exists, this triple zonation can be detected on gamma ray logs, however, in Brevard County on the barrier island, the upper low-intensity gamma ray zone predominates at the expense of one or both of the other zones. On the mainland of Brevard County, the upper zone contains several "marly" unlithified beds which thicken at the expense of the pure, low gamma ray intensity portions toward the west.

On electric logs, the formation consists of two higher (limestone) resistivity zones surrounding a lower-resistivity valley. The three resistivity zones generally correlate with the three gamma ray zones.

A Tamiami Limestone equivalent also exists in Duval County (center of Jacksonville basin where the entire stratigraphic section is thicker and more complete), in eastern Baker County and in Nassau County (northeast Florida). This formation is here referred to as the Jacksonville Limestone because it is typically and best developed in Duval County. It is composed mainly of dolostone in the forms of hard, recrystallized microcrystalline dolostone and chalky, softer dolostone. Very high moldic porosity is common in the upper bed, as are beds of silica sand and dolomite calcarenite. Here, the same three gamma ray zones are recorded as delineated above, with the following differences. The upper zone is typically thicker, composing up to one-half of the total formation thickness. This zone represents a brown, moderately hard, very high molluscan moldic porosity dolostone containing no sand or phosphate. The middle zone consists of a thick, broad, low-medium-intensity peak below the well-defined low-intensity upper zone. The lower zone consists of a single low-to low-medium-intensity valley, usually sharply defined and relatively thin, just above the marked increase in intensity associated with the upper Hawthorn Formation (usually a well-defined peak, but occasionally an increase to a sustained medium-intensity zone lacking peaks).

In some wells, only the upper, well-defined, low-intensity zone is recorded. In other wells the middle and lower zones merge and are apparently interbedded resulting in a 2-zone differentiation of the formation. Here the upper low-intensity zone is underlain by a series of sharp, low-medium to medium-intensity peaks which are separated by thin, sharp, low-intensity valleys. It is also possible that these lower two zones are best considered part of the Hawthorn Formation. Thickness of the formation varies from zero feet (toward the south) to approximately 65 feet.

In both of these areas, the shape of the gamma ray trace recorded in the limestone is extremely variable, even from adjacent wells, and frequently is recorded as medium-low-intensity (characteristic of the middle zone) throughout the entire thickness of the formations.

Also, both formations cannot be identified on gamma ray logs from some wells. This could be due to either their absence or to the masking effects of well construction. Most of the wells logged are Floridan aquifer wells which are cased (and usually grouted) through the portion of the section in which these limestones exist. It is not uncommon for several sizes of casing to be emplaced concentrically in large public supply wells, with the annular spaces filled with grout. Since the geophysical characteristics of these formations can be more variable than those of deeper formations and are rather local in character, the gamma ray log obtained from large wells can be useless for correlation of the formations, and identification of the presence of the formations in a particular well is sometimes difficult if not impossible without well cuttings, cores or a neutron log. These factors make correlation solely on the basis of gamma ray logs questionable at best.

APPENDIX B

Tabulation of Selected Deep

Wells Logged Showing Formation

Contacts

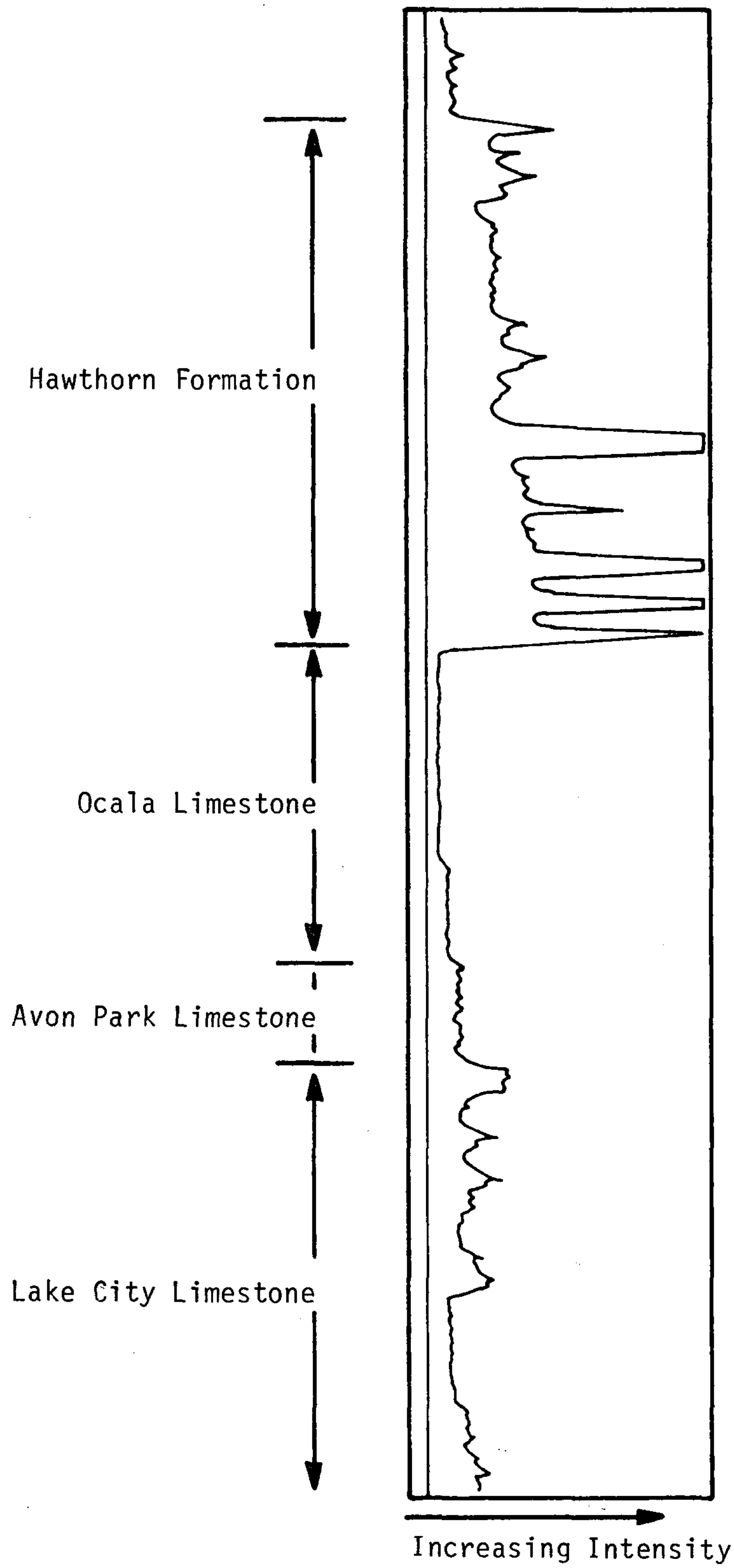
COUNTY	LATITUDE LONGITUDE	TDL	ELEV LSD	DEPTH TO TOP OF: HAWTHORN	TAMPA	SUWANNEE	OCALA	AVON PARK	LAKE CITY	OLDSMAR	CEDAR KEYS
Alachua	29-49-48 82-35-54	506	75	25	-	-	33	197	485	-	-
Baker	30-26-20 82-17-35	897	116	55	-	-	388	709	775	-	-
Charlotte	26-47-45 82-01-35	1,085	15	122	509	692	-	-	-	-	-
Duval	30-24-16 81-52-26	2,166	87	140	-	-	405	685	722	1,331	1,978
	30-22-29 81-40-08	1,334	19	89	-	-	515	750	794	-	-
	30-20-07 81-35-47	1,401	45	110	-	-	549	797	856	-	-
	30-22-00 81-23-57	1,971	15	81	-	-	411	679	752	1,464	-
Gilchrist	29-36-32 82-51-53	333	c.35	18	-	-	32	102	-	-	-
Indian River	27-36-07 80-31-03	1,101	23	173	-	419	443	539	964	-	-
	27-42-06 80-22-55	1,969	4	132	-	607	785	820	1,280	-	-
	27-46-25 80-24-21	1,272	8	116	-	409	538	574	1,075	-	-
Lake	28-48-26 81-51-33	840	70	36	-	-	51	116	359	-	-
Manatee	27-24-55 82-08-46	1,213	56	71	335	454	676	956	-	-	-

COUNTY	LATITUDE LONGITUDE	TDL	ELEV LSD	DEPTH TO TOP OF: HAWTHORN	TAMPA	SUWANNEE	OCALA	AVON PARK	LAKE CITY	OLDSMAR	CEDAR KEYS
Marion	29-10-51 82-08-12	369	115	20	-	-	38	109	-	-	-
Martin	27-03-27 80-35-26	1,056	24	142	722	733	766	794	-	-	-
Monroe	24-42-38 81-05-39	2,138	4	307	832	1,060	-	1,232	1,544	-	-
	25-10-51 80-22-05	1,194	11	277	944	1,134	-	-	-	-	-
Nassau	30-40-00 81-28-05	2,002	3	78	-	-	547	848	925	1,677	-
Okeechobee	27-34-51 80-51-48	984	17	210	-	355	393	437	-	-	-
Orange	28-41-27 81-28-10	791	90	31	-	-	186	240	555	-	-
Osceola	27-47-42 80-58-53	876	71	168	-	251	292	355	756	-	-
Palm Beach	26-56-04 80-08-26	1,244	13	244	819	892	955	1,037	-	-	-
Polk	28-14-23 81-42-23	440	145	73	-	-	94	164	-	-	-
Putnam	29-37-38 81-35-16	1,656	17	73	-	-	224	282	670	1,166	-
	29-46-18 82-47-34	1,397	57	21	-	-	145	250	528	990	-
St. Johns	29-48-03 81-27-10	910	29	70	-	-	203	349	605	-	-
St. Lucie	27-31-13 80-27-16	705	22	187	-	439	535	608	-	-	-

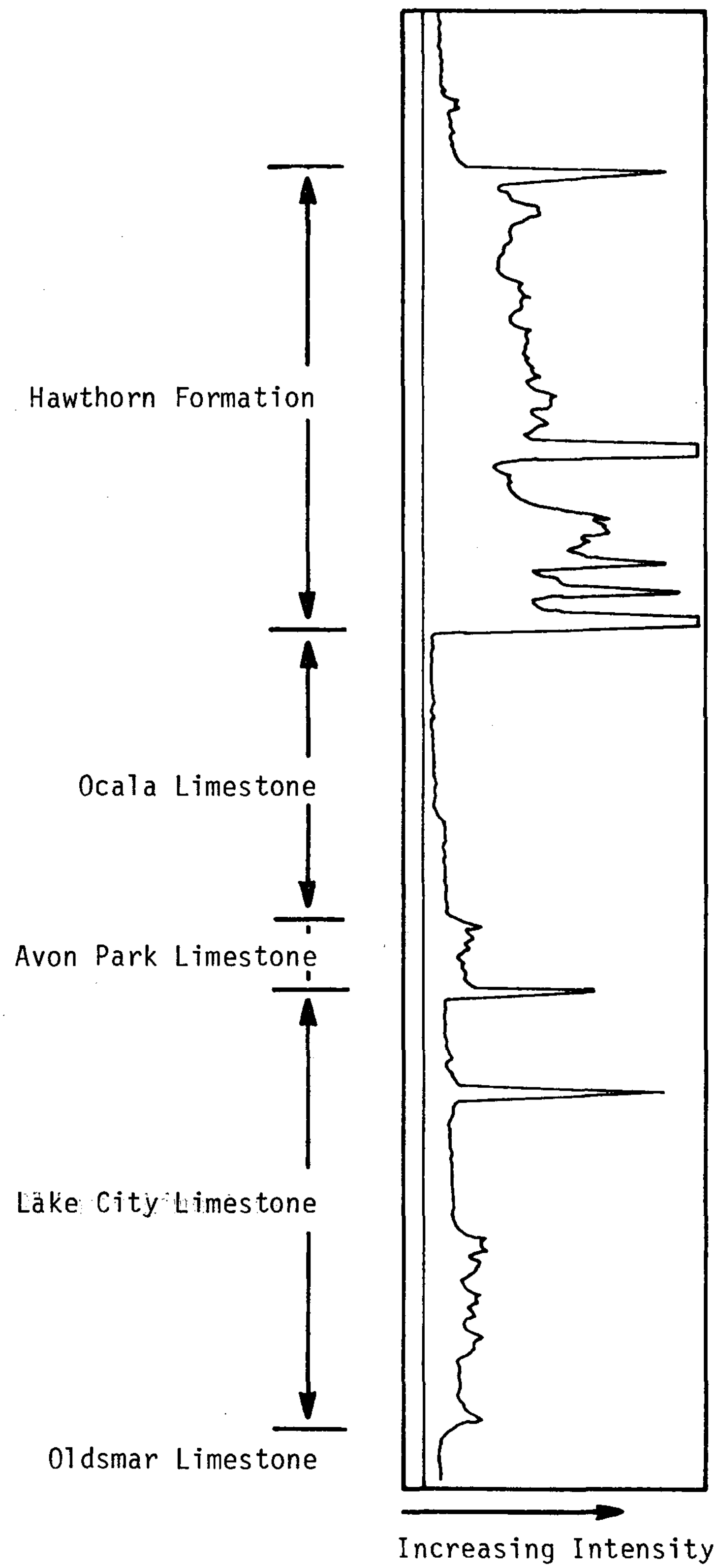
COUNTY	LATITUDE LONGITUDE	TDL	ELEV LSD	DEPTH TO TOP OF: HAWTHORN	TAMPA	SUWANNEE	OCALA	AVON PARK	LAKE CITY	OLDSMAR	CEDAR KEYS
Sarasota	27-20-50 82-32-04	3,482	22	-	-	-	-	-	1,782	2,216	3,231
	27-22-55 82-17-22	1,196	78	56	315	461	676	976	-	-	-
	27-15-30 82-31-23	1,326	20	11	269	502	781	1,045	-	-	-
Seminole	28-41-51 81-26-08	906	58	44	-	-	119	185	515	-	-
Volusia	29-01-03 80-55-19	998	8	93	-	-	105	196	578	-	-

APPENDIX C

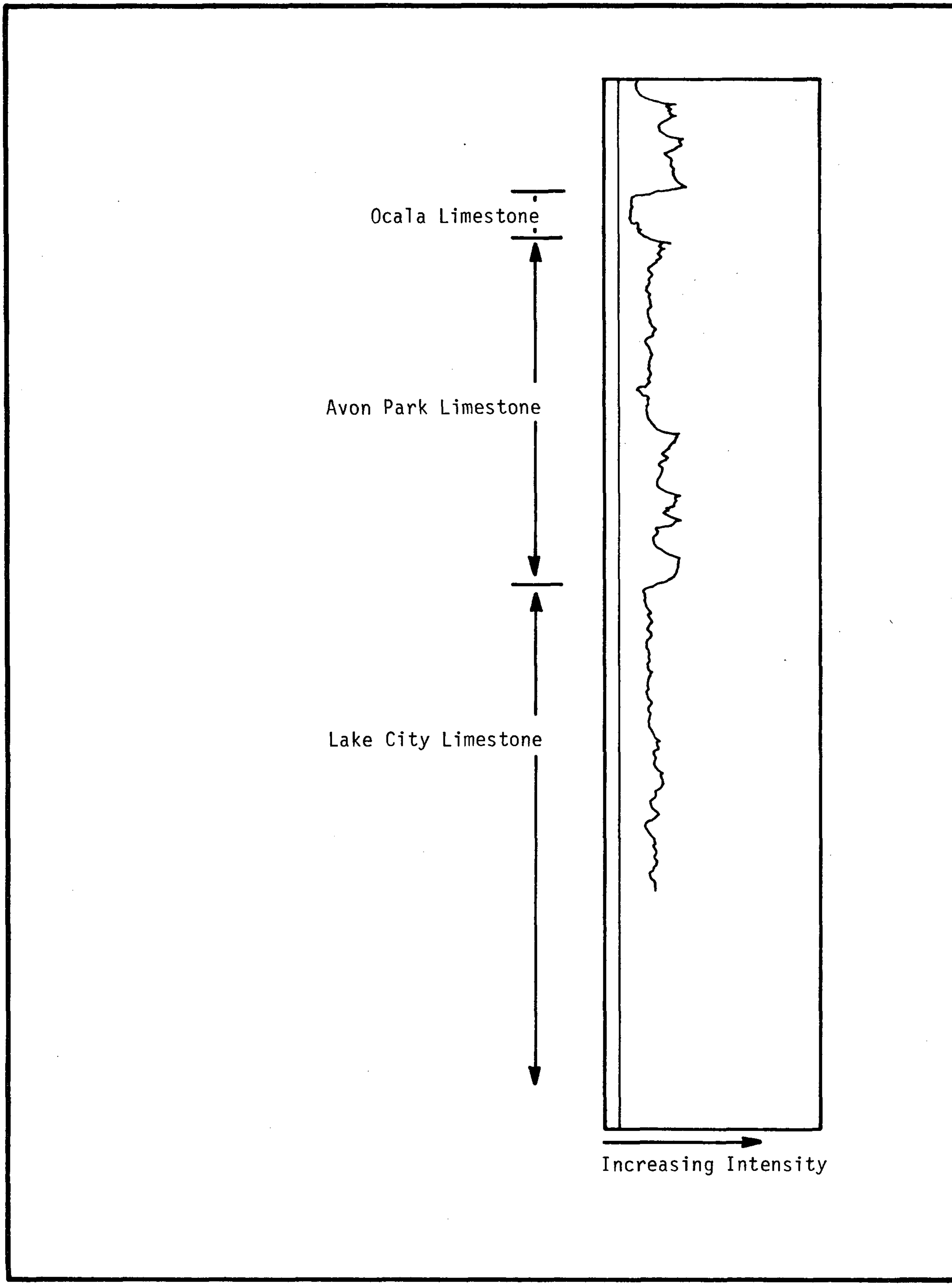
Graphical Representations of Gamma Ray Logs from Wells Along the Atlantic and Gulf Coasts of Florida



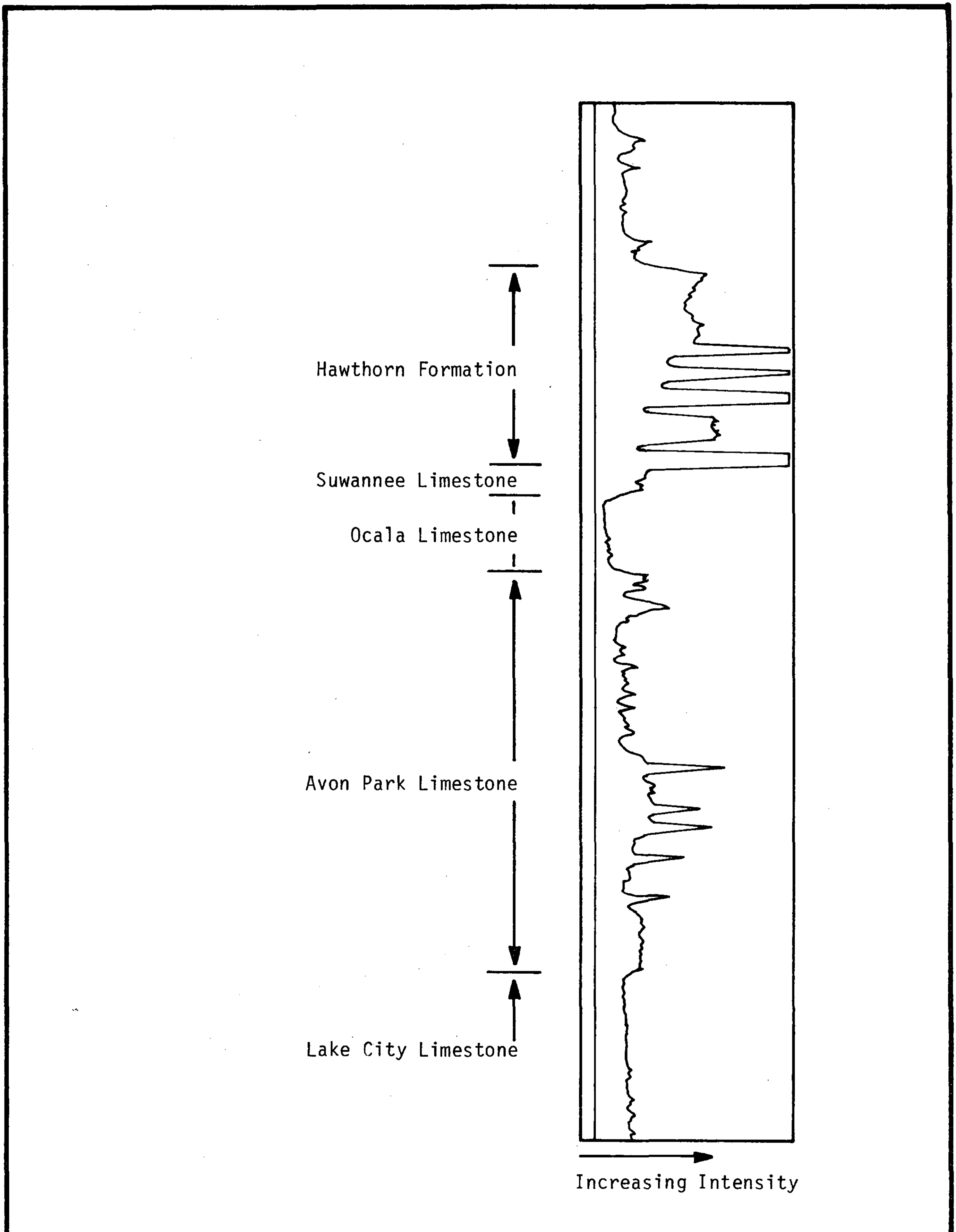
Gamma Ray Log from Well in Northeastern Nassau County



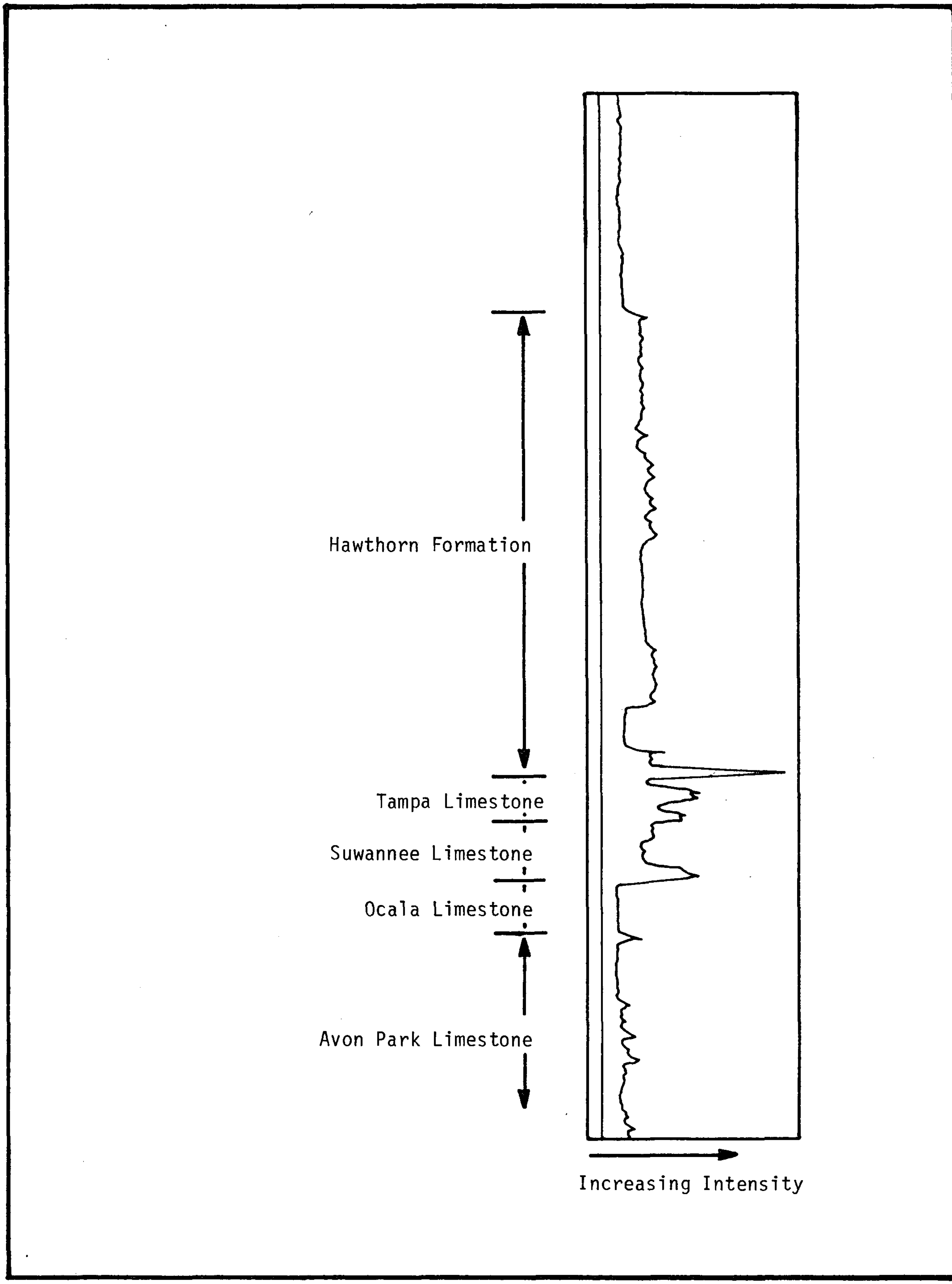
Gamma Ray Log from Well in Central Duval County



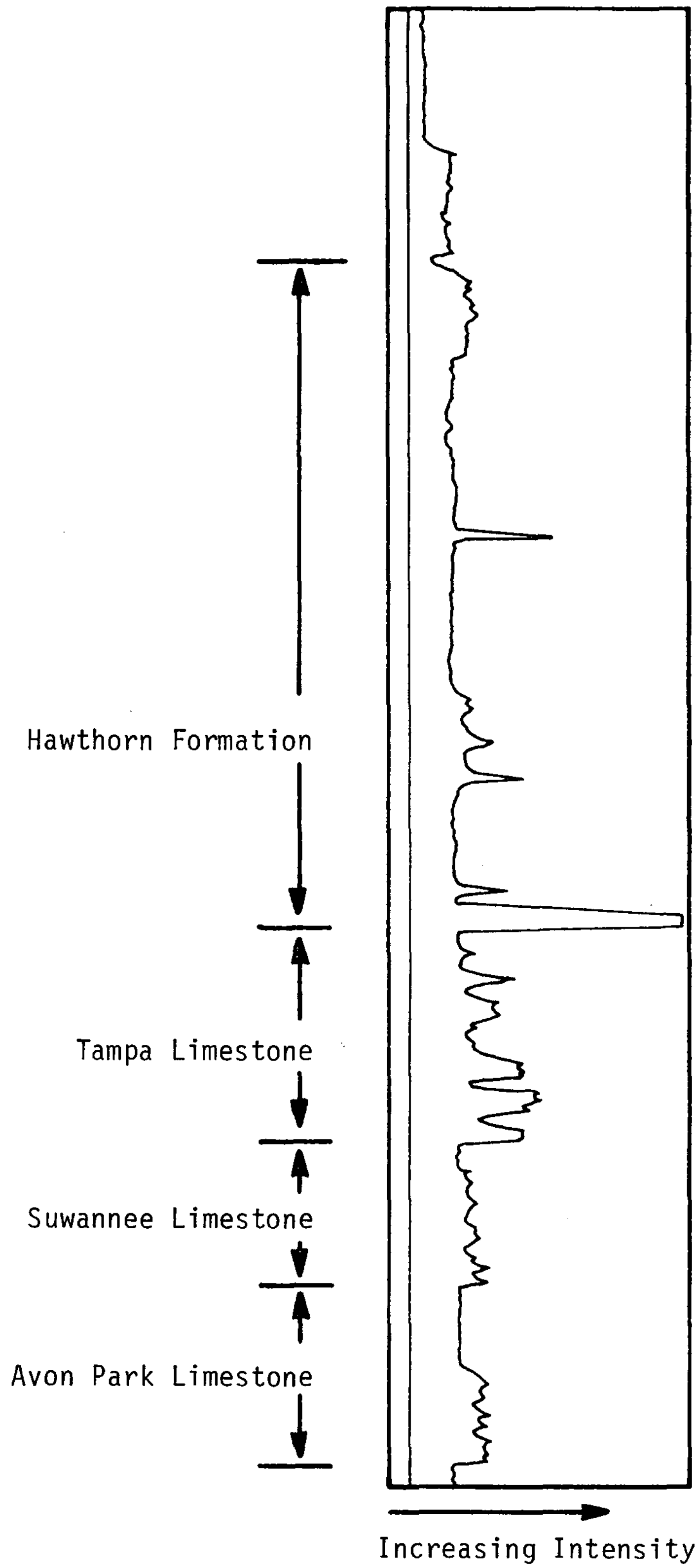
Gamma Ray Log from Well in Eastern Volusia County



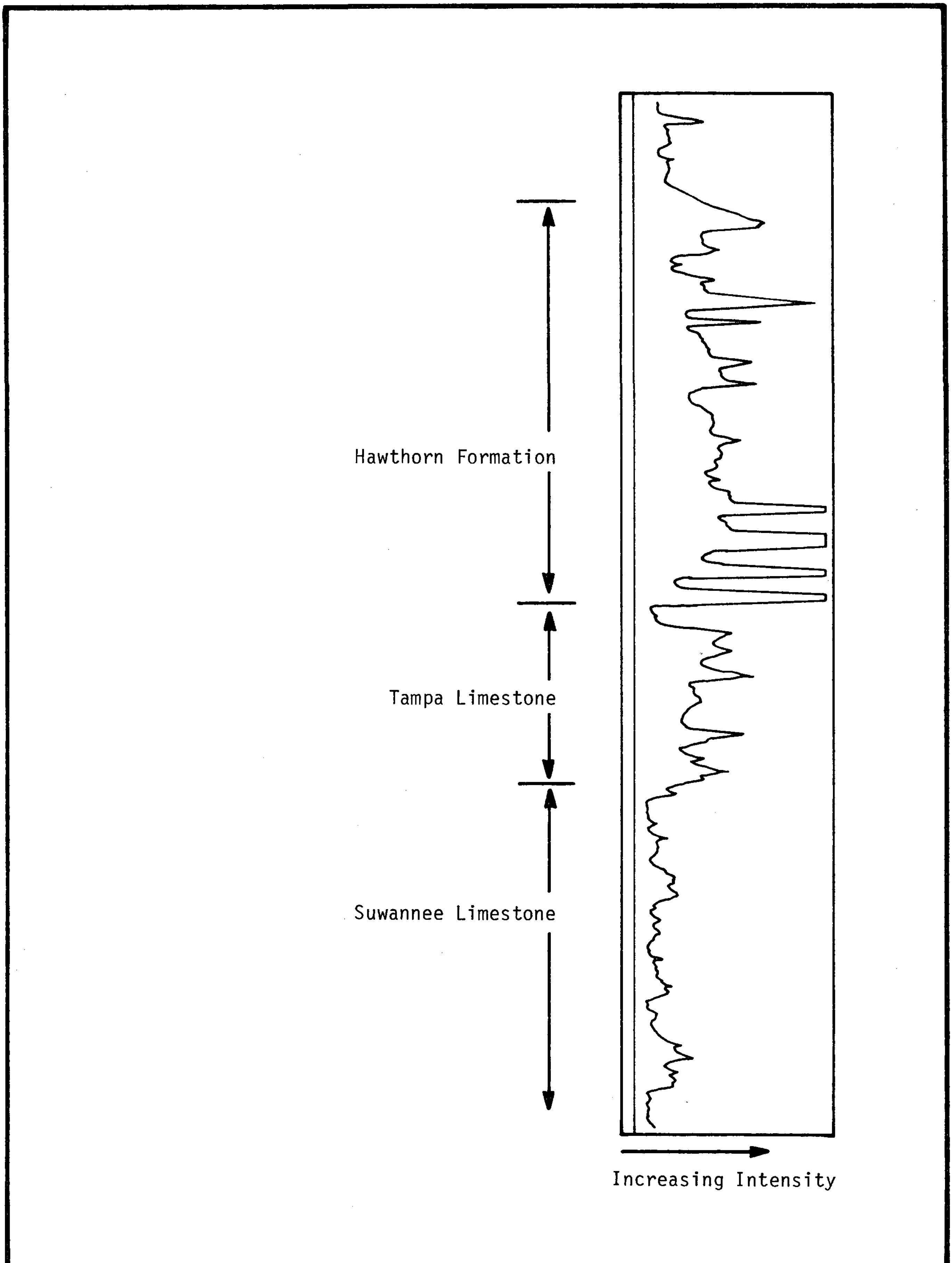
Gamma Ray Log from Well in South Central Indian River County



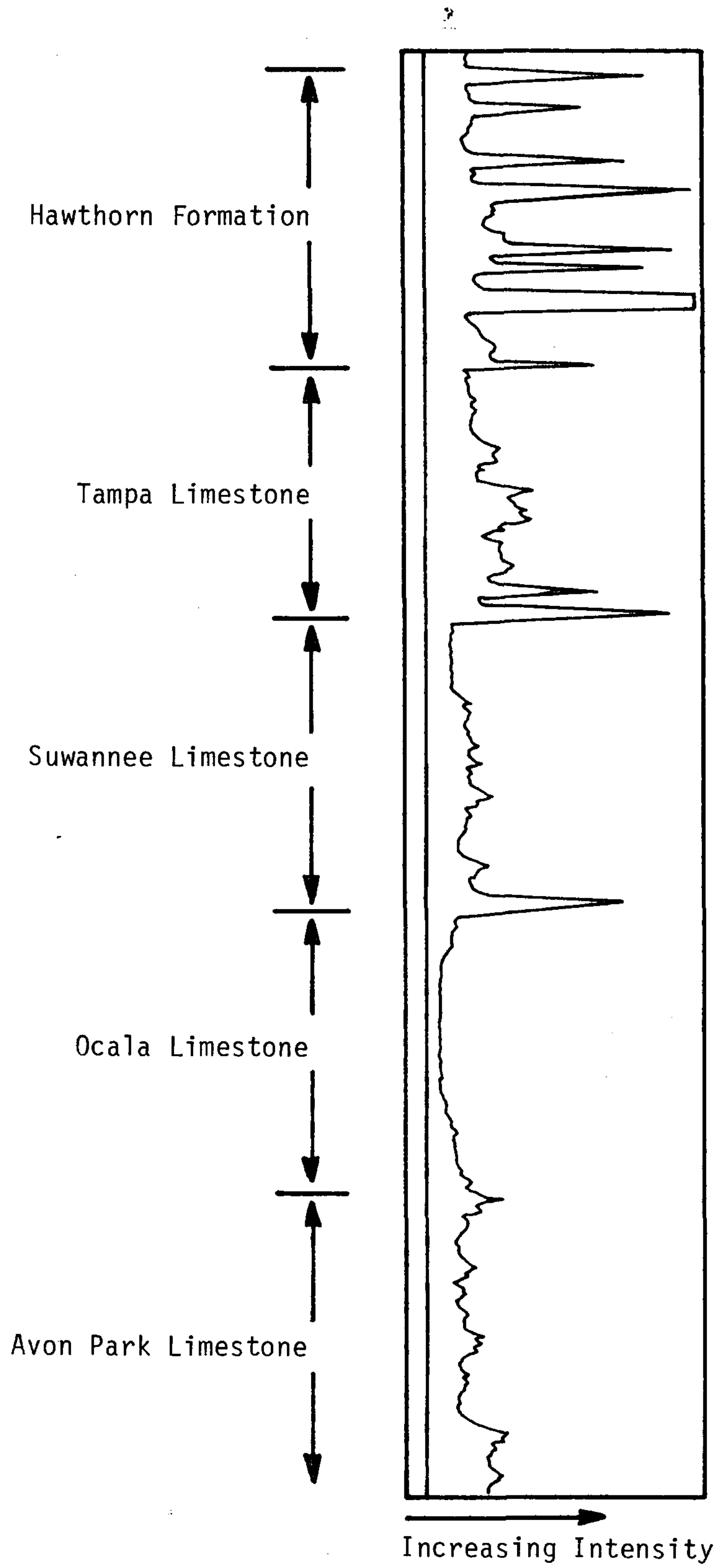
Gamma Ray Log from Well in Northeast Palm Beach County



Gamma Ray Log from Well in Upper Keys, Monroe County



Gamma Ray Log from Well in Western Charlotte County



Gamma Ray Log from Well in Western Sarasota County