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Borehole Geophysics Evaluation of the Raft River Geothermal Reservoir, Idaho

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ABSTRACT

Borehole geophysics techniques have been utilized for over forty years to detect and evaluate petroleum reservoirs with much success. It is only natural that as the geothermal exploration programs culminate with drilling, that borehole geophysical techniques be applied. However, only a limited number of geothermal reservoirs have been drilled and of those drilled little information has been released on the reservoir evaluation.

One of the reservoirs that has been drilled is the Raft River Geothermal System in Idaho. Three deep holes (5000-6000 ft) have been drilled into this reservoir by the Energy Research and Development Administration - Aerojet Nuclear Company. These holes have all been geophysically logged by commercial firms.

The Raft River Valley is part of the Basin and Range geomorphic province. The valley is filled with approximately 5000 feet of sediments and metamorphosed sediments ranging in age from Precambrian to Recent with a quartz monzonite basement. The geothermal system does not appear to have a local heat source, but results from a blanket of sediments insulating an area of high heat flow.

A major problem in evaluating the Raft River geothermal reservoir is to establish a viable model for the system. The assumed model for the hot water (145°C) reservoir was a zone of higher conductivity, increased porosity, decreased density, and lower sonic velocity. It was believed that the long term contact with the hot water would cause alteration producing these effects. With this model in mind, cross-plots of the above parameters were made to attempt to delineate the reservoir. It appears that the most meaningful data include smoothed and expanded plots of transit time, porosity, and density as a function of depth; and triangular plots of transit time, porosity, and density. This data yields discrete zones which appear to be the productive zones. Further studies and testing are going on to verify these relationships.

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INTRODUCTION

Borehole geophysics techniques have been utilized for over forty years to detect and evaluate petroleum reservoirs with much success. It is only natural that as geothermal exploration programs culminate with drilling that borehole geophysical techniques be applied. However, only a limited number of geothermal reservoirs have been drilled and logged and thus the borehole geophysical techniques applicable to geothermal are not well developed.

The limited utilization of the borehole geophysics has been at least partially motivated by the diversity of geothermal reservoir types. All geothermal reservoirs do not appear to have relatively narrow and discrete productive zones as would be typified by an oil-bearing sand. Instead many geothermal reservoirs probably have varying production from throughout a large zone. This possibility plus the lack of significantly unique physical properties for most geothermal fluids limits not only the delineation of the reservoir, but also the definition of the productivity of the reservoir.

Many of these gaps in our understandings can undoubtedly be filled through the use of logging techniques. There it is important that work continue in this area because a significant data bank must be established to allow the development of techniques and procedures needed to more clearly understand the nature of geothermal reservoirs.

The Raft River geothermal area has been designated as a low temperature geothermal demonstration project. Thus numerous studies have been made in the area. The USGS began geophysical studies of the Raft River valley in 1973. Since that time the USGS, several educational institutions and Aerojet Nuclear Company (ANC) have undertaken geological, geophysical and engineering studies. The studies have been funded by the Energy Research and Development Administration (ERDA). USGS personnel (Mabey et al, 1975; Williams et al, 1975; Zohdy et al, 1975; and Ackerman, 1975) and Boise State University (BSU) personnel (Nichols and Applegate, 1974; Applegate and Donaldson, 1976) have discussed various aspects of the geology and geophysics. In 1974-75, ANC/ERDA drilled three wells ranging in depth from approximately 5000 to 6250 ft (1500 to 1900 meters).

The study described in this report was undertaken to attempt to use geophysical logs to describe the Raft River reservoir. If accurate techniques could be developed, then the costs of completion and testing for future wells could be minimized. To be of maximum use, the data in this report should be correlated with further testing being conducted by Aerojet Nurclear Company (now E.G. & G.) and with data yet to be open-filed by the USGS.

GEOLOGICAL AND GEOPHYSICAL STUDIES

The Raft River geothermal system is located in the Raft River valley in south-central Idaho, south of the Snake River plain and north of the Utah-Idaho boundary (Figure 1). The Raft River valley is part of the Basin and Range geomorphic province.

Geological Studies

The USGS has conducted extensive surface geology studies and has also studied samples obtained in the three drill holes. Some of the data has already been open-filed, other data has been released in abstracts and additional information will soon be open-filed.

According to Williams et al (1975), the valley is a late Cenozoic structural downwarp bounded by faults on the west, south and east. The downwarp is filled with Tertiary and Paleozoic sediments and volcanics which overlie Precambrian rocks. The Tertiary deposits are composed of (1) 5 to 70 meters (15-230 ft) of Pleistocene and Holocene fan gravels and alluvium, (2) 0-200 meters (0-655 ft) of silt and sand composing the Pleistocene Raft Formation, and (3) up to 1800 meters (5905 ft) of the Pliocene Salt Lake Formation which consists of lower tuffaceous sediments, middle volcanics...felsic lava flows, and ash flows, and upper basin-fill tuffaceous sediments and conglomerates (Williams et al, 1975). Beneath these rocks are complex Paleozoic rocks consisting of interbedded quartzite, limestone, shale, dolomite and sandstone. These rocks overlie Precambrian rocks which consist of the Upper Narrows Schist, the Elba Quartzite and quartz monzonite basement.

structure

The geothermal area appears to be controlled by the intersection of a major ENE-trending feature through the Narrows (the Narrows ~~fault~~) and a north-trending feature (the Bridge fault). The Narrows ~~fault~~ is a major feature on LANDSAT imagery. The Bridge fault has been mapped by both geological and geophysical techniques (Williams et al, 1975; Mabey et al, 1975). The first exploration hole, RRGE #1, was located to intersect areas of suspected increased porosity at the postulated intersection of the Narrows fault and the Bridge fault (Nichols and Applegate, 1974; Williams et al, 1975; Mabey et al, 1975). RRGE #1 produced water of approximately 145°C. The two other wells were drilled to further evaluate the reservoir. Figure 2 is a sketch of the locations of RRGE #1, RRGE #2 and RRGE #3 and the approximate location of the Narrows and Bridge fault zones.

A generalized correlation section showing the relative structural relationships between the holes is shown in Figure 3. This section is based on correlations of the logs and information compiled from Aerojet Nuclear Company and USGS information. Looking at Figures 2 and 3 together, one can see that structural complexities undoubtedly complicate the correlation section (Figure 3). Zone 2 may even be the actual fault zone or may represent areas of leakage of fluids from the fault into the adjacent formation.

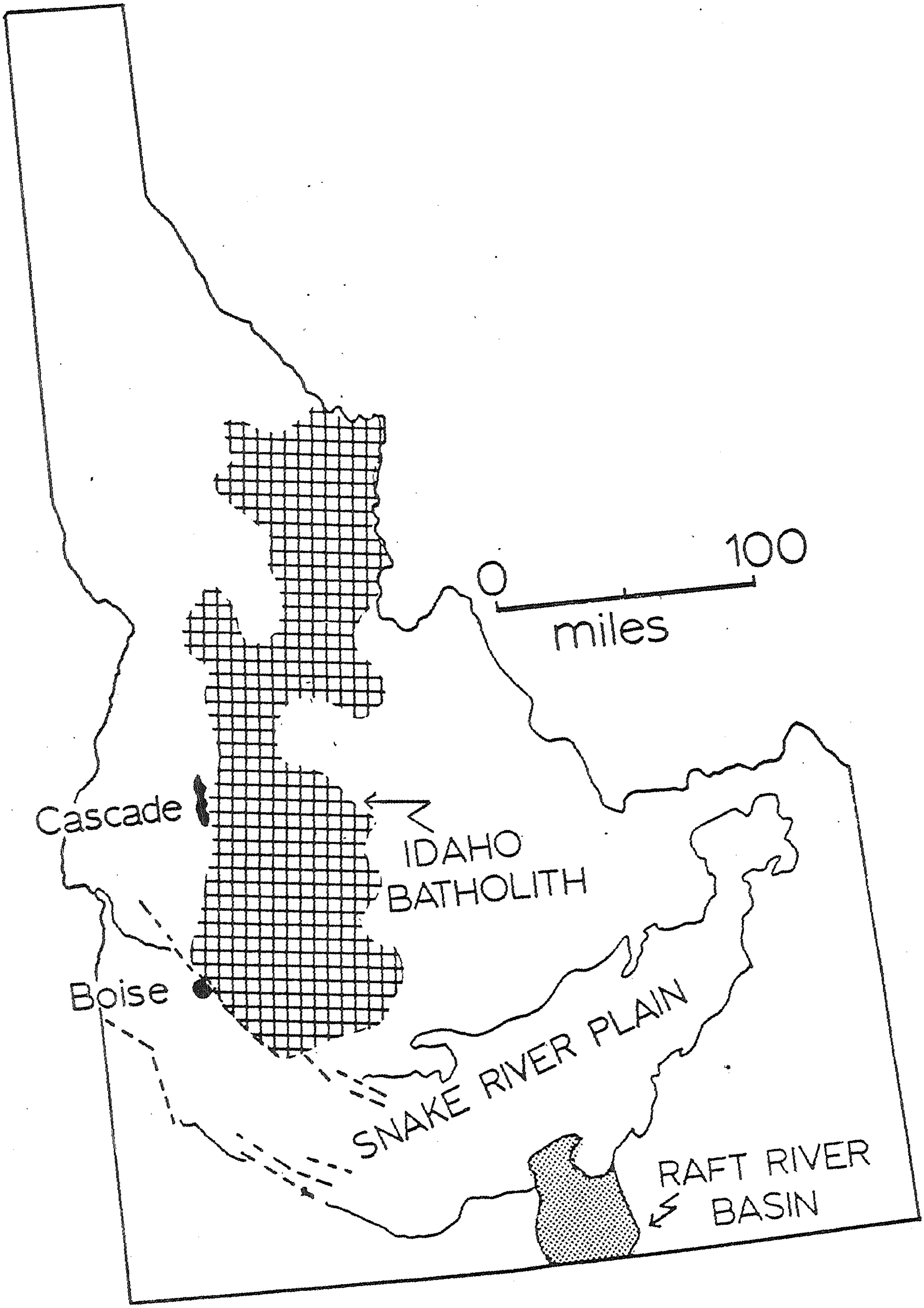

FIGURE 1. LOCATION MAP

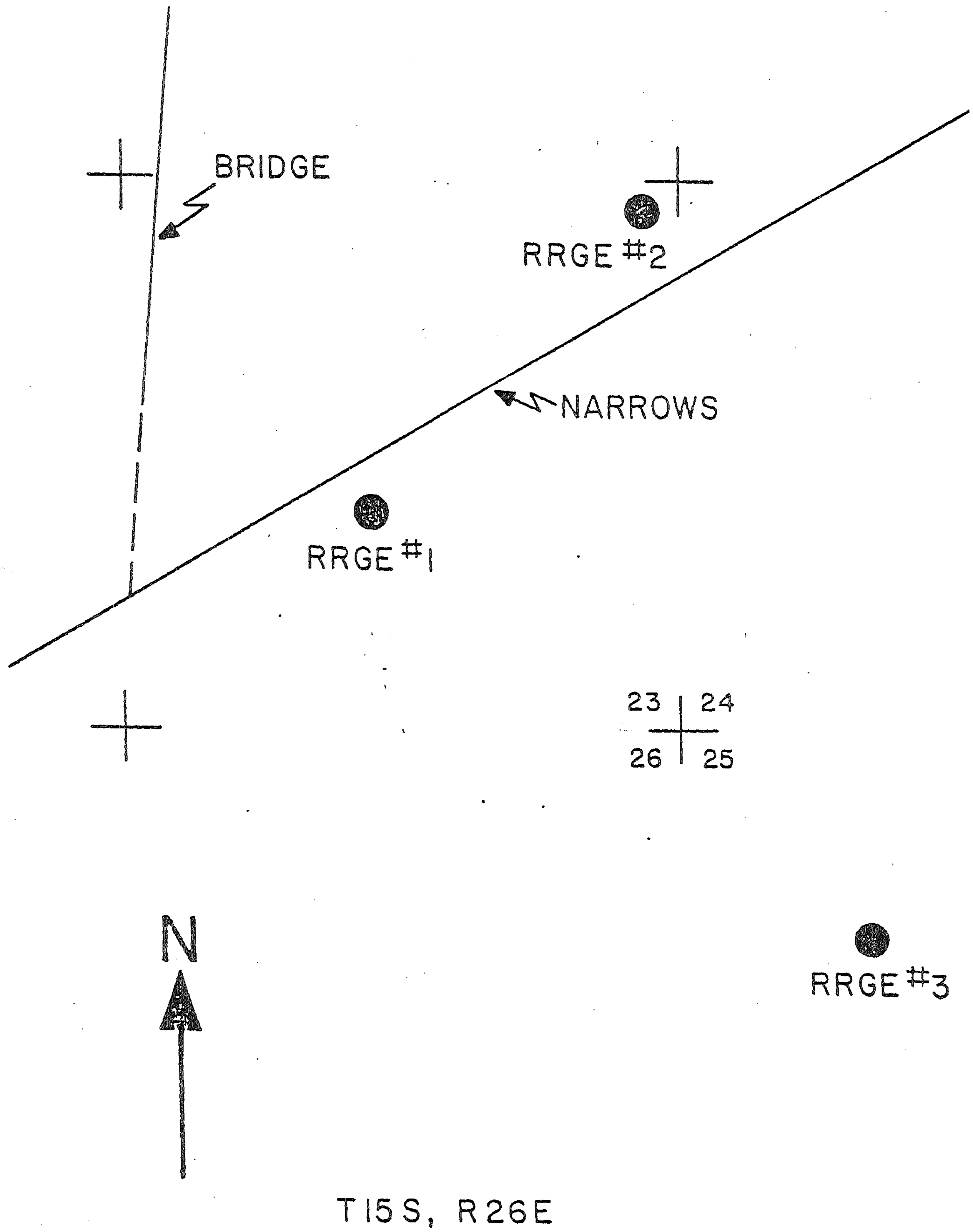

FIGURE 2 - SCHEMATIC SKETCH OF WELLS AND FAULT LOCATION

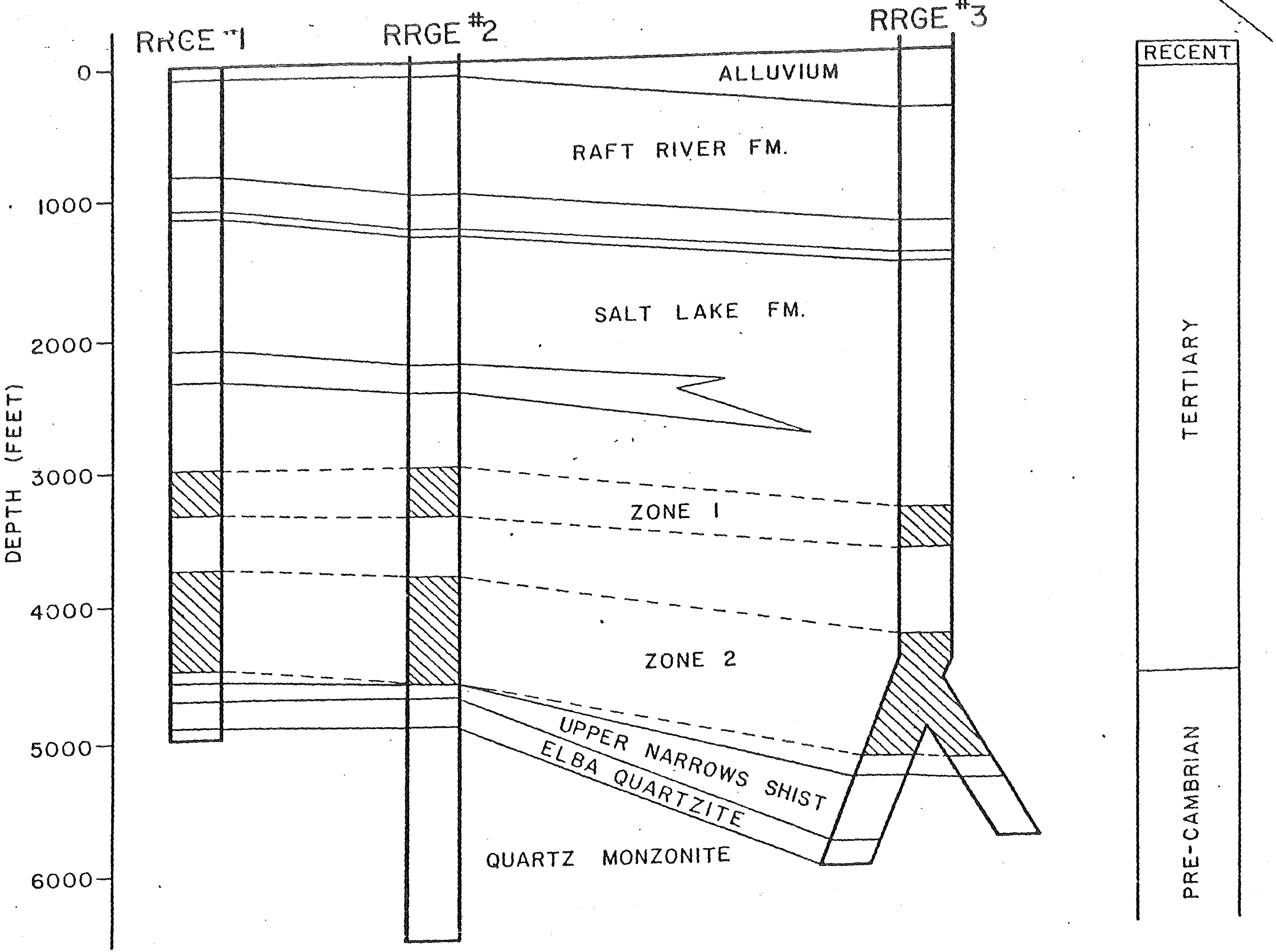

FIGURE 3 - WELL CORRELATION CHART

Geophysical Studies

Extensive surface geophysical surveys were conducted by the USGS. The study included gravity, magnetic, refraction seismic, resistivity, audio magnetotelluric, self-potential, and telluric current surveys. The geophysical surveys indicated a maximum thickness of about 2 km of Cenozoic sedimentary and volcanic rock which supported the general geology (Mabey et al, 1975).

Resistivity anomalies have been interpreted to be indicative of variations in composition as well as degree of induration and alteration of Cenozoic rocks (Mabey et al, 1975). This view is supported by conductivity increases recorded by the well logs in suspected productive zones. Reinterpretation of surface geophysical data in the context of the borehole geophysics and geological data should provide an insight to the structural controls for the reservoir.

Additional geophysical data particularly high resolution seismic reflection studies would be extremely useful in evaluating fault systems, which are believed to be the structural controls in the Raft River model. These studies offer additional interpretative value in defining rock typing parameters necessary for the direct detection of the reservoir from the surface.

BOREHOLE GEOPHYSICAL STUDIES

Numerous geophysical logs were used in the three boreholes. The suite ran in each borehole generally consisted of natural gamma, SP, neutron, density, caliper, induction-electric, sonic and temperature. The dipmeter was run in some holes and provided some useful structural information. Flow meters were also run in the various holes with no significant success due to tool failures.

The tools used in this study generally included the neutron, density and sonic. The other tools were not considered in detail because of the apparent lack of significant response. The conductivity log, for example, was expected to show significant response in the productive zones. However, the conductivity appeared to increase only slightly in the productive zones.

The Reservoir Model

The major goal in evaluating the Raft River geothermal reservoir or any geothermal reservoir is to establish a viable model for the system. Classically, geothermal reservoirs have been assumed to be closely associated with shallow magma bodies. However as exploration has progressed in the western U.S., it has become obvious that geothermal reservoirs do not require a shallow magma chamber as a heat source. Instead near-surface geologic conditions can focus heat flow such that local "hot spots" - geothermal reservoirs - develop (Keller, 1975; Applegate and Donaldson, 1976).

The Raft River valley is an example of such a system. In this case, a relatively thick layer of low conductivity material (sediments) would have excess temperatures at the base (Figure 4). For example, if one assumes a heat flow of 4.5 HFU, and a thermal conductivity of 7.0 mcal/cm S °C for the quartz monzonite basement rocks, and a conductivity of 3.0 for the sediments, one can calculate an excess temperature of 171 °C for 2.0 km (6550 ft) of sediments, and 214 °C for 2.5 km (8200 ft) of sediments (see Diment et al, 1975; Applegate and Donaldson, 1976). Brott et al (1976) have also shown that this heat concentration is focused along a boundary fault to the basin. In the case of the Raft River this could be the Bridge fault zone.

The reservoir model for the Raft River system is, thus, a sediment-filled basin with a boundary fault causing heat retention and focussing. The productive reservoir would be anticipated to be from fracture porosity in the fault zone (or the intersection of the Bridge and Narrows fault zones) or from porous and permeable formations intersected by the fault zone into which leakage of thermal fluids has occurred. Ground water would be expected to circulate into this system and heated. The circulation of thermal water would cause alteration and in some cases, healing of the fracturing (Batzle and Simmons, 1976).

With the model in mind, one must evaluate the response of various geophysical logs to such a model. The model would have a reservoir with fracture-controlled porosity resulting from faulting, and alteration resulting from long term hot water effects. These effects should produce zones of increased porosity, decreased density, lower sonic velocity and higher conductivity.

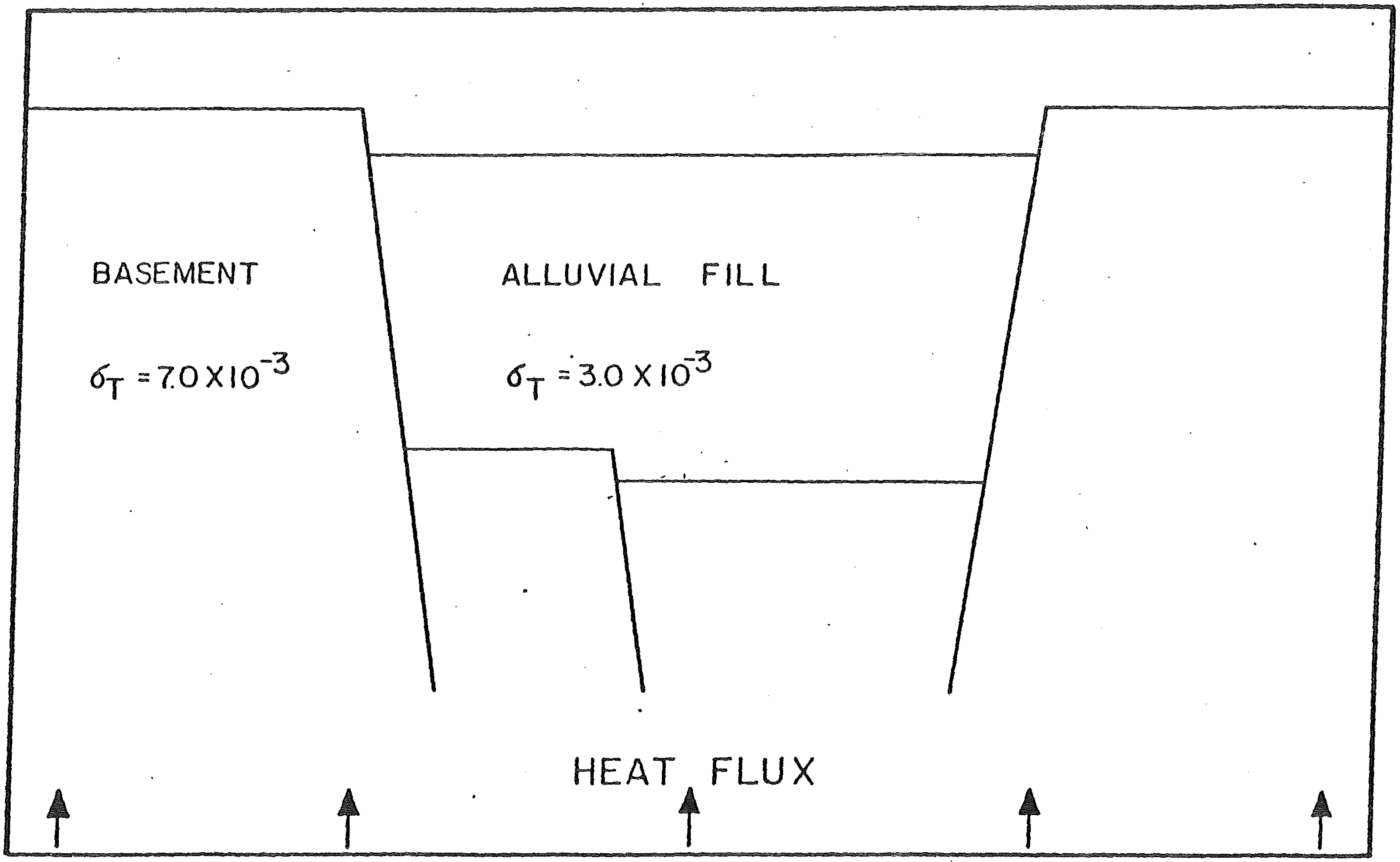

FIGURE 4 - ALLUVIAL - FILLED BASIN GEOTHERMAL MODEL

Log Analysis

Numerous techniques of log interpretation have been developed in the petroleum industry. Some of these have been labeled as empirical, cook book and cross plotting techniques (Pickett, 1971).

Analysis of the Raft River logs was begun using cross plotting techniques. It was hoped that the cross plotting would allow differentiation of productive zones by rock typing. Numerous parameters were cross plotted with only partial success. The limitation was the lack of variation in properties of the suspected productive zones from non-productive zones slightly shallower in the section. The most successful cross plotting approach was plotting bulk density (ρ_B), neutron porosity (ϕ_N), and transit time (Δt) on a triangular plot (Figure 5). With judicious handling of the data these plots broke out two zones of interest in each well. Careful handling of the data was necessary, however, because the shallow section has the physical properties suspected for the productive zone. For this reason, the traingle plot has limited applicability and it was necessary to pursue additional analysis approaches. Plots of ρ_B, ϕ_N, and Δt as a function of depth for RRGE #1 (Figures 6, 7 and 8), RRGE #2 (Figures 9, 10 and 11) and RRGE #3 (Figures 12, 13, and 14) show some zones of interest on each of the logs.

From past experience and from observation of the data in figures 6-14, one can see that some functional relationship exists between the aforementioned parameters and depth. The basic trends are that ϕ_N and Δt decrease with depth while ρ_B increases with depth. These observations offer the possibility of utilization of these trends to recognize the reservoir since the anticipated reservoir rock has significant departures at depth from these trends (e.g. ρ_B decreases, Δt increases and ϕ_N increases in the reservoir).

Therefore the next step in the procedure was to establish functional relationships of the various parameters with depth. Normalized parameters were then calculated for each well. The normalized parameters are the difference between the observed data and the predicted trend. Intuitively these parameters should show significant anomalies throughout the productive zones.

The normalized parameters are shown in Figures 15, 16 and 17 (RRGE #1); 18, 19 and 20 (RRGE #2) and 21, 22 and 23 (RRGE #3). Study of the information delineates two zones that appear to deviate significantly from the normal trend. The shallower zone (zone 1) is from 3100 to 3300 ft in RRGE #1, from 3000 to 3350 ft in RRGE #2, and from 3300-3700 ~~3100 to 3300~~ ft in RRGE #3. Figure 3 shows the relationships between this zone in the three wells. Zone 1 does not appear to be a significant producer of large quantities of hot water. This zone probably represents leakage along faults or fractures into a shallow horizon where mixing with cool water occurs.

RRGE #1

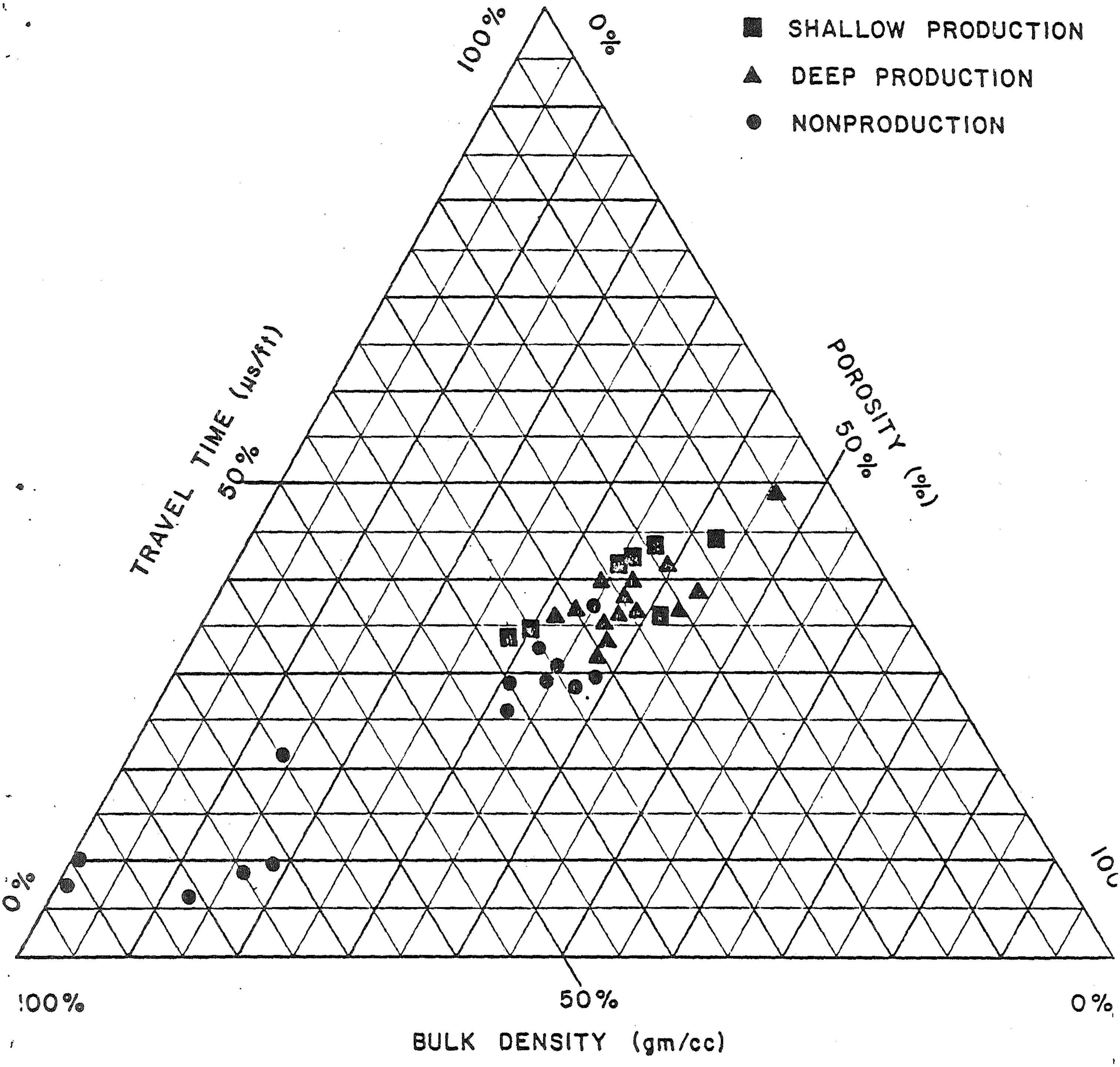

FIGURE 5 - TRIANGULAR PLOT OF BULK DENSITY, POROSITY, AND TRANSIT TIME

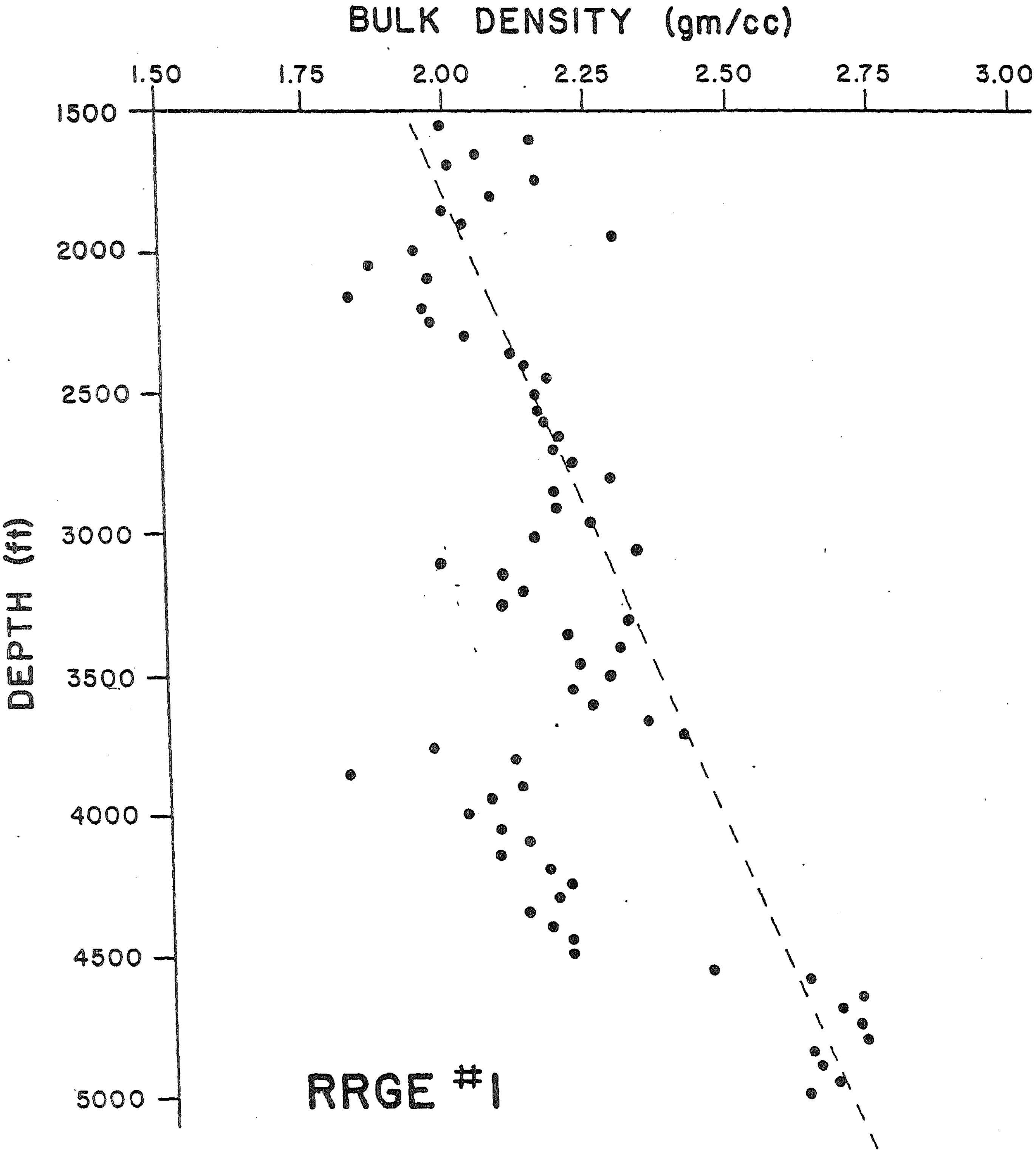

FIGURE 6 - BULK DENSITY FOR RRGE # 1

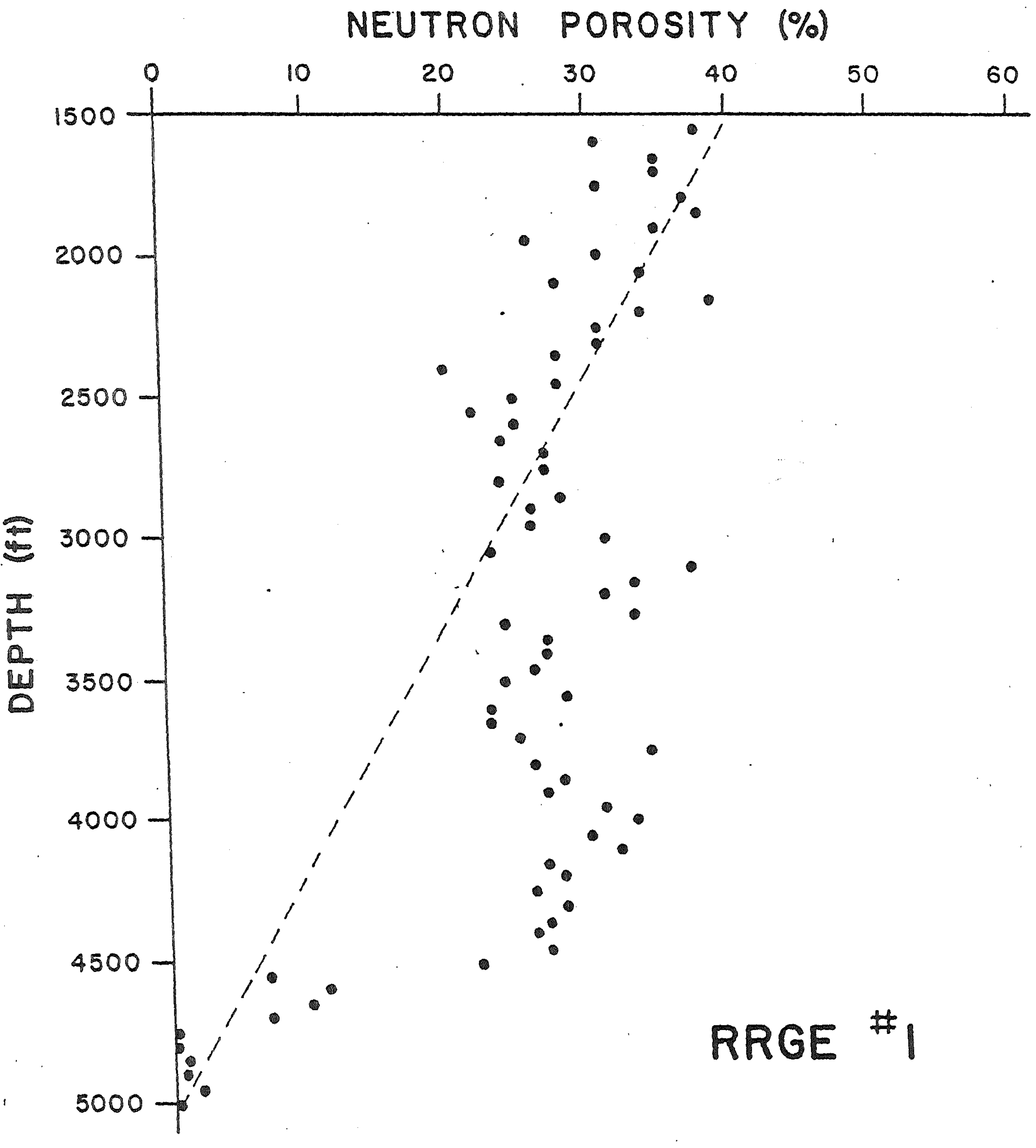

FIGURE 7 - NEUTRON POROSITY FOR RRGE # 1

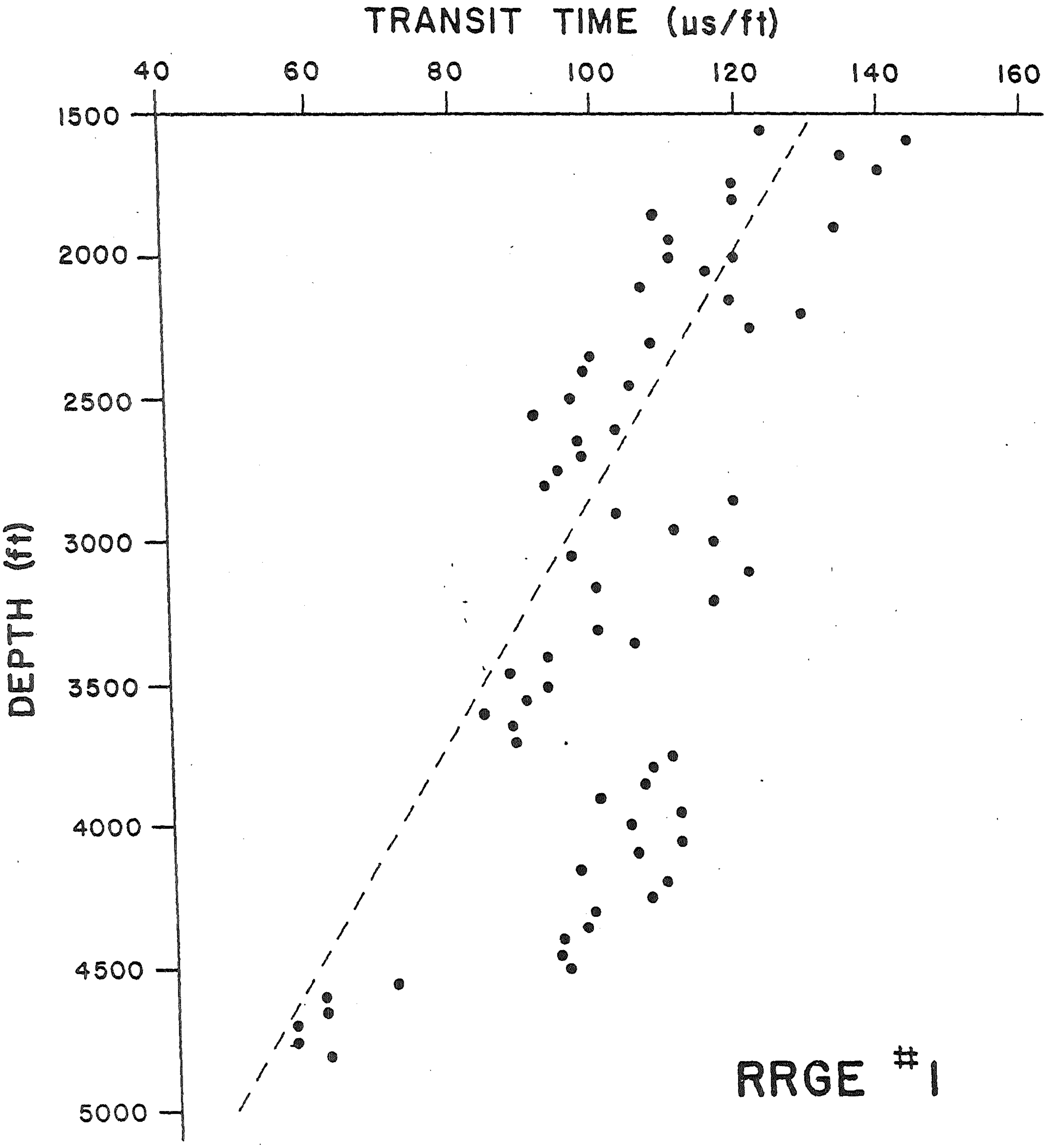

FIGURE 8 - TRANSIT TIME FOR RRGE # 1

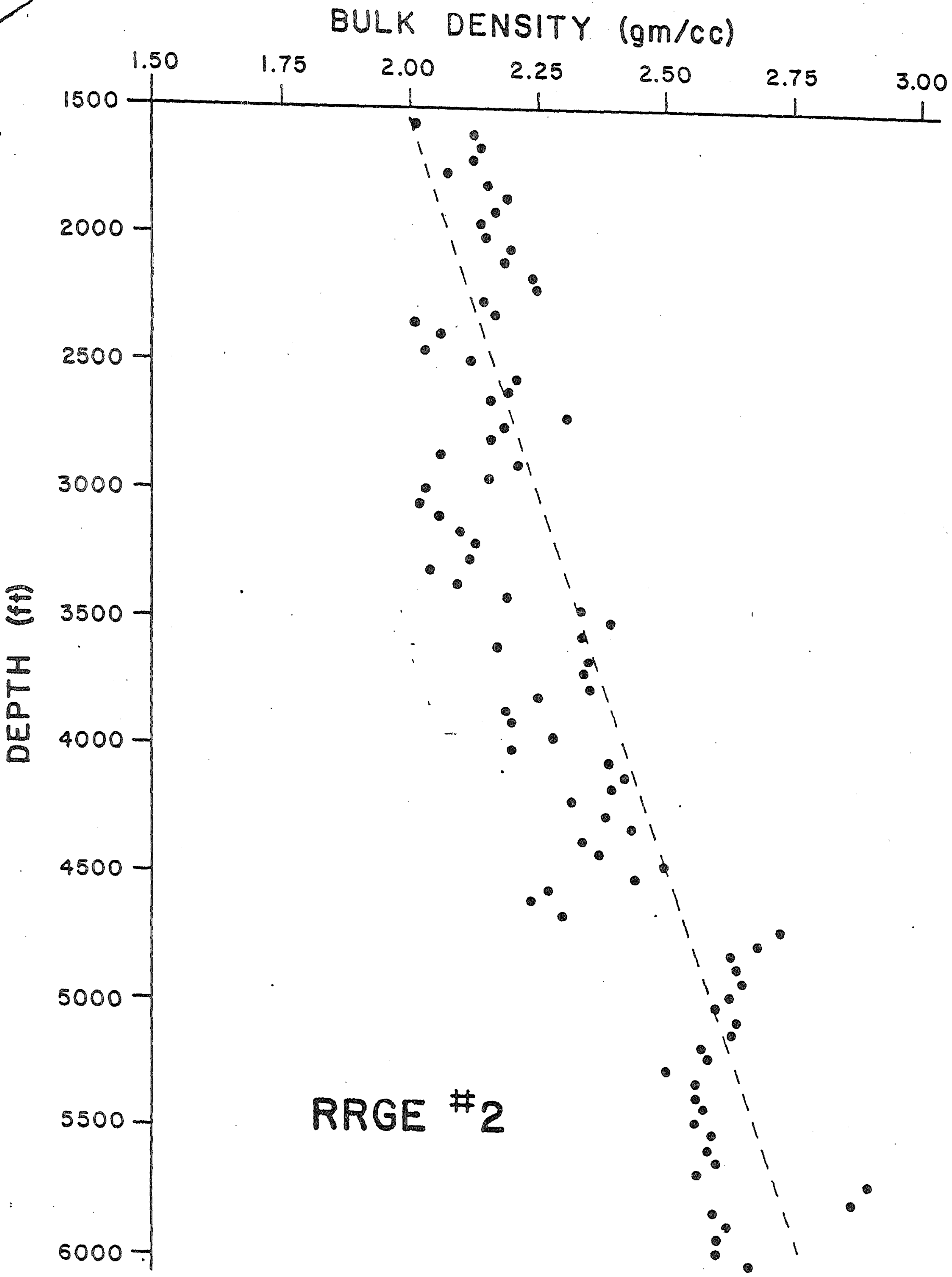

FIGURE 9 - BULK DENSITY FOR RRGE # 2

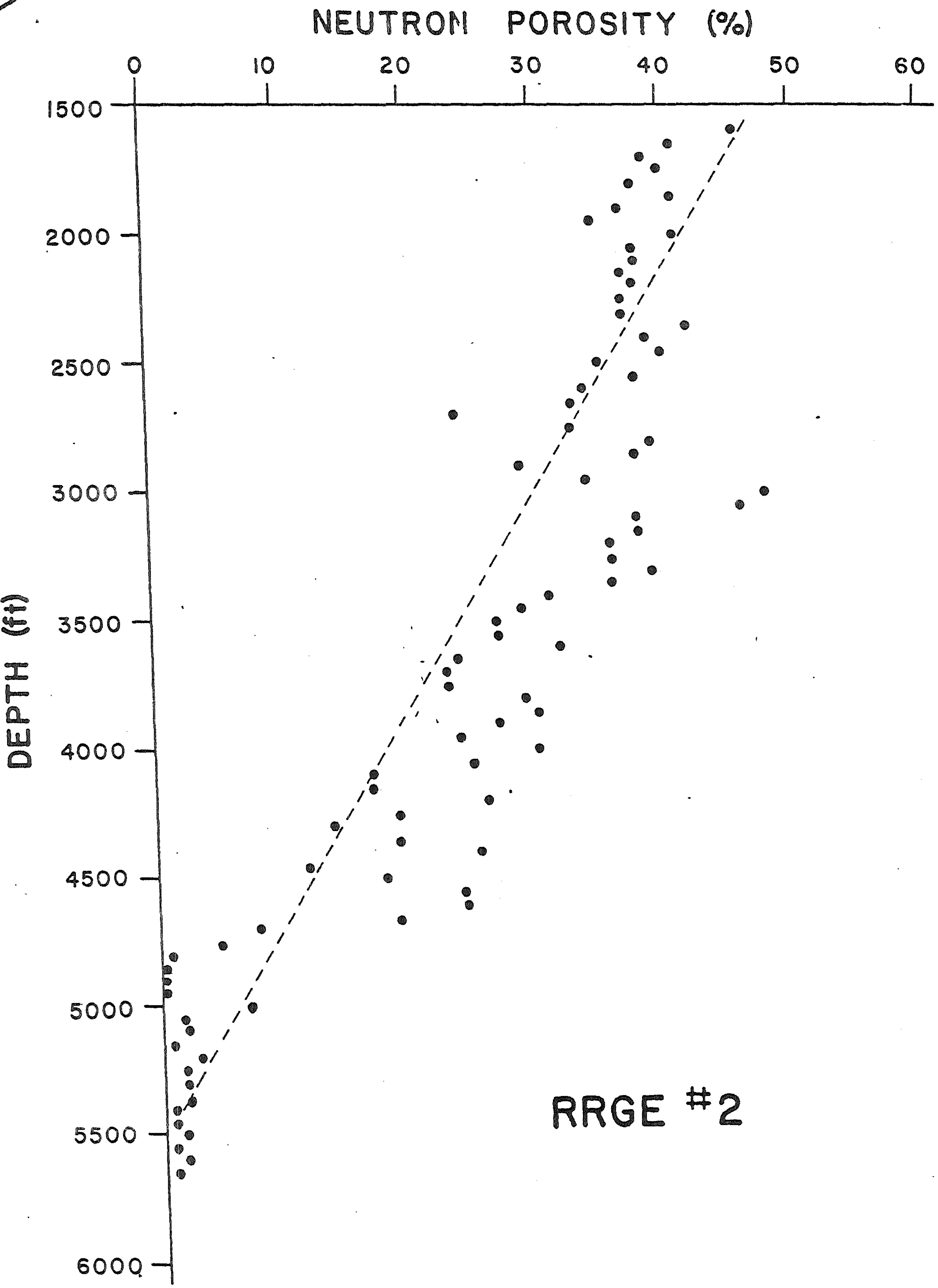

FIGURE 10 - NEUTRON POROSITY FOR RRGE # 2

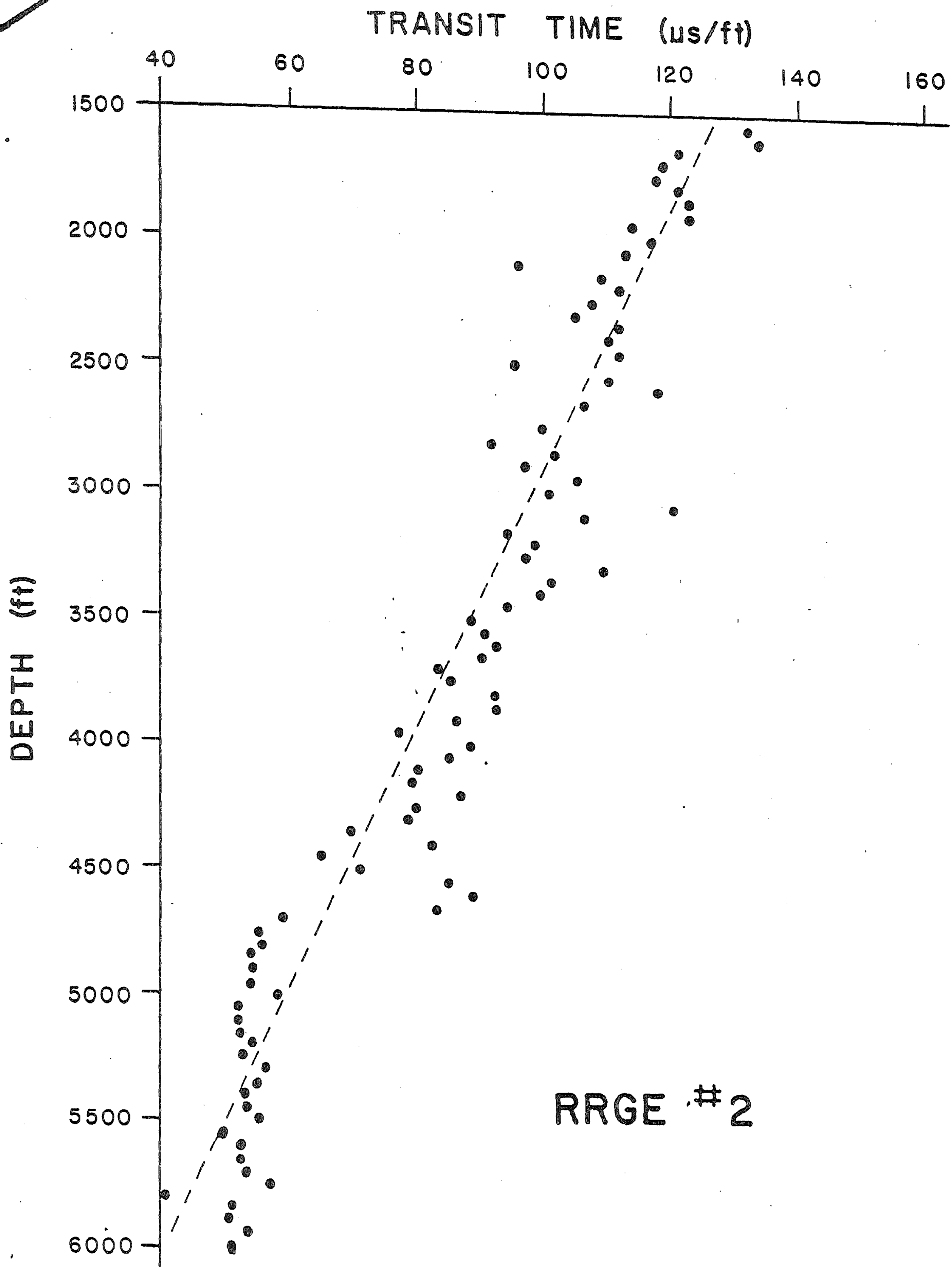

FIGURE 11 - TRANSIT TIME FOR RRGE # 2

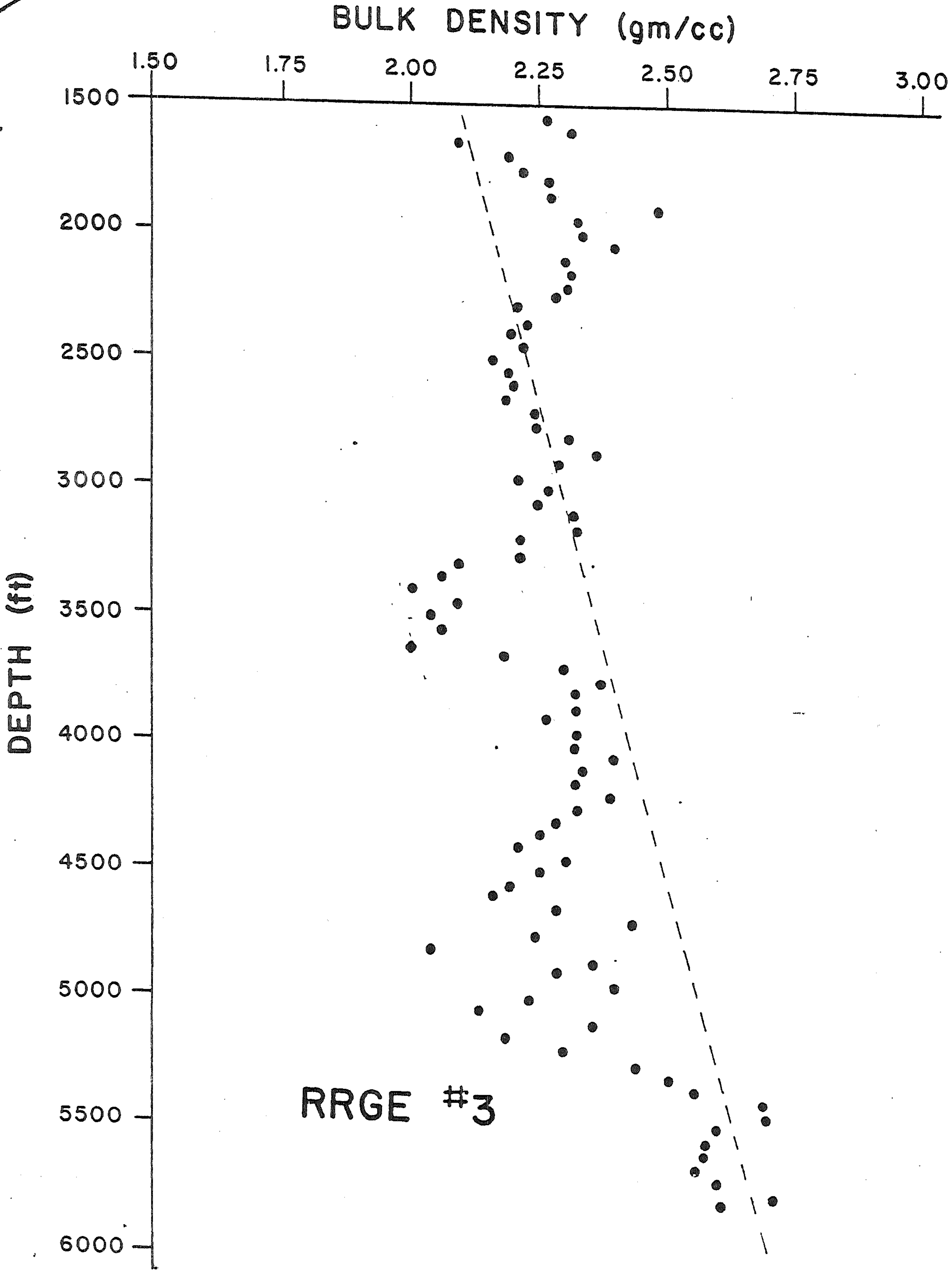

FIGURE 12 - BULK DENSITY FOR RRGE # 3

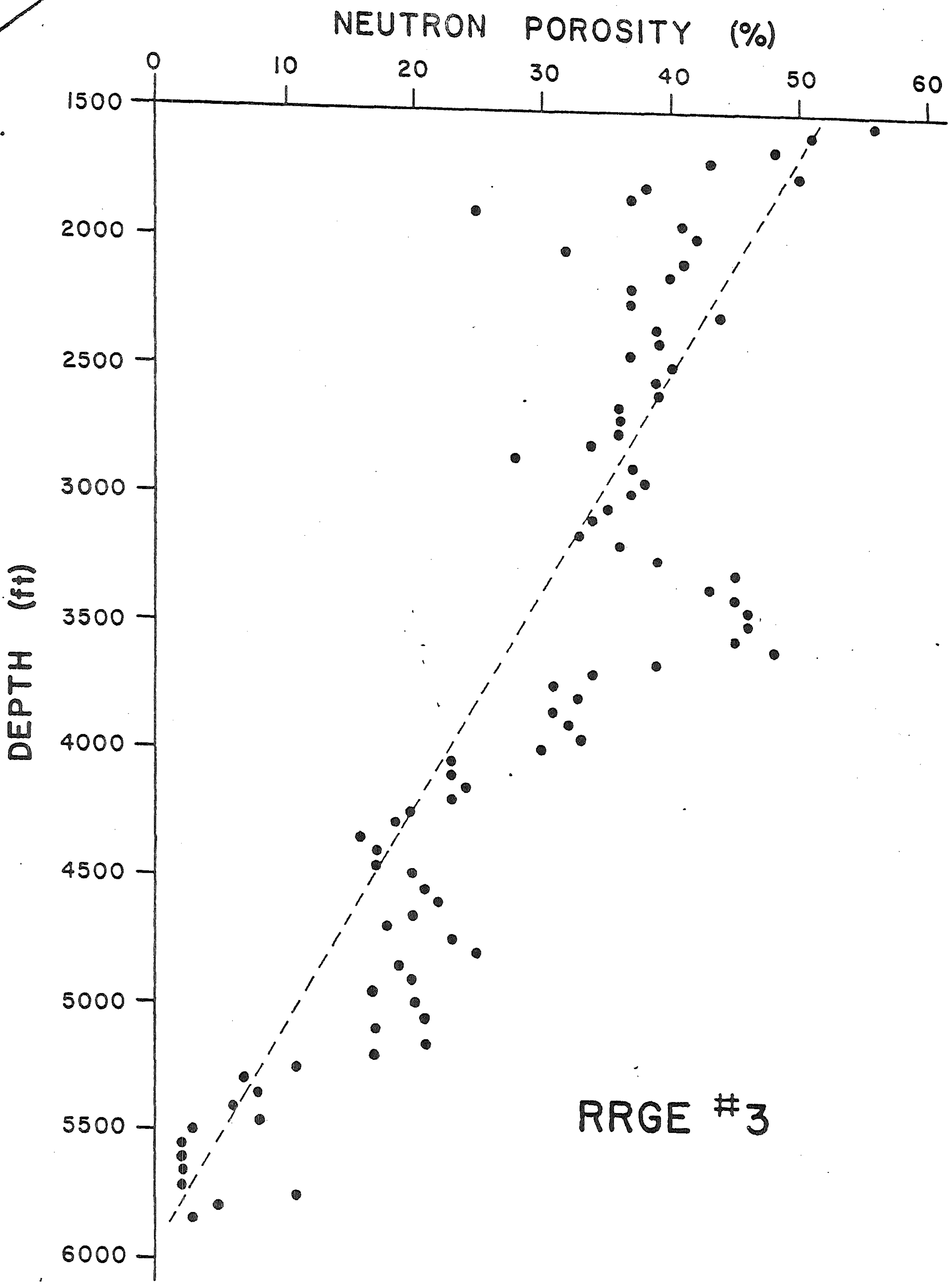

FIGURE 13 - NEUTRON POROSITY FOR RRGE # 3

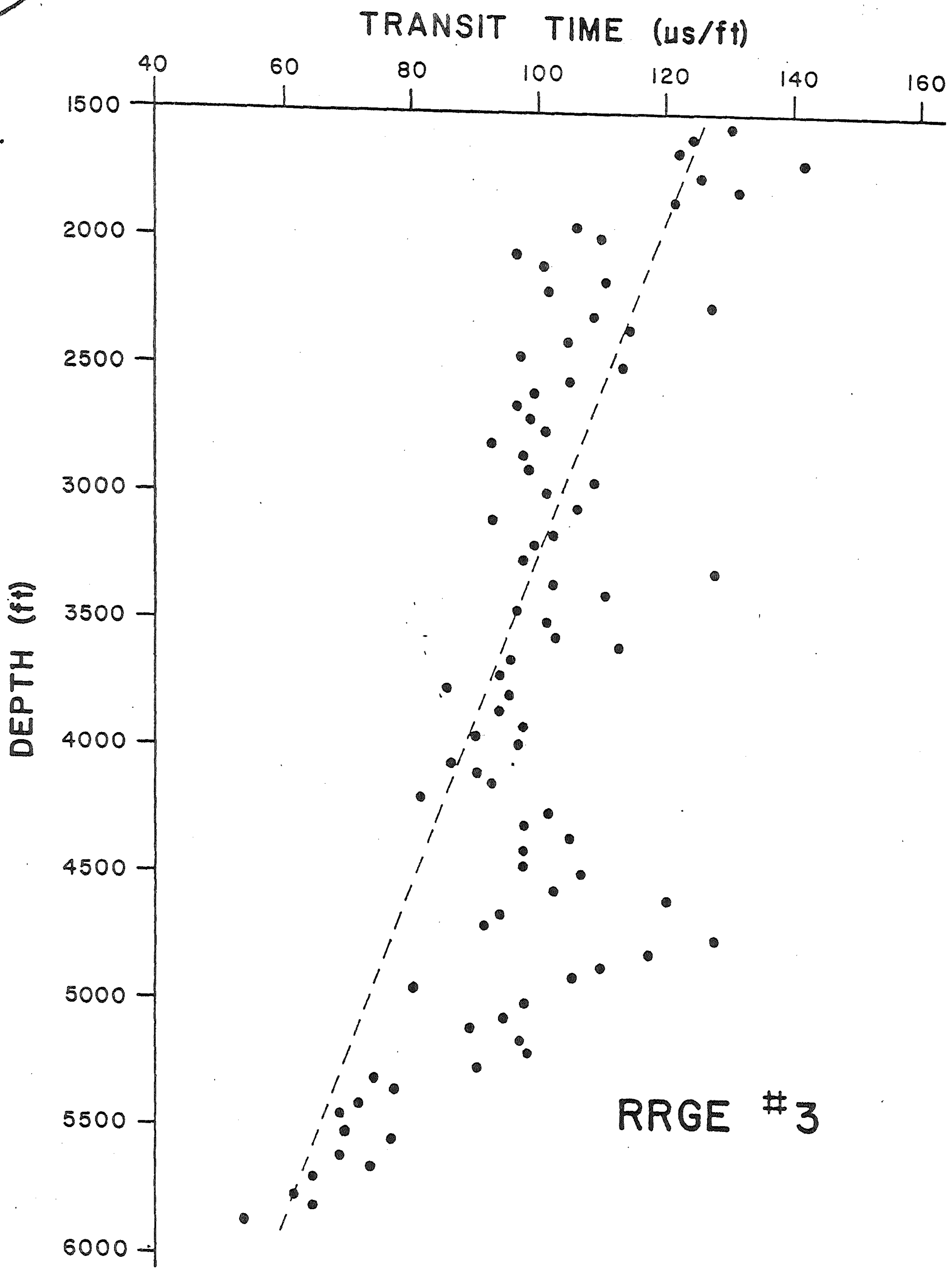

FIGURE 14 - TRANSIT TIME FOR RRGE # 3

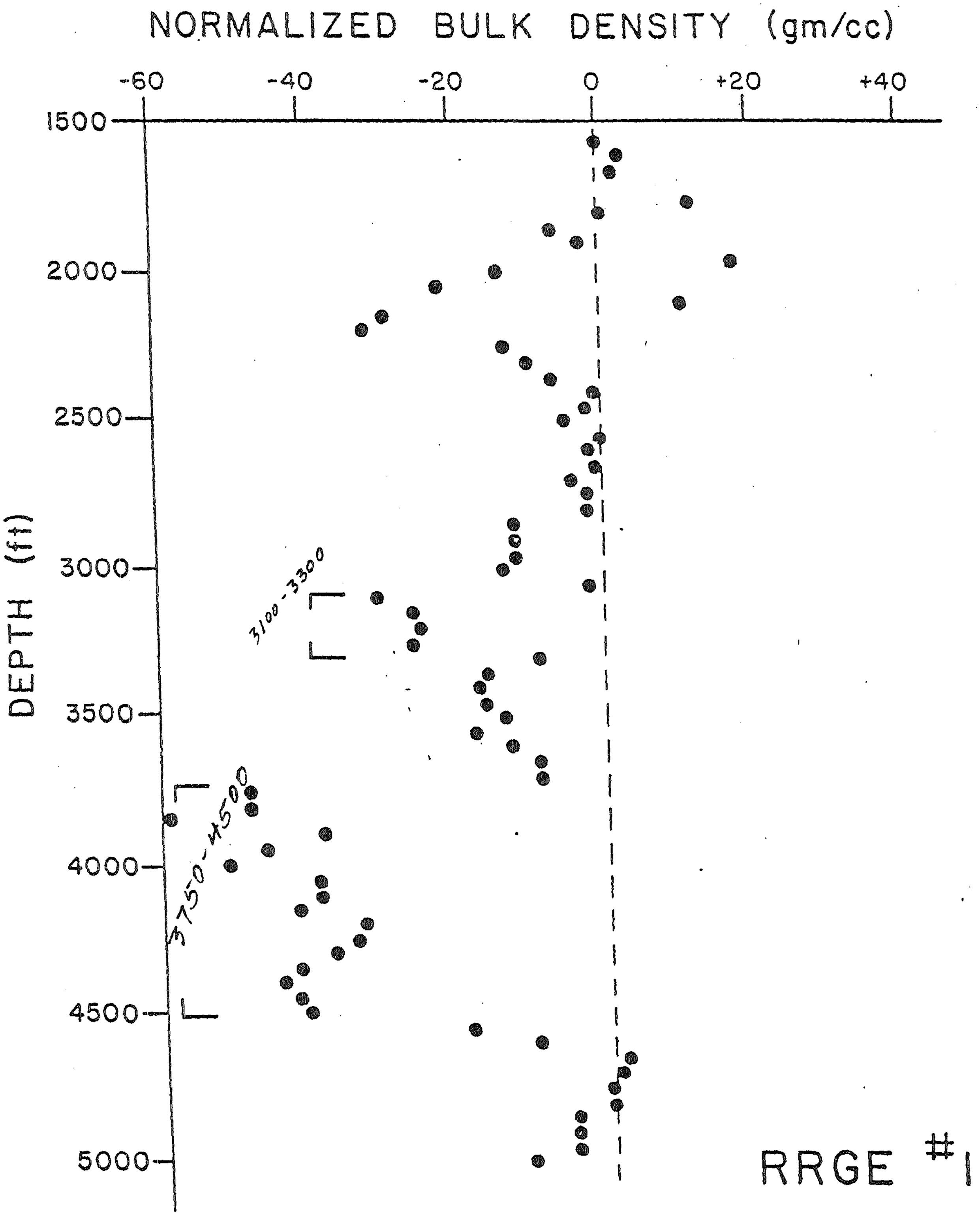

FIGURE 15 - NORMALIZED BULK DENSITY FOR RRGE # 1

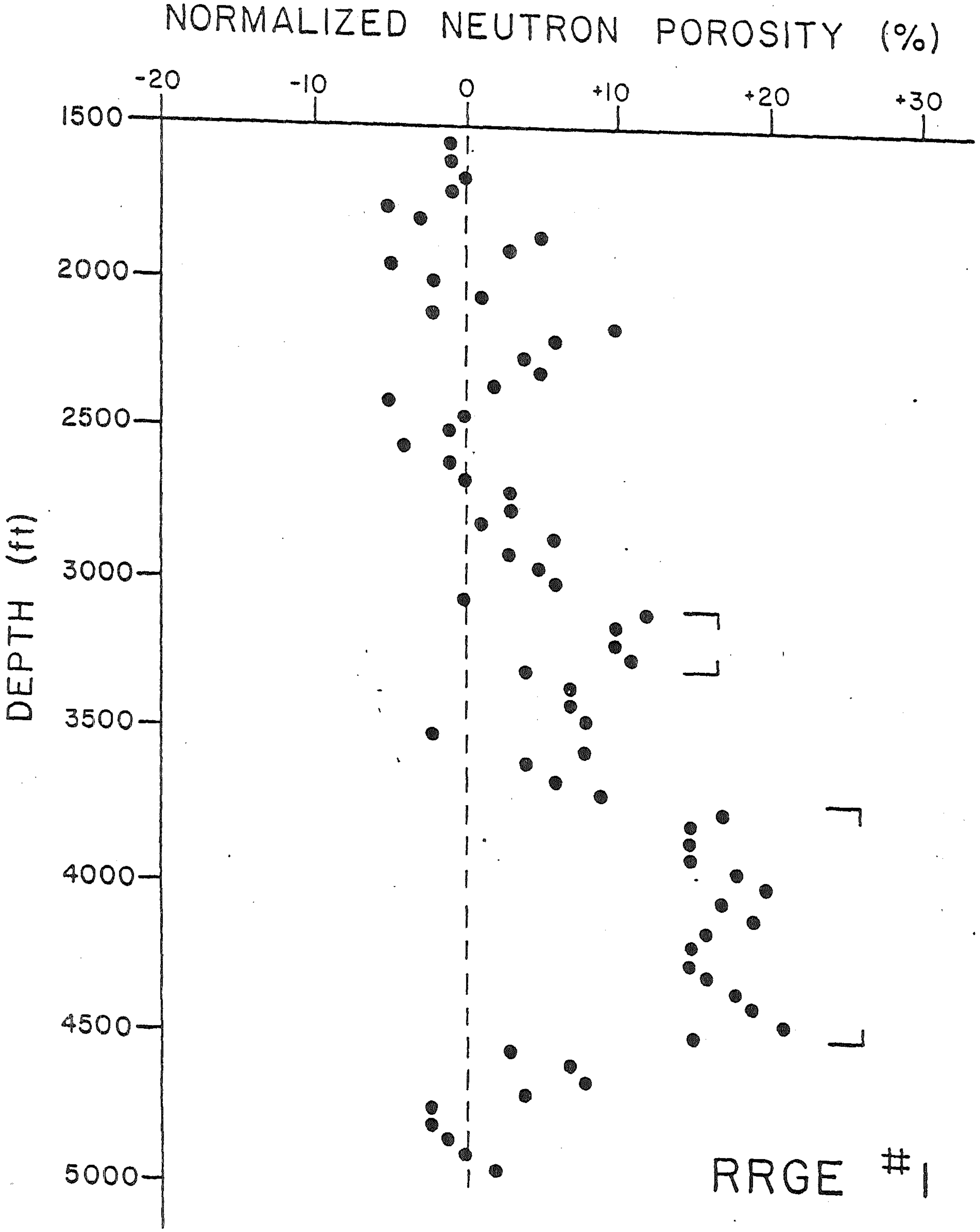

FIGURE 16 - NORMALIZED NEUTRON POROSITY FOR RRGE # 1

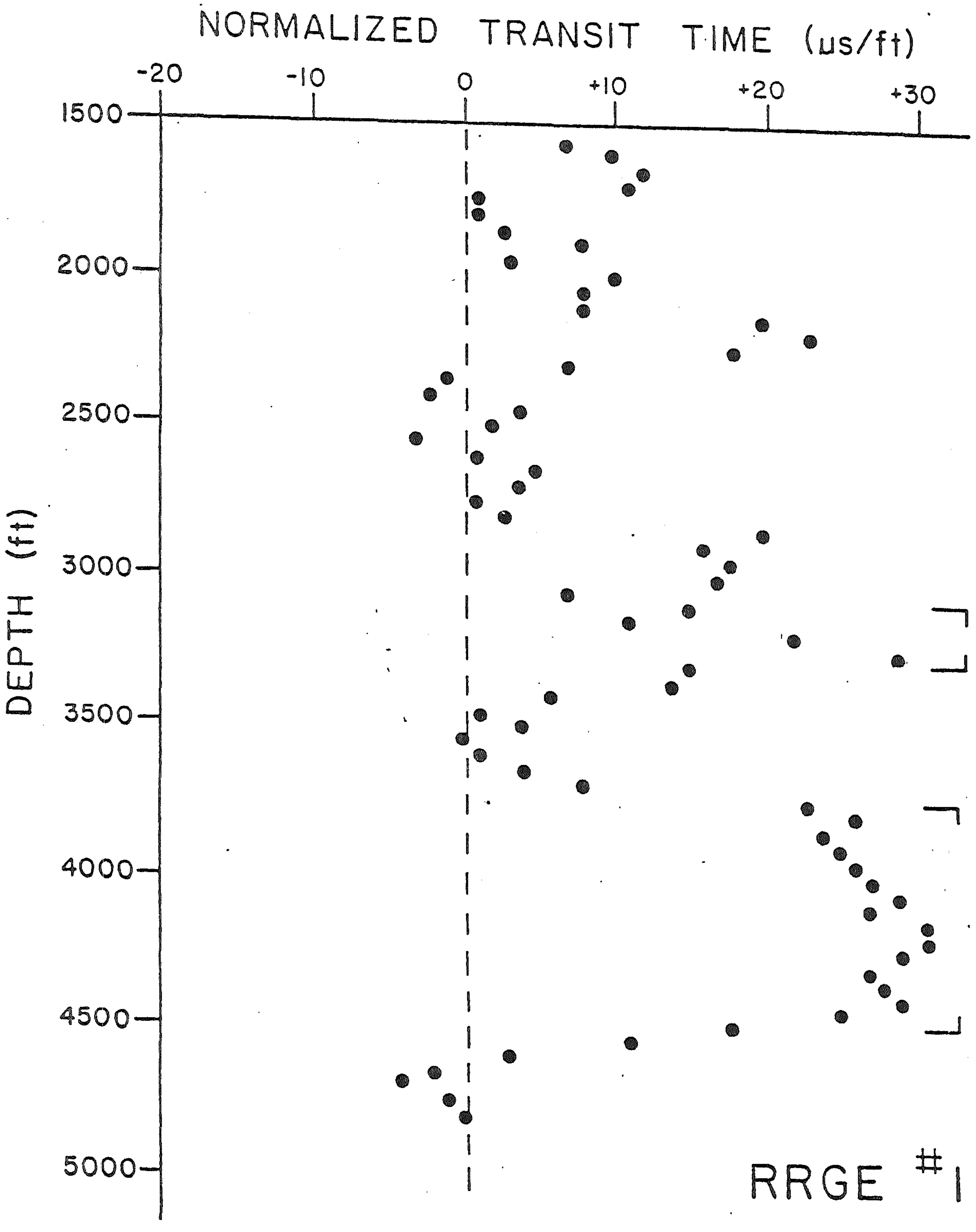

FIGURE 17 - NORMALIZED TRANSIT TIME FOR RRGE # 1

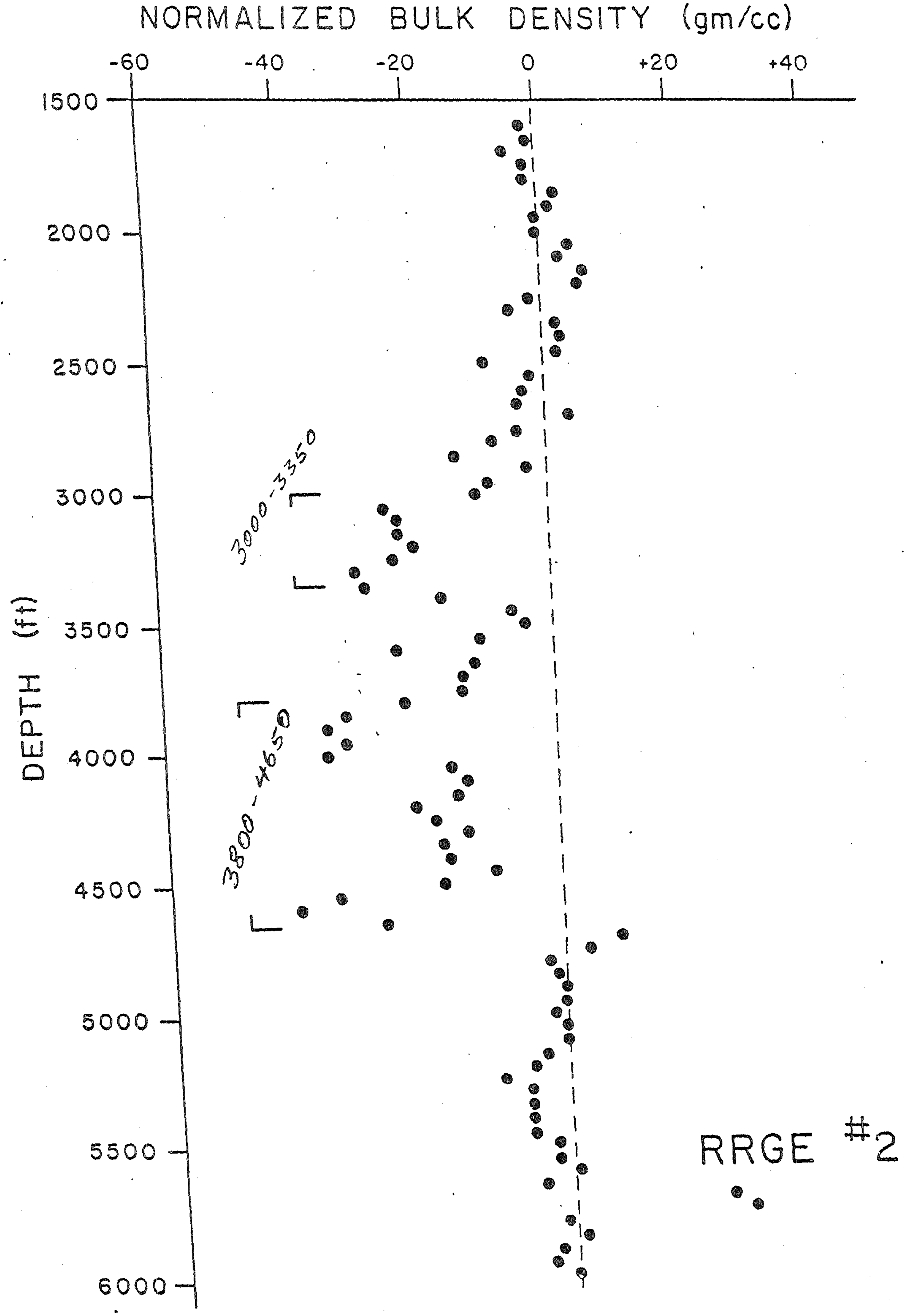

FIGURE 18 - NORMALIZED BULK DENSITY FOR RRGE # 2

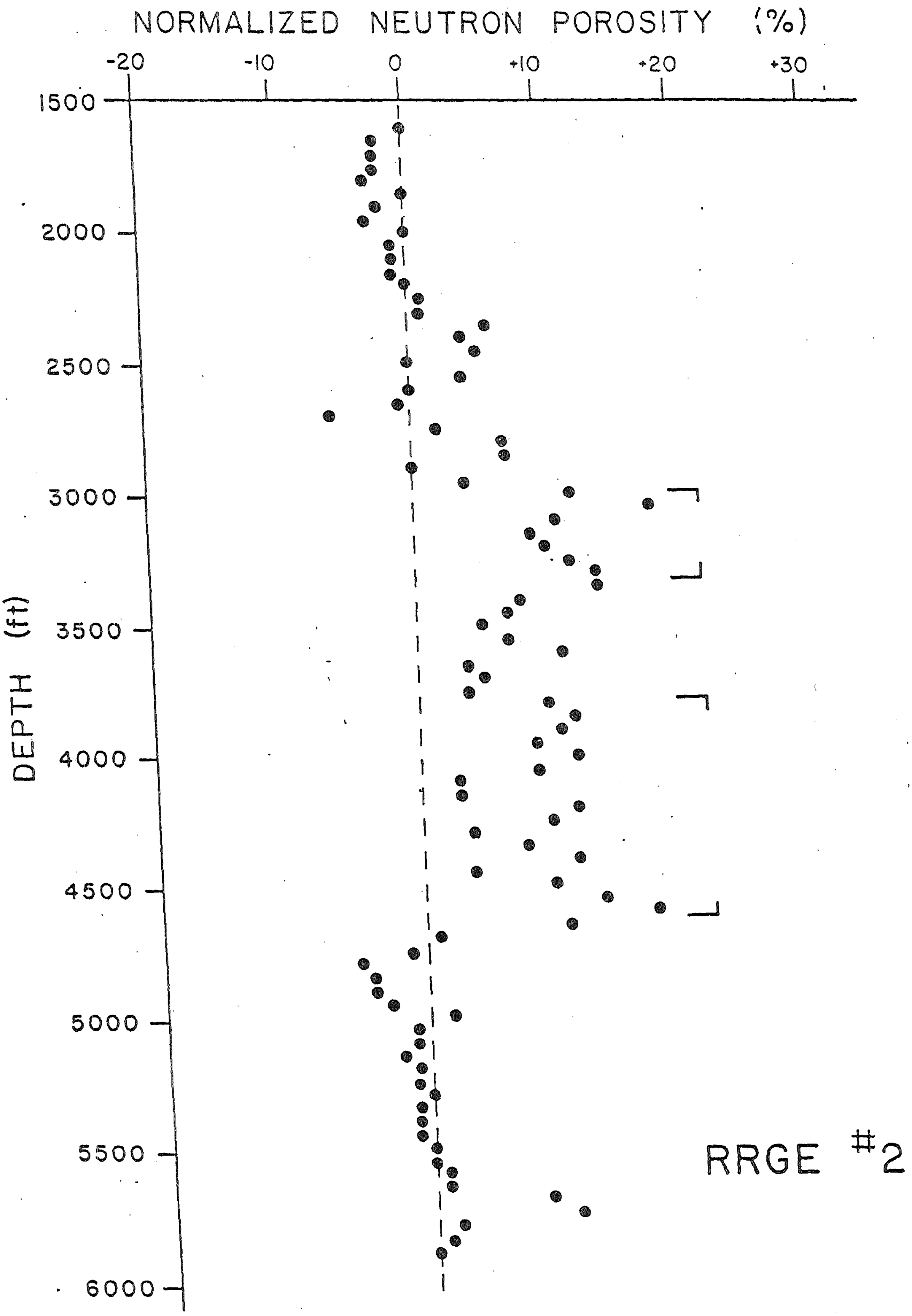

FIGURE 19 - NORMALIZED NEUTRON POROSITY FOR RRGE # 2

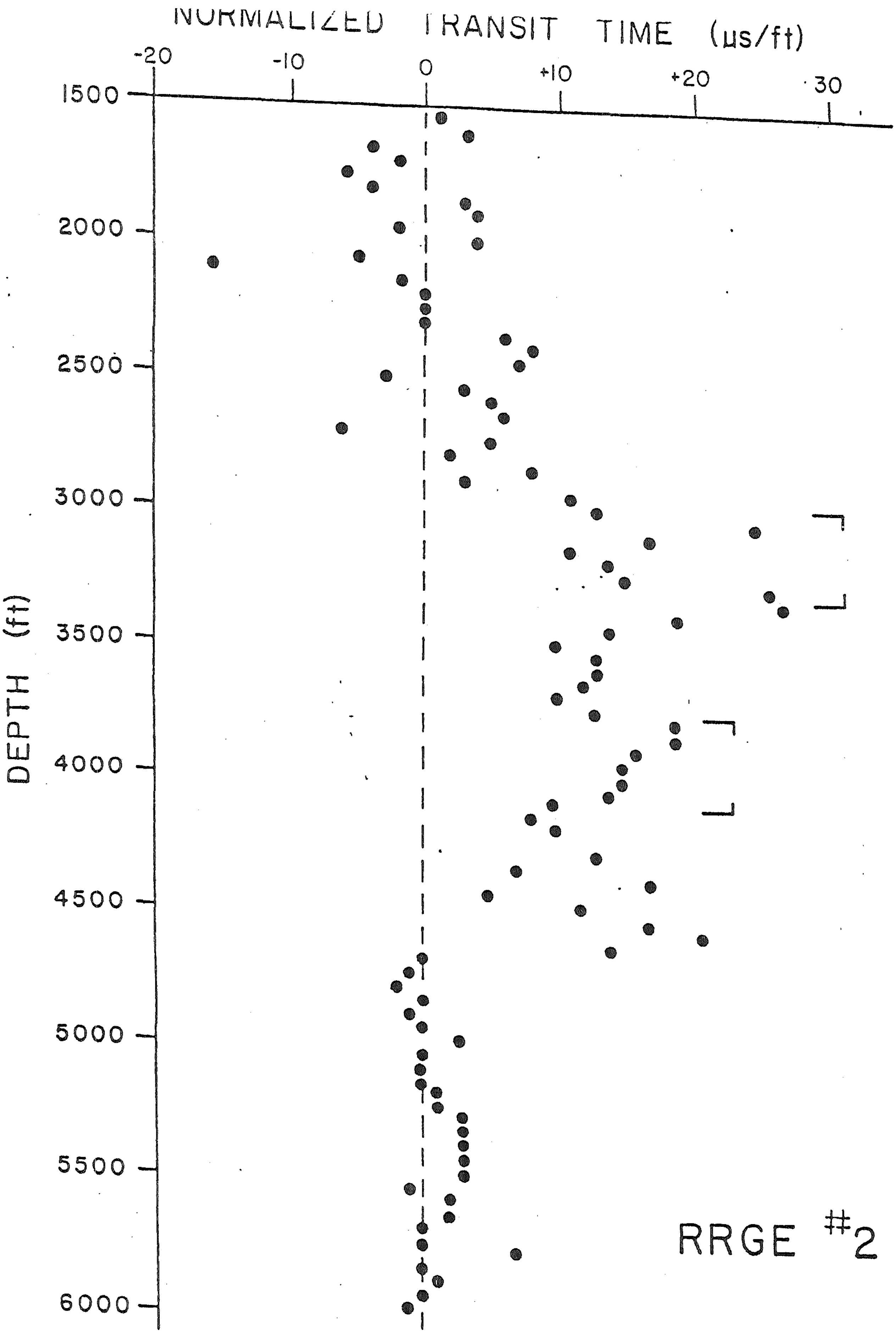

FIGURE 20 - NORMALIZED TRANSIT TIME FOR RRGE # 2

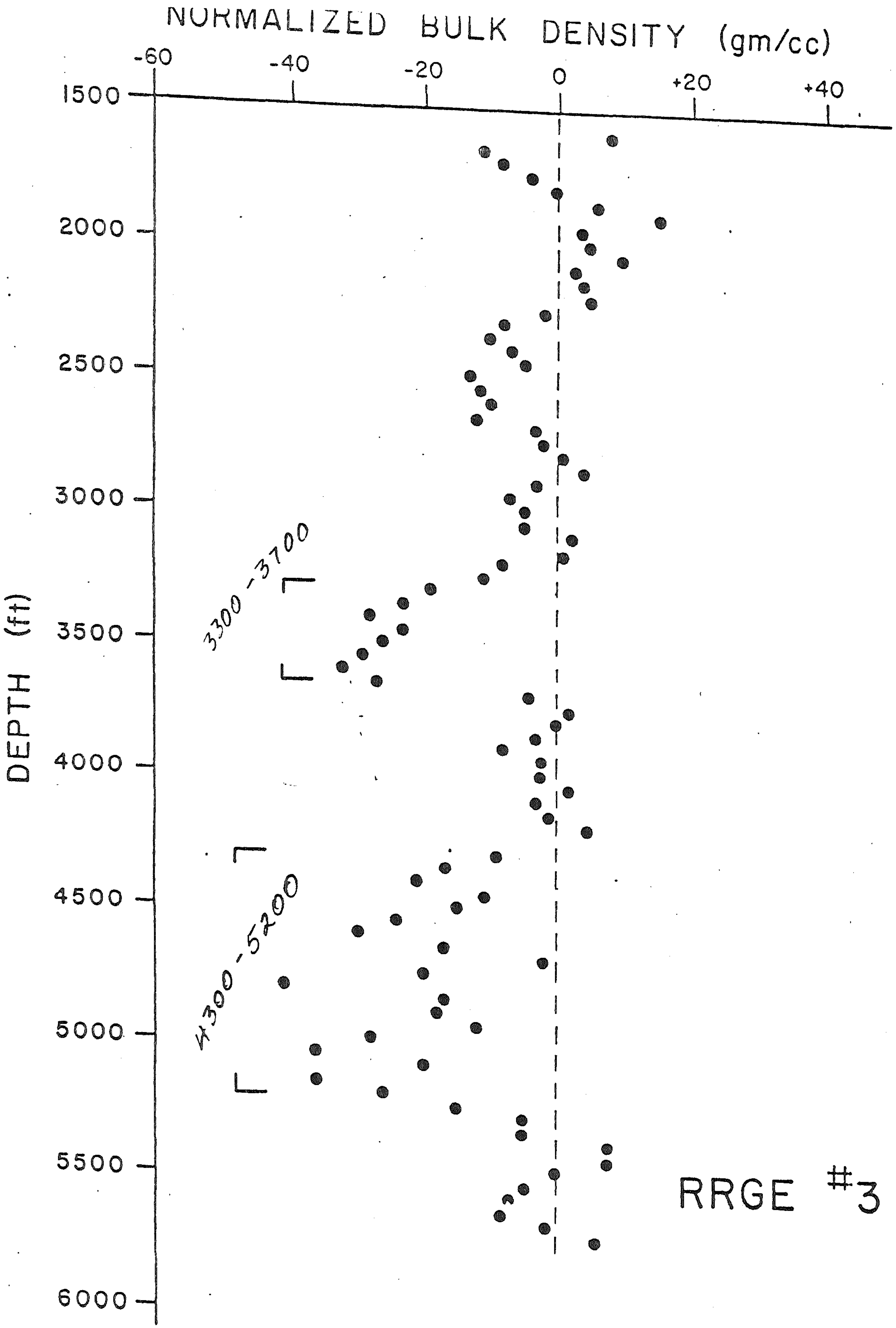

FIGURE 21 - NORMALIZED BULK DENSITY FOR RRGE # 3

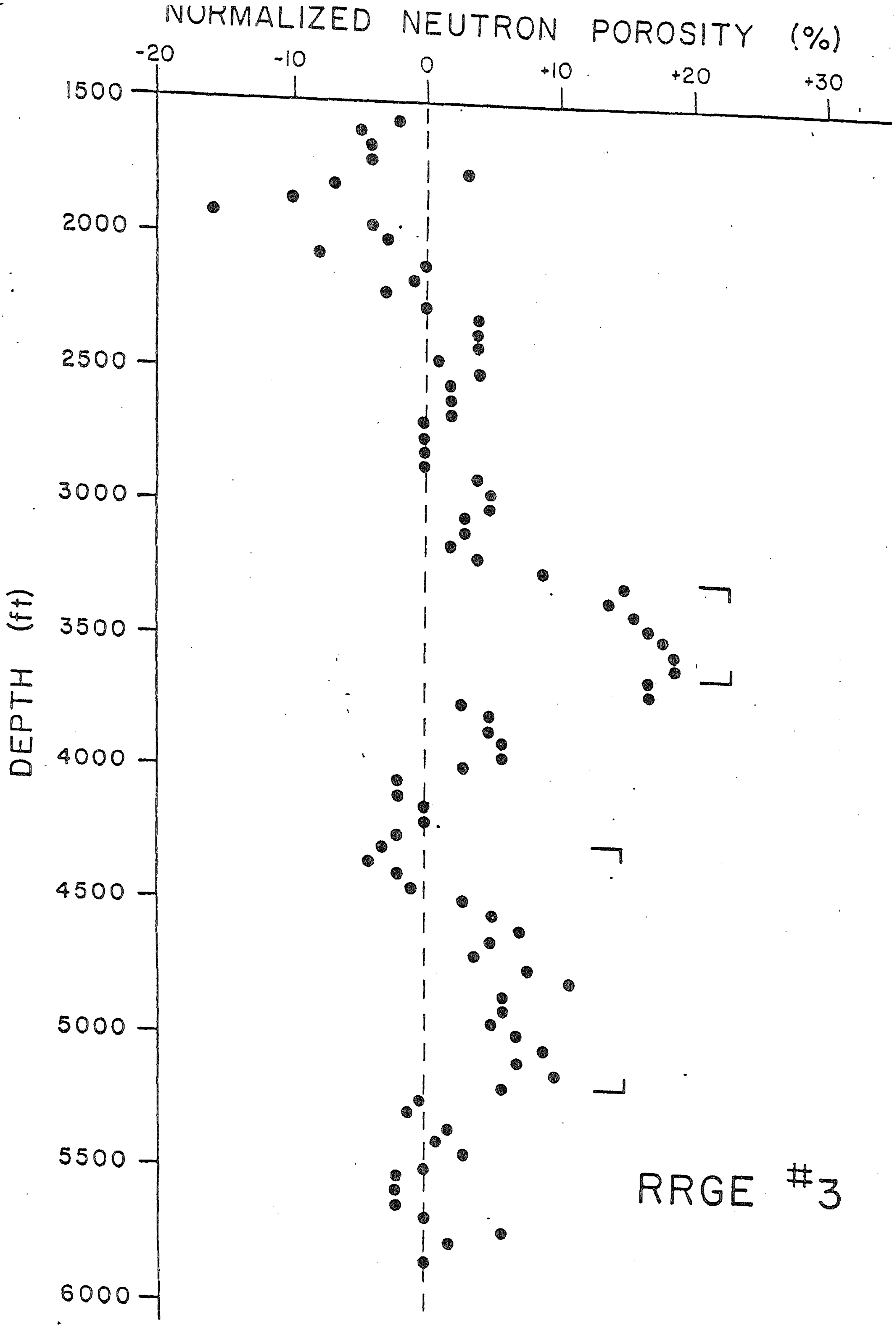

FIGURE 22 - NORMALIZED NEUTRON POROSITY FOR RRGE #3

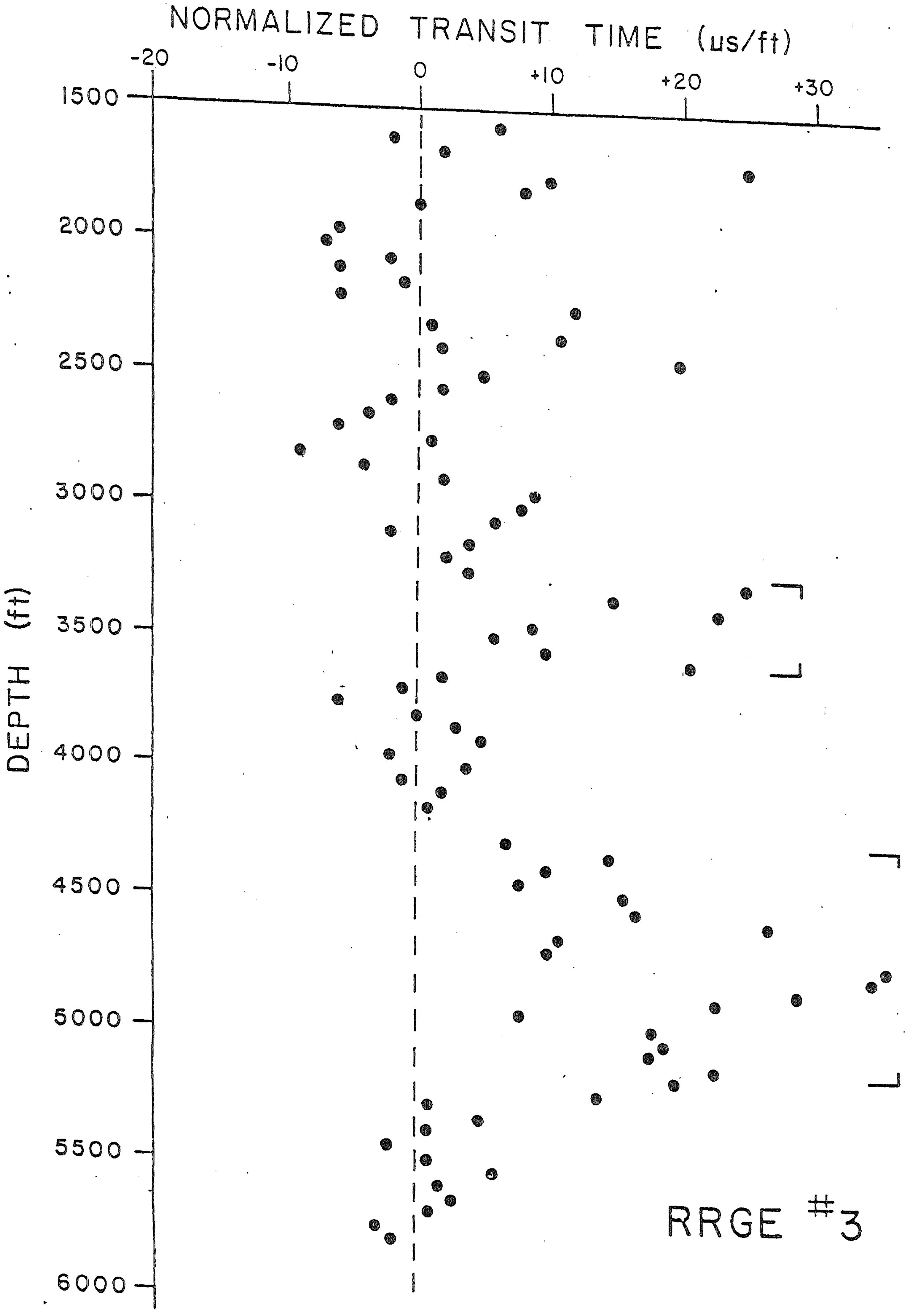

FIGURE 23 - NORMALIZED TRANSIT TIME FOR RRGE # 3

Zone 2 which is undoubtedly the major productive zone is better defined in all of the wells than is zone 1. The zone in RRGE #1 is between the depths of 3750 to 4500 feet. Certain portions of the zone (around 3850 ft, and from 4400 to 4500 ft) appear to be more productive. Zone 2 in RRGE #2 is between 3800 and 4650 feet. Smaller zones from 3800 to 4000 ft and from 4500 to 4650 ft within this zone are probably more productive. In RRGE #3, zone 2 is between 4300 to 5200 feet. The main productive portions of this zone are probably around 4800 ft and between 5000-5200 ft.

Zone 2 is either mostly composed of the fault zone (or fault zone intersections) or consists partially of fault zone material and partially of permeable formations invaded by fluids from the fault zones. Additional structural information to perhaps resolve this question could be obtained by integrating the borehole geophysics, borehole geology, surface geology and geophysics. Much of the data to accomplish this task should be available at a later time.

CONCLUSIONS AND RECOMMENDATIONS

Borehole geophysics offers the best possibility of defining productive zones in the Raft River geothermal system. While the techniques described here are not as definitive as the techniques used in the petroleum industry, they do offer the possibility when integrated with other data, of understanding the nature of the reservoir.

The data gathered in the Raft River studies will be of further use as the resource is developed, i.e., a generalized model for Basin and Range-type geothermal models may be developed which would be useful in designing drilling and production programs to maximize recovery.

Detailed analysis of the apparent productive zones in the wells may allow the development of techniques to more clearly define the discrete intervals of production. Cross plotting techniques probably offer the most quantitative method for evaluating these zones. In order to undertake these studies, future log data should be digitized as it is collected. With field digitized data the empirical-trend type of interpretation as described in this paper would provide a very quick first pass at the data to determine zones to investigate in detail.

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