VPI&SU-78ET-27001-7

EVALUATION AND TARGETING OF GEOTHERMAL ENERGY RESOURCES IN THE SOUTHEASTERN UNITED STATES

Progress Report

John K. Costain, Lynn Glover, III, and A. Krishna Sinha
Principal Investigators

Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

July 1, 1979 — September 30, 1979

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. DE - AC05 - 78ET27001

VPI&SU-78ET27001-7

EVALUATION AND TARGETING OF GEOTHERMAL ENERGY RESOURCES IN THE SOUTHEASTERN UNITED STATES

Progress Report

John K. Costain, Lynn Glover III, and A. Krishna Sinha

Principal Investigators

Department of Geological Sciences

Virginia Polytechnic Institute and State University

Blacksburg, VA 24061

July 1, 1979 - September 30, 1979

PREPARED FOR THE U. S. DEPARTMENT OF ENERGY UNDER

CONTRACT NO. DE-AC05-78ET27001

(Formerly ET-78-C-05-5648)

DISCLAIMER

TABLE OF CONTENTS

	Page
ABSTRACT AND OVERVIEW	iv
RESEARCH OBJECTIVES	vi
PERSONNEL OF PROGRAM	vii
PAPERS PUBLISHED	ix
PAPERS SUBMITTED FOR PUBLICATION	x
ABSTRACTS PUBLISHED TO DATE	xi
TALKS GIVEN TO DATE	xii
PROGRESS	xiv
A. REGIONAL GEOPHYSICS LABORATORY (RGL)	A- 1
The Crisfield, Maryland Deep Geothermal Test Hole	
Introduction	A- 2
Description of Basement Rocks from Crisfield, Deep, Geothermal Test Well	A- 5
Coastal Plain Stratigraphy at DGT-1, Crisfield, Maryland	A- 7
Summary of Temperature Logging of Crisfield, Maryland Geothermal Test Hole	A-22
Comparison of Geothermal Gradients and Gamma Logs	A-33
Temperature Logs at Other Locations in the Eastern Atlantic Coastal Plain	A-83
B. OROGENIC STUDIES LABORATORY (OSL)	B- 1
General Geology of the East Coast with Emphasis on Potential Geothermal Energy Regions: A Detailed Summary	B- 2
Study of the Pre-Cretaceous Basement Below the Atlantic Coastal Plain	B- 8
Petrography of the Granitic Basement (portion of the)	

DO-1 Drill Hole in the North Carolina Coastal Plain B-11

Field Relations and Petrology of the Postmetamorphic, Coarse-grained Granites and Associated Rocks in the Southern Appalachian Piedmont B-20

Abstract and Overview

The first, deep geothermal test hole (DGT-1) was drilled May-June, 1979 to a total depth of 1.693 km at the Crisfield airport, Hopewell, Somerset Co., Maryland: longitude 75°49.53"; latitude 38°0.97". Ground surface is 1.1 m above mean sea level and is the reference used for all depths. This quarterly report contains preliminary reports on DGT-1 by the Regional Geophysics and Orogenic Studies Laboratory, Department of Geological Sciences, VPI&SU as well as reports on our activities for the period July 1 - September 30, 1979.

Temperature measurements made in the DGT-1 hole at various stages of drilling, hydraulic fracturing and pump testing are reported by Dashevsky and McClung. The equilibrium temperature at the base of the Atlantic Coastal Plain sediments (1.36 km) is 59°C (137°F). Bottom hole temperature (1.69 km) is 66°C. The gradient in the basement is between 22.6 and 24.8 °C/km. The mean thermal conductivity is 3.20 W/m-°C and the heat flow is between 72-79 mW/m^2. Thermal conductivity of the overlying sediments is between 1.72 - 2.30 W/m-°C. With thermal gradients of 29.2 - 36.4 °C/km in the Atlantic Coastal Plain, the heat flow is 63-78 mW/m^2. The average heat flow at the DGT-1 site is 72 mW/m^2.

Gleason describes the basement rock encountered between the depths of 1.36 - 1.69 km. It is a fine-grained, massive to laminated volcaniclastic rock with a greenschist grade metamorphic assemblage of chlorite + muscovite + epidote + albite + quartz. The hole was drilled on the edge of the Chesapeake gravity low. As discussed by Costain and Glover in the Introduction, there was a good chance that at the Crisfield site, the granite causing the gravity low would not be encountered.

Svetlichny and Lambiase present the stratigraphy, lithologic descriptions, gamma log, and electric log of the Atlantic Coastal Plain sediments in the DGT-1 well. The formations encountered:

Formation	Age	Depth of Base
Yorktown	Miocene	76.2 m
St. Marys	Miocene	106.7
Choptank	Miocene	131.7
Calvert	Miocene	238.4
Piney Point	Eocene	259.7
Midway - Upper Cretaceous		338.9
Magothy	U. Cretaceous	360.3
Raritan	U. Cretaceous	564.5 (?)
Patapsco	L. Cretaceous	701.6
Arundel	L. Cretaceous	820.5
Patuxent	L. Cretaceous	1286.9
"lower acoustical zone"	Pre-Cretaceous	1362.2

In the continuing effort to acquire temperature data and heat flow from available wells, Dashevsky and McClung report on temperature logs for 3 drill holes: Smith Island, MD, 41 °C/km; Parris Island,

SC, 33 °C/km; and Colonels Island, GA, heat flow = 42 (7) mW/m^2. In addition they report on DO-1, drilled by this project at Dort, Gates Co., NC. DO-1 has a thermal gradient of 31 °C/km in the Atlantic Coastal Plain and 23 °C/km in the granite basement, which is the highest gradient determined to date in a granite in the southeast USA.

Because of the expense of recovering core for direct study; sample unavailability for previously drilled holes and the obligation to obtain as much information as possible from drill holes, it is important to be able to interpret in-hole measurements such as gamma ray, electrical, and temperature logs to yield information on thermal conductivity, permeability, mineralogy and thermal gradients. McClung and Dashevsky find that units with high gamma-ray readings tend to be clay-rich rocks with low thermal conductivities and higher geothermal gradients. Deviations are encountered in sands with abundant heavy mineral concentrations, glauconite-bearing rocks, or water-saturated rocks.

Glover presents a review of the geology of the east coast of the USA with emphasis on features having potential geothermal energy resources. The primary features of interest are radiogenic heat sources in the crystalline rocks and insulating properties of sedimentary basin fillings.

Gleason presents locations and information available for drill holes penetrating basement in South Carolina. It is a summary of his continuing work on the Atlantic Coastal Plain thickness and underlying PreCretaceous rocks.

The VPI&SU drilling program is constantly obtaining core of crystalline rock beneath the sediments of the Atlantic Coastal Plain, an area about which very little is known. Becker describes the 287 feet of basement core obtained from the DO-1 drill hole near Dort, Gates Co., NC. The rock is a coarse-grained, amphibole-biotite granite which closely resembles the Petersburg, VA granite which is exposed 75 km to the northeast. The paper by Speer, Becker and Farrar summarizes four years of work on the field relations, petrography and mineralogy of the post-metamorphic, coarse-grained granites and associated rocks in the southern Appalachian Piedmont. The paper provides the comparative data base for 1) better understanding the granites encountered in basement cores recovered from beneath the Atlantic Coastal Plain, and 2) improving targeting procedures for locating concealed radiogenic granites in the basement.

RESEARCH OBJECTIVES

The objective of this research is to develop and apply targeting procedures for the evaluation of low-temperature radiogenically-derived geothermal resources in the eastern United States utilizing geological, geochemical, and geophysical data.

The optimum sites for geothermal development in the tectonically-stable Eastern United States will probably be associated with areas of relatively high heat flow derived from crustal igneous rocks containing relatively high concentrations of radiogenic heat-producing elements. The storage of commercially-exploitable geothermal heat at accessible depths (1-3 km) will also require favorable reservoir conditions in rocks overlying a radiogenic heat source. In order to systematically locate these sites, a methodology employing geological, geochemical, and geophysical prospecting techniques is being developed and applied. The distribution of radiogenic sources within the igneous rocks of various ages and magma types will be determined by a correlation between radioelement composition and the bulk chemistry of the rock. Surface sampling and measurement of the radiogenic heat-producing elements are known to be unreliable as they are preferentially removed by ground-water circulation and weathering. The correlation between the bulk chemistry of the rock (which can be measured reliably from surface samples) and radiogenic heat generation is being calibrated by detailed studies at a number of locations in the eastern United States

Initial studies are developing a methodology for the location of radiogenic heat sources buried beneath the insulating sedimentary rocks of the Atlantic Coastal Plain. Choice of a drill site in the Atlantic Coastal Plain with a high geothermal resource potential depends on favorable:

(1) concentration of radiogenic elements in granitic rocks beneath a sedimentary insulator;
(2) thermal conductivity of the sedimentary insulator;
(3) thickness of the sedimentary insulator; and
(4) reservoir conditions in the permeable sedimentary rocks overlying the radiogenic heat source.

Because it is not economically feasible to select drilling sites on the Atlantic Coastal Plain without geophysical and geological models, it is advisable to base the development of these models on a substantial and accurate data base which can be partially derived from the exposed rocks of the Piedmont and enhanced by basement studies beneath the Atlantic Coastal Plain.

PERSONNEL OF PROGRAM

July 1, 1979 - September 30, 1979

GEOLOGY AND PETROLOGY, Lynn Glover III, Principal Investigator

J. A. Speer, Research Associate
S. S. Farrar, Research Associate
S. W. Becker, Research Associate
R. J. Gleason, Research Associate
G. Russell, Research Associate
W. Russell, Analytical Chemist
J. Reilly, Graduate Research Assistant
C. Newton, Graduate Research Assistant
M. W. Dellers, Secretary

GEOCHEMISTRY, A. Krishna Sinha, Principal Investigator

J. R. Sans, Research Associate
S. T. Hall, Research Associate
D. McKay, Research Associate
B. Hanan, Graduate Research Assistant
T. Chang, Computer Programmer
S. Dickerson, Laboratory Aide
C. R. Miner, Laboratory Aide (part-time)
P. Stock, Laboratory Aide
N. Schurig, Secretary

GEOPHYSICS, John K. Costain, Principal Investigator

L. D. Perry, Research Associate
J. J. Lambiase, Research Associate
S. Dashevsky, Research Specialist
M. Svetlichny, Research Specialist
W. McClung, Research Specialist
S. Higgins, Research Specialist
T. H. Arnold, Laboratory Aide (part-time)
M. McKinney, Laboratory Aide
B. Thoreson, Computer Programmer (part-time)
M. Hoffman, Laboratory Technician
D. Hostvedt, Laboratory Technician
K. King, Computer Programmer
R. Laczniak, Graduate Research Assistant
P. W. Glosh, Secretary

ADMINISTRATIVE ASSISTANT
Patricia Hubble

BOOKKEEPER

Mildred Memitt

DRAFTSMAN-PHOTOGRAPHER

David Brown

DRILLING STAFF

W. G. Coulson, Supervisor and Core Driller
J. Childress, Core Driller
G. Childress, Core Driller Helper
R. Dalton, Core Driller Helper
R. Bowman, Core Driller Helper
R. Gravley, Core Driller Helper
D. Thomas, Core Driller Helper
S. Long, Secretary

VIBROSEIS SEISMIC DATA ACQUISITION STAFF

W. Shumate, Laboratory Instrument Maker
W. Ranck, Laboratory Instrument Maker
W. Davis, Laboratory Mechanic
H. Neuburg, Research Associate
H. Bodell, Laboratory Technician
C. Conway, Laboratory Technician
P. Coyle, Laboratory Technician
J. Creiman, Laboratory Technician
A. Davis, Laboratory Technician
M. Friedly, Laboratory Technician
C. Greene, Laboratory Technician
K. Hurst, Laboratory Technician
K. Nickell, Laboratory Technician
C. Ross, Laboratory Technician
J. Sheridan, Laboratory Technician
D. VanNostrand, Laboratory Technician
S. Long, Secretary

PAPERS PUBLISHED

Speer, J.A, 1978, Molybdenum mineralization in the Liberty Hill and Winnsboro plutons, South Carolina, Ec. Geol., v. 73, p. 558-561.

Glover, L. III, 1979, General geology of the East Coast with emphasis on potential geothermal energy regions: a detailed summary, Proceedings: A Symposium of geothermal energy and its direct uses in the eastern United States - Geothermal Resources Council Special Report No. 5, p. 9-11.

Costain, J.K, 1979, Geothermal exploration methods and results: Atlantic Coastal Plain. Proceedings: A Symposium of geothermal energy and its direct uses in the eastern United States - Geothermal Resources Council Special Report No. 5, p. 13-22.

PAPERS SUBMITTED FOR PUBLICATION

Costain, J. K., L. Glover, III, and A. K. Sinha, 1979, Low-temperature geothermal resource potential of the eastern United States, in press, EOS, Transactions, American Geophysical Union.

Muffler, L. J. P., J. K. Costain, D. Foley, E. A. Sammel and W. Younguist, 1979, Nature and distribution of geothermal energy, Proceedings: Klamath Falls Symposium on Geothermal Energy, in press.

Lambiase, J. J., S. S. Dashevsky, J. K. Costain, R. J. Gleason and W. S. McClung, 1979, Geothermal resource potential of the Northern Atlantic Coastal Plain, submitted to Geology.

Perry, L. D., J. K. Costain and P. A. Geiser, 1979, Heat flow in western Virginia and a model for the origin of thermal springs in the folded Appalachians, Jour. of Geophysical Research, in press.

Speer, J. A., 1979, Prograde metamorphism of the pelitic rocks in the contact aureole and xenoliths of the Liberty Hill pluton, South Carolina, submitted to Amer. Jour. of Science.

Bourland, W. C. and S. S. Farrar, 1979, Tectogenesis of the rocks surrounding the Winnsboro Intrusive Complex, submitted to Geologic Notes, South Carolina Development Board, Division of Geology.

ABSTRACTS PUBLISHED TO DATE

Geiser, P.A. and J.K. Costain, 1977, Evaluation of the geothermal potential of the hot springs of northwestern Virginia, Abstracts of ANS Topical Meeting on Energy and Mineral Resource Recovery. Golden, Colorado, April 12-14, p. 33.

Geiser, P.A. and J.K. Costain, 1977, Structural controls of thermal springs in the Warm Springs anticline, Virginia, Abstracts, Geol. Soc. America SE Section, Winston-Salem, North Carolina.

Costain, J.K., L. Glover III, A.K. Sinha, 1977, Low-temperature geothermal resources in the eastern United States, Program with Abstracts, Annual Meeting of Geological Society of America, Seattle, Washington.

Costain, J.K. and A.K. Sinha, 1978, Relationship between heat flow and heat generation in the southeastern United States, Program with Abstracts, Geological Society of America, SE Section Meeting, April.

Costain, J.K., A new model for the linear relationship between heat flow and heat generation, Transactions, American Geophysical Union, 59:p. 392.

Becker, S.W., 1978, Petrology of the Cuffytown Creek pluton, Geol. Soc. Amer. Abstracts with Programs, v. 10.

Farrar, S.S., 1979, Tectonics of the fault bounded Raleigh block, eastern Piedmont, North Carolina, Geol. Soc. Amer., Abstracts with Programs, v. 11.

Farrar, S.S., 1979, Lithology and metamophism of Raleigh block, eastern Piedmont, North Carolina, Geol. Soc. Amer. Abstracts with Programs, v. 11, p. 177-178.

Lambiase, J. J., M. Svetlichny, S. S. Dashevsky, B. U. Conrad, and J. K. Costain, 1979, Detailed temperature logging as a useful tool for lithologic interpretation, AAPG Abstracts, p. 120.

Speer, J. A., S. W. Becker, and S. S. Farrar, 1979, Field relations and petrology of the post metamorphic, coarse-grained granites and associated rocks in the Southern Appalachian Piedmont, Abstracts, the Caledonides in the USA I.G.C.P. project, Caledonide Orogen, p. A9.

Speer, J. A., 1979, Magnetic anomalies coinciding with metamorphic isograds in the Liberty Hill aureole, South Carolina, Geol. Soc. Amer. Abstracts with Programs, 11, 522.

TALKS GIVEN TO DATE

Geiser, P. A., 1977, Evaluation of the geothermal potential of hot springs in Northwestern Virginia, American Nuclear Society, Denver, Colorado, April.

Geiser, P. A. and J. K. Costain, 1977, Structural controls of thermal springs in the Warm Springs Anticline, Southeastern Geological Society of America, Winston-Salem, North Carolina, April. (Speaker: P. A. Geiser)

Costain, J. K., 1977, Low-temperature resources of the eastern United States, Second NATO-CCMS Meeting on Dry Hot Rock Geothermal Energy, Los Alamos Scientific Labortory, Los Alamos, New Mexico, June.

Costain, J. K., 1977, Low-temperature geothermal resources of the eastern United States, Geological Society of Washington, Washington, D.C., October.

Costain, J. K., 1977, Low-temperature geothermal resources in the eastern United States, 1977 Annual Meeting of the Geological Society of America, November.

Costain, J. K., 1977, Low-temperature geothermal resources in the eastern United States, Potomac Geophysical Society, November.

Costain, J. K., 1978, Geothermal resource potential of the eastern United States, Geothermal Resource Conci Special Short Course No. 7, "Geothermal Energy: A National Opportunity" (The Federal Impact), Washington, D.C., May.

Costain, J. K., 1978, Geothermal resource potential of the eastern United States, Nordic Symposium on Geothermal Energy, Gothenburg, Sweden, May.

Costain, J. K., 1979, Geothermal resources of the Atlantic Coastal Plain, The Energy Technology Conference and Exposition, Washington, D.C., February.

Dashevsky, S. S., 1979, Geothermal resource potential of the Atlantic Coastal Plain, Smithfield, Virginia Rotary Club, May.

Lambiase, J. J., 1979, Geothermal resource potential of the Atlantic Coastal Plain, North-South Carolina section of the American Institute of Mining Engineers, Raleigh, North Carolia, March.

Lambiase, J. J., S. S. Dashevsky, R. J. Gleason and J. K. Costain, 1979, Geothermal resource potential of the Atlantic Coastal Plain, 2nd Symposium n the Southeastern Coastal Plain, Americas, Georgia, March. (Speaker: J. J. Lambiase)

Lambiase, J. J., M. Svetlichny, S. S. Dashevsky, B. U. Sans, and J. K. Costain, 1979, Detailed temperature logging as a useful tool for lithologic interpretation, American Association of Petroleum Geologists Annual Meeting, Houston, Texas, March. (Speaker: J. J. Lambiase)

Speer, J. A., S. W. Becker and S. S. Farrar, 1979, Field relations and petrology of the post metamorphic, coarse-grained granites and associated rocks in the Southern Appalachian Piedmont, Blacksburg, VA, I.G.C.P. Caledonides in the USA, August. (Speaker: J. A. Speer).

Speer, J. A., 1979, Magnetic anomalies coinciding with metamorphic isograds in the Liberty Hill aureole, South Carolina, Geol. Soc. of America, March.

Farrar, S. S., 1979, Tectonics of the fault-bounded Raleigh block, eastern Piedmont, North Carolina, Geol. Soc. Amer., March.

Farrar, S. S., 1979, Lithology and metamorphism of Raleigh block, eastern Piedmont, North Carolina, Geol. Soc. Amer., March.

PROGRESS

A. REGIONAL GEOPHYSICS LABORATORY (RGL)

Introduction

J. K. Costain and L. Glover, III

This report contains some preliminary results of the first deep geothermal test in the eastern United States made at Crisfield, Md. The test was successful and the outlook for utilization of the geothermal potential of the Atlantic Coastal Plain is encouraging.

It has been apparent from some newspaper accounts that there might have been a lack of communication concerning the geological and geophysical data base available before selection of the first deep geothermal test site in the eastern United States. This brief introduction will help to clarify 1) why Crisfield, Md., was selected as the first test site, 2) what data base was available at the time the site was selected, 3) what temperature was predicted by VPI&SU before the drilling began, and 4) what temperature was actually measured when the drilling was completed.

A Site Selection Meeting was held at Blacksburg, Va. on January 16-17, 1979. During this meeting possible drill sites were discussed for which:

a) the geothermal gradient was known to be relatively high as a result of the VPI&SU shallow (300 m) drilling program on the Atlantic Coastal Plain in New Jersey, Delaware, Maryland, and North Carolina,

b) the thickness of Coastal Plain sediments was not excessive and depths could be reached that would result in a cost-effective drilling program.

No hard data were available with regard to well yields of any deep aquifers in the areas discussed, and the final selection of a site was therefore not prejudiced by the occurrence of known or suspected aquifers.

Maximum temperatures predicted at the base of the sediments by VPI&SU were determined by assuming that the average geothermal gradient in a cased, cemented 300 m hole remained constant to the base of the sediments. Temperatures predicted by this method would therefore be maximum expectable temperatures because it was felt unlikely that, for the areas under consideration, the thermal conductivity of the sediments would decrease with depth. Our basement temperature predictions are always called maximum because they are based on data from the upper 305 m where thermal conductivities might be expected to be somewhat low in the northern part of the Atlantic Coastal Plain.

At the time of the Site Selection Meeting in Blacksburg, an accurate estimate of the depth to basement at Crisfield was not available. A depth was therefore computed using the nearest wells that penetrated basement, under the assumption that the slope of the basement surface was approximately constant between these wells. Subsequent reflection seismic data (obtained before the drilling began) indicated that our assumption was incorrect, and that the depth to the 'basement' reflector was approximately 1.30 km, about 16% less than the depth stated at the Site Selection Meeting in January; the maximum predicted temperature would therefore also be less by about the same amount. (The final depth and temperature estimate were made by VPI&SU more than two months before the drilling at Crisfield began; the revised estimates were also incorporated into our Progress Report VPI&SU-5648-5, p. A-79 and C-24). The impact of the new seismic data was immediately reported to DOE-Washington, but it was clear that the selection of Crisfield was consistent with program objectives and the decision was made not to change the site. However, VPI&SU should have issued a formal statement about the revised depth estimate (and therefore temperature) to those who had attended the Site Selection Meeting. We regret this oversight. Subsequent discussions between the press and sources other than DOE or VPI&SU apparently did not use the updated estimates.

The drill site at Crisfield, Md. is located off but near the flank of a major negative gravity anomaly that underlies the Chesapeake Bay. We have named this gravity minimum the 'Chesapeake Bay Gravity Low' (CBGL). The highest gradient we have determined to date in the eastern United States was determined in one of our shallow (300 m) heat flow sites at Smith Point, Va. The Smith Point site is on the western flank of the CBGL. Based on our growing data base and confirmation of the radiogenic model (Costain, Glover, and Sinha, 1980) at Portsmouth, Va., we believe that the CBGL is associated with a large radiogenic granite in the basement. Our contract for FY 80-81 includes funds to deepen the hole at Smith Point to basement and to core approximately 300 feet of basement. The depth to basement at Smith Point is approximately 0.92 - 0.96 km. Although the geothermal gradient at Smith Point is higher than that at and near Crisfield, the sediment thickness is greater at Crisfield; the Crisfield site is as close as possible to the CBGL on the Delmarva Penninsula without drilling on Smith Island (an attractive possibility because of the potential geothermal energy resource on Smith Island and the demonstrated need there).

Upon completion of the Crisfield well it was discovered that the 'basement' reflector marked the top of a poorly known 75-m thick (locally) indurated high-velocity section of Coastal Plain sediments, and that true crystalline basement was at the base of this indurated sequence at a depth of 1.36 km. Temperature at the top of crystalline basement was found to be about 58°C (137°F). Thus, the predicted temperature was within 16% of the actual temperature, and the difference was entirely due to problems in estimating the thermal conductivity of Coastal Plain sedimentrs in the lower 80% of the sedimentary sequence.

Finally, VPI&SU did not predict a rock type for the basement core to be taken at Crisfield. The uncertainties and possibilities were discussed by Glover at the Blacksburg meeting in April, and again separately with LASL during the planning stages for the deep drilling. It was pointed out that we were drilling near but not on the CBGL which probably does mark a large granite batholith. Because of the high heat flow at Crisfield it was felt that the granite did in some way (i.e., perhaps through a broad migmatite zone surrounding the pluton) contribute to the high gradient and heat flow, but it was recognized that a variety of crystalline rock types was possible. We did not recommend the Crisfield site as a test of the radiogenic model because of the basement complexity indicated by the potential field data. The Crisfield site was recommended because the high geothermal gradient, high heat flow, and moderate depth to basement there suggested a useable temperature near the base of the sediments of the Atlantic Coastal Plain. Predicted temperature was our final criterion. A preliminary discussion of some results of the Crisfield test is given in the following sections of this report.

Description of Basement Rocks from Crisfield, Deep Geothermal Test Well

Richard J. Gleason
(OSL, Geology and Petrology Group)

The first deep geothermal test well was drilled at the Crisfield airport, in Somerset County, Maryland. Drilling began on May 13 and was completed on June 14, 1979. Total depth was 1693 m. The basal Coastal Plain section overlying basement is an indurated unit containing clasts of basement lithology. Because the contact between this unit and basement was not cored, the identification of this contact was interpretive, based on analyses of drill cuttings, drilling penetration rate, and electric/geophysical logs, all of which indicated the top of weathered (?) basement at a depth of approximately 1362m. 331 m of basement rock were drilled. Cores were obtained from depth intervals of 1418 - 1421 m, 1528-1532 m, and 1688-1693 m. Drill cuttings were collected from the uncored sections.

Analysis of drill cuttings indicates a consistent lithology over the 331 m of basement penetrated. The basement is a grey-green, fine-grained metamorphic rock, at least in part of volcanic origin. Core sections vary from massive to finely laminated. The massive sections are up to 2 meters in thickness. Laminations and thin beds, where present, are generally a few millimeters to a maximum of approximately 2 centimeters in thickness, and locally display graded bedding.

Microscopically, the basement material is composed of massive beds with grain size varying from tens of microns to hundreds of microns and laminae with grain sizes generally from 5-10 microns to tens of microns. Contacts between the massive and laminated sections vary from sharp to diffuse. Locally, well-developed, upright, graded bedding is preserved, with grain size grading from silt to clay. In the more massive, coarse-grained sections of the core, rounded and flattened ash fragments of devitrified volcanic glass occur along with subangular to subrounded mildly strained grains of quartz and subordinate plagioclase. The original mineralogy and texture of the matrix were partially obscured by low-grade metamorphic recrystallization which produced the present assemblage of white mica (phengite?) + chlorite + epidote + titanite + quartz + feldspar. In most of the core sections, the metamorphic foliation, as defined by the orientation of micaceous minerals, is parallel to bedding. In more pelitic laminae near the base of the lowest core, a crenulation cleavage was developed at a small angle (20-35°) to original layering. The core is cut by several types of veinlets and fractures, indicating the possibility of several episodes of syn-(?) and post-metamorphic deformation.

The Crisfield basement material appears to represent a sequence of volcaniclastic debris which was likely erupted in or near a submarine environment. Settling of such debris through a fairly deep water column during semi-continuous eruptions of variable intensity and proximity, as well as possible reworking of the sequence, might account for the texture of the basement material. Subsequent to deposition, the rock was subjected to a greenschist-facies metamorphic event, and the present mineral assemblage was developed. Post-metamorphic fracturing and mineralization further affected the sequence. Subsequent detailed investigations will better define the paragenesis, mineralogy, and time-framework of the crystalline basement in the Crisfield area.

Coastal Plain Stratigraphy at DGT-1, Crisfield, Maryland

Michael Svetlichny and Joseph J. Lambiase

The first deep geothermal test hole (DGT-1) drilled in the Atlantic Coastal Plain province was completed June 14, 1979. Drill cuttings were sampled every 3m, and ten 10-meter core attempts were made at selected intervals in the Coastal Plain sediments. Core intervals and recoveries are listed in Table A-1; the cores have not yet been analyzed. Preliminary lithologic descriptions of drill cuttings have been completed (Table A-2).

Tentative geologic formation boundaries have been defined using drill cuttings , a natural gamma ray log, and an electric log consisting of a self-potential curve and three resistivity curves (Figure A-1). The descriptions of the cuttings and a gamma log from the nearby Janes Island well (Som-Dc3) (Hansen, 1967) facilitated choosing formation boundaries in the first 461 m of DGT-1. For the remainder of the hole, determination of formation contacts was made by comparing lithologic and geophysical data with established criteria for the coastal plain of Maryland. The formation contacts, depths, and thicknesses are described below, and are summarized in Table A-3.

Overlying the basement rock at a depth of 1362 m is a 75 m thick, well-indurated unit. From drill cuttings, this unit appears to be a lithologically heterogeneous composite of buff, blue-gray, brown, and red shale clasts, and gradually downward increasing amounts of subrounded to subangular sand-sized gray-green metavolcanic fragments. This unit is interpreted to be the westward extension of the "lower acoustical zone" of Jurassic and/or Triassic age, which is believed to occupy deep, graben-like structures beneath the Atlantic Continental Shelf (Schlee and others, 1976). The top of this unit is marked by major breaks in the gamma and electric logs (Figure A-1), and an abrupt change in lithology from shale to the medium-to-coarse grained sand that is typical of the overlying Patuxent Formation. Seismic profiles from VIBROSEIS Line Dor-1, located east of Church Creek (Hansen, 1978) and VPI Line 6, along Route 413 in the vicinity of Hopewell, show conspicuous reflectors at the top of this unit, which is referred to as horizon "Z". (Hansen, 1978). Earlier reports assumed that the lower acoustical unit pinched out offshore, but a seismic line from the Maryland - Virginia portion of the Delmarva Peninsula indicates an up-dip wedge of the lower acoustical unit beneath the Outer Coastal Plain of Maryland (Schlee and others, 1976).

Figure A-1.

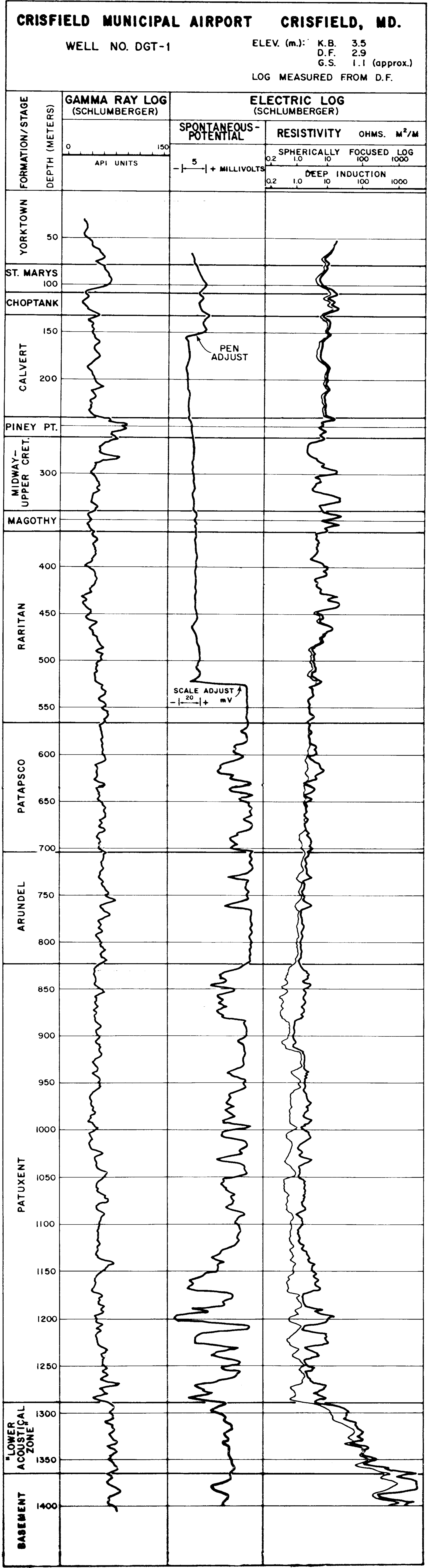

CRISFIELD MUNICIPAL AIRPORT CRISFIELD, MD.
WELL NO. DGT-1
ELEV. (m.): K.B. 3.5
D.F. 2.9
G.S. 1.1 (approx.)
LOG MEASURED FROM D.F.
FORMATION/STAGE
DEPTH (METERS)
GAMMA RAY LOG (SCHLUMBERGER)
0 150
API UNITS
ELECTRIC LOG (SCHLUMBERGER)
SPONTANEOUS-POTENTIAL
5
+ MILLIVOLTS
RESISTIVITY OHMS. M²/M
SPHERICALLY FOCUSED LOG
0.2 1.0 10 100 1000
DEEP INDUCTION
0.2 1.0 10 100 1000
YORKTOWN
50
ST. MARYS
100
CHOPTANK
150
PEN ADJUST
CALVERT
200
PINEY PT.
MIDWAY-UPPER CRET.
300
MAGOTHY
400
RARITAN
450
500
SCALE ADJUST
20
+ mV
550
PATAPSCO
600
650
700
ARUNDEL
750
800
850
900
950
1000
PATUXENT
1050
1100
1150
1200
1250
"LOWER ACOUSTICAL ZONE"
1300
1350
BASEMENT
1400

TABLE A-1. Coring intervals and recoveries, DGT-1.

Depths are recorded in meters from the ground surface.

Attempt	Interval Cored	Interval(s) Recovered	Recovery in Meters
1	332.0 - 341.1	335.7 - 341.1	5.5
2	341.1 - 347.2	345.4 - 345.6,	0.8
		346.3 - 346.9	
3	347.2 - 356.3		0.0
4	793.4 - 802.6	796.4 - 802.6	6.2
5	802.6 - 811.7	804.4 - 811.7	7.3
6	811.7 - 820.9	811.9 - 814.3,	8.3
		815.1 - 820.9	
7	946.7 - 955.9	946.7 - 950.1,	7.9
		951.3 - 955.9	
8	1250.9 - 1260.1	1253.2 - 1260.1	6.9
9	1260.1 - 1269.2	1260.1 - 1264.0,	7.8
		1265.0 - 1268.8	
10	1269.2 - 1278.4	1276.5 - 1277.5	0.9

TABLE A-2. Lithologic descriptions of drill cuttings

All depths are referenced to the ground surface, 1.1 m above mean sea level.

Formation	Lithology
Miocene Series	
Yorktown Formation	
43.3 - 52.5	Fine sandy silt, white
52.5 - 58.6	Gray silt
58.6 - 64.7	Silty granule sized gravel. Minor shells
64.7 - 67.7	Slightly granular fine sandy silt. Minor shells
67.7 - 76.2	Fine sandy gray silt
Miocene Series	
St. Marys Formation	
76.2 - 79.3	Gray silt. Minor shells
79.3 - 85.4	Dark gray clay and silt. Minor shells
85.4 - 88.4	Light gray clay and silt. Minor shells
88.4 - 91.5	Gray clay and silt, slightly micaceous. Minor shells
91.5 - 106.7	Gray clay and silt, no mica. Minor shells
Miocene Series	
Choptank Formation	
106.7 - 115.9	Very fine gray sandy silt. Abundant shells
115.9 - 122.0	Very fine to fine sandy silt, micaceous. Abundant shells from 115.9 - 118.9
122.0 - 128.1	Very fine sandy silt, light gray. Abundant shells
128.1 - 131.7	Light gray clay and silt, minor amounts of fine sand. Abundant shells
Miocene Series	
Calvert Formation	
131.7 - 152.4	Light gray clay and silt, minor fine sand. Abundant shells from 131.7 - 134.2. Minor shells from 137.2 - 140.2 and 143.3 - 152.4. No shells from 140.2 - 143.3
152.4 - 158.5	Clayey, silty shell bed
158.5 - 164.6	Gray clay. Shells
164.6 - 170.7	Dark gray clay
170.7 - 176.8	Light gray clay and silt
176.8 - 182.9	Dark organic clay. Minor shells from

	179.9 - 182.9
182.9 - 192.1	Light gray clay and silt. Minor shells from 182.9 - 186.0
192.1 - 195.1	Dark gray clay
195.1 - 198.2	Clay and silt
198.2 - 207.3	Brown and green clay
207.3 - 213.4	Gray clay and silt. Minor shells from 207.3 - 210.4
213.4 - 216.4	Dark gray clay
216.4 - 226.2	Gray clay and silt. Minor shells from 223.2 - 226.2
226.2 - 229.2	Clay
229.2 - 232.3	Very fine sandy clay and silt, light gray
232.3 - 235.3	Fine sandy clay
235.3 - 238.4	Very fine sandy clay

Eocene Series
Piney Point Formation

238.4 - 253.6	Very fine sandy clay and silt, glauconitic. Minor shells from 238.4 - 241.4
253.6 - 256.7	Fine-medium sand and clay, glauconitic
256.7 - 259.7	Gray silty fine-medium sand, glauconitic

Rocks of Midway Age and/or
Upper Cretaceous (undivided)

259.7 - 262.8	Gray glauconitic clay
262.8 - 265.8	Gray fine sandy silt and clay, glauconitic
265.8 - 280.0	Gray glauconitic clay
280.0 - 284.1	Gray glauconitic clay with medium sand
284.1 - 290.2	Same as 278.0 - 284.1, but with abundant mica
290.2 - 293.3	Clayey fine-medium sand, glauconitic, micaceous
293.3 - 299.4	Clayey, silty fine-medium sand, glauconitic, slightly micaceous
299.4 - 302.4	Sample missing
302.4 - 305.4	Silty fine-medium quartz sand, glauconitic, micaceous
305.4 - 308.5	Same as 302.4 - 305.4, but slightly micaceous. Minor shells
308.5 - 311.5	Sample missing
311.5 - 314.6	Silty fine-medium quartz sand, slightly glauconitic. Minor shells
314.6 - 317.6	Light gray fine sandy silt and clay
317.6 - 320.7	Light gray fine sandy micaceous silt, slightly glauconitic
320.7 - 323.7	Sample missing
323.7 - 329.8	Light gray fine-medium quartz sand, micaceous, slightly glauconitic
329.8 - 332.9	Silty fine-medium quartz sand,

		micaceous, slightly glauconitic
332.9 -	335.9	Silty, clayey fine sand. Minor shells
335.9 -	338.9	Same as 332.9 - 335.9, but with plant remains

Upper Cretaceous Series
Magothy Formation

338.9 -	342.0	Sample missing
342.0 -	345.1	Slightly silty fine-medium sand, minor glauconite
345.1 -	348.1	Fine-medium quartz sand
348.1 -	351.2	Silty fine-medium quartz sand, micaceous, slightly glauconitic
351.2 -	354.2	Fine-medium quartz sand, minor glauconite and lignite
354.2 -	357.3	Fine to coarse quartz sand, clay aggregates
357.3 -	360.3	Fine to medium sand, some clay aggregates

Upper Cretaceous Series
Raritan Formation

360.3 -	363.4	Silty fine-medium sand, lignitic. Minor shells
363.4 -	366.4	Same as 360.3 - 363.4, but no lignite or shells
366.4 -	369.5	Reddish gray silty fine-medium sand with clay aggregates
369.5 -	372.5	Reddish silty fine-medium sand, slightly micaceous
372.5 -	375.6	Brown silty very fine-fine sand, lignite, mica and plant remains
375.6 -	378.6	Light brown fine sandy silt with lignite and mica. Minor shells.
378.6 -	381.6	Light brown silt and fine sand, even amounts of each. Slightly micaceous
381.6 -	384.7	Light brown fine sandy silt with clay aggregates
384.7 -	387.7	Reddish brown and gray silty fine-medium sand, lignitic, minor mica and plant remains
387.7 -	393.8	Reddish brown fine sandy silt
393.8 -	399.9	Silty fine sand, lignitic, slightly micaceous
399.9 -	403.0	Silty fine-medium sand, no lignite or mica
403.0 -	406.0	Reddish silty fine-medium sand, abundant lignite and plant remains
406.0 -	412.1	Light brown sandy silt. Lignite from 406.0 - 409.1
412.1 -	415.2	Light brown sand and silt

415.2 -	418.2	Silty fine-medium sand, micaceous, lignitic
418.2 -	421.3	Silty fine-medium sand, clay aggregates, lignitic, slightly micaceous
421.3 -	427.4	Silty fine-medium sand. Shells from 421.3 - 424.3
427.4 -	430.4	Fine-medium sand, some coarse grains, minor clay chips
430.4 -	433.5	Fine-coarse sand, clay aggregates, lignite
433.3 -	436.5	Fine to coarse sand with lignite
436.5 -	439.6	Mostly lignite with fine-medium sand
439.6 -	442.6	Silty fine to medium sand with lignite
442.6 -	445.7	Medium sand with lignite
445.7 -	448.7	Medium sand, minor lignite and mica
448.7 -	451.8	Silty fine-medium sand, mica, lignite. Minor shells
451.8 -	457.8	Silty fine-medium sand, mica, lignite. Minor shells.
457.8 -	460.9	Silty fine-coarse sand with granules. Minor shells
460.9 -	463.9	Silty medium sand, slightly micaceous
463.9 -	467.0	Silty fine-coarse sand
467.0 -	473.1	Silty fine-medium sand, lignite
473.1 -	476.1	Sample missing
476.1 -	479.2	Silty fine-medium sand, some granules, minor lignite
479.2 -	485.3	Same as 476.1 - 479.2, but no granules or lignite
485.3 -	488.3	Silty fine-medium sand and lignite. Minor shells.
488.3 -	494.4	Fine-coarse sand, lignite from 491.4 - 494.4. Minor shells
494.4 -	497.5	Silty fine-coarse sand with shale. Shells
497.5 -	503.6	Silty fine-medium sand, micaceous
503.6 -	506.6	Fine-medium sand. Minor shells
506.6 -	509.7	Silty fine-medium sand
509.7 -	515.8	Fine-coarse sand with red and yellowish shale. Shells (granules in 512.7 - 515.8)
515.8 -	540.1	Samples contaminated by cement from float shoe
540.1 -	543.2	Fine-medium sand
543.2 -	546.2	Fine-medium sand with mica
546.2 -	558.4	Shale with silty fine s2cnd, micaceous. Fine-medium sand from 549.3 - 552.3, 555.4 - 558.4
558.4 -	561.5	Varicolored shale, silty fine sand, some coarse grains, micaceous
561.5 -	564.5	Red and gray shale with silty fine sand, some coarse grains, micaceous

Lower Cretaceous Series
Patapsco Formation

564.5 - 570.6	Same as 561.5 - 564.5 but no coarse grains
570.6 - 573.7	Shale with silty fine sand and lignite
573.7 - 579.8	Varicolored shale with silt
579.8 - 601.1	Varicolored shale with silt, mica, and minor lignite
601.1 - 604.2	Very fine-fine silty sand, abundant lignite and mica
604.2 - 613.3	Medium-coarse quartz sand
613.3 - 616.3	Mostly coarse sand, some silty fine sand, minor shale
616.3 - 619.4	Silty medium-coarse sand with lignite
619.4 - 622.4	Silty medium-coarse sand, red and gray shale
622.4 - 631.6	Samples missing
631.6 - 677.3	Shale with some fine sand and silt. Micaceous from 634.6 - 637.7, 649.9 - 652.9; lignitic from 643.8 - 646.8, 665.1 - 668.2
677.3 - 692.5	Fine-medium sand with varicolored shale. Minor shale from 683.4 - 686.4
692.5 - 695.6	Fine-coarse sand, minor shale
695.6 - 701.6	Medium-coarse sand, minor shale

Lower Cretaceous Series
Arundel Formation

701.6 - 704.7	Fine-medium sand and shale
704.7 - 713.9	Shale with fine to medium sand
713.9 - 716.9	Fine sandy shale and silt
716.9 - 726.1	Shale with fine-medium sand
726.1 - 729.1	Shale with fine sand
729.1 - 732.2	Fine-medium sand, lignite, minor shale
732.2 - 735.2	Fine-medium sand with more shale than 729.1 - 732.2
735.2 - 756.6	Shale with some fine-medium sand. Few coarse grains from 744.4 - 747.4
756.6 - 759.6	Fine-coarse sand with some shale
759.6 - 765.7	Silty fine-coarse sand with shale. Minor shale from 759.6 - 762.6
765.7 - 771.8	Shale with silty fine-medium sand
771.8 - 811.4	Shale, some silty fine sand. Sample missing from 793.1 - 796.2. Minor shells from 802.3 - 811.4
811.4 - 820.5	Shale, fine-medium sand. Minor shells

Lower Cretaceous Series
Patuxent Formation

820.5 - 829.7	Shale, fine sand. Minor shells
829.7 - 832.8	Shale, fine-medium sand
832.8 - 838.8	Fine-coarse sand with shale. Equal amounts of each from 832.8 - 835.8, more sand than shale from 835.8 - 838.8
838.8 - 841.9	Fine-coarse sand, granules, minor shale
841.9 - 844.9	Fine-coarse sand, few granules, shale
844.9 - 848.0	Mostly coarse sand, some shale. Minor shells
848.0 - 851.0	Coarse-granular sand, some shale
851.0 - 860.2	Medium-coarse sand, minor shale
860.2 - 866.3	Fine-medium sand, minor shale. Minor shale from 863.2 - 866.3
866.3 - 875.4	Fine-coarse sand, minor shale
875.4 - 878.5	Clean fine-coarse sand. Minor shells
878.5 - 881.5	Clean fine-coarse sand, charcoal
881.5 - 884.6	Fine-coarse sand, minor shale
884.6 - 887.6	Shale with fine-medium sand. Minor shells
887.6 - 893.7	Shale with silty fine-medium sand
893.7 - 902.9	Shale with minor silty fine sand. Minor shells from 893.7 - 899.8
902.9 - 939.4	Shale with silty fine sand. Slightly micaceous from 902.9 - 909.0. Minor charcoal from 936.4 - 939.4
939.4 - 942.5	Fine-medium sand, minor shale, lignite
942.5 - 945.5	Fine-medium sand, some coarse grains, shale
945.5 - 957.7	Shale with some silty fine-medium sand
957.7 - 960.8	Shale with fine-coarse sand
960.8 - 973.0	Medium-coarse sand, minor shale
973.0 - 976.0	Medium-coarse sand with more shale than 960.8 - 973.0. Slightly calcareous
976.0 - 979.1	Medium-coarse sand, minor shale
979.1 - 985.2	Fine-coarse sand and shale. Minor shells
985.2 - 988.2	Medium-granular sand, minor shale. Minor shells
988.2 - 991.2	Fine-coarse sand, minor shale
991.2 - 994.3	Fine-medium sand, shale, slightly calcareous
994.3 - 1000.4	Shale with silty fine sand
1000.4 - 1003.4	Silty fine-medium sand, shale
1003.4 - 1012.6	Fine-coarse sand, minor shale
1012.6 - 1015.6	Mostly coarse sand with some fine-medium grains, minor shale
1015.6 - 1018.7	Clean fine-coarse sand
1018.7 - 1027.8	Medium-coarse sand, minor shale
1027.8 - 1033.9	Clean medium-coarse sand
1033.9 - 1037.0	Medium-coarse sand, minor shale
1037.0 - 1040.0	Fine-coarse sand with shale
1040.0 - 1043.1	Shale with silty fine-medium sand

1043.1 - 1049.2	Shale and silt, minor fine sand
1049.2 - 1052.2	Fine-coarse sand with shale
1052.2 - 1055.3	Shale with silt, minor fine sand
1055.3 - 1058.3	Silty fine-medium sand, minor shale
1058.3 - 1061.4	Fine-coarse sand, minor shale
1061.4 - 1070.5	Medium-coarse sand, minor shale
1070.5 - 1073.5	Medium-granular sand, minor shale
1073.5 - 1076.6	Clean medium-coarse sand
1076.6 - 1082.7	Fine-coarse sand and shale, even amounts of each
1082.7 - 1091.8	Shale with some fine-medium sand
1091.8 - 1094.9	Fine-coarse sand, minor shale
1094.9 - 1101.0	Mostly coarse sand, minor shale and fine-medium sand
1101.0 - 1104.0	Shale, silty fine sand
1104.0 - 1113.2	Shale with silty fine-coarse sand
1113.2 - 1119.3	Shale with fine-medium sand, even amounts of each
1119.3 - 1125.4	Fine-coarse sand, minor shale
1125.4 - 1128.4	Silty fine-coarse sand with shale
1128.4 - 1158.9	Fine-coarse sand, minor shale
1158.9 - 1168.0	Clean fine-coarse sand
1168.0 - 1177.2	Fine-coarse sand with minor shale
1177.2 - 1183.3	Shale with fine-coarse sand
1183.3 - 1192.4	Shale with minor silty sand. Minor shells from 1189.4 - 1192.4
1192.4 - 1201.6	Shale and fine-medium sand. Minor shells from 1192.4 - 1195.5
1201.6 - 1213.8	Fine-coarse sand, shale
1213.8 - 1216.8	Shale, minor fine sand
1216.8 - 1219.8	Fine-medium sand, minor shale
1219.8 - 1225.9	Medium-coarse sand, minor shale
1225.9 - 1229.0	Same as 1219.8 - 1225.9, but more shale
1229.0 - 1232.0	Medium-coarse sand, minor shale
1232.0 - 1250.3	Slightly sandy silt with shale. Slightly micaceous from 1235.1 - 1238.1
1250.3 - 1277.8	No samples - cores drilled
1277.8 - 1280.8	Fine sandy silt with shale and some gravel
1280.8 - 1283.9	Medium-coarse sand with minor shale
1283.9 - 1286.9	Coarse sand with some granules

Pre-Cretaceous
"lower acoustical zone"

1286.9 - 1290.0	Even mixture of sand, silt, and shale
1290.0 - 1311.3	Slightly sandy silt with abundant shale
1311.3 - 1314.3	Shale and silt
1314.3 - 1338.7	Silty shale, minor fine sand. Plant remains from 1326.5 - 1329.6
1338.7 - 1341.8	Shale, with more fine sand than 1314.3 - 1338.7
1341.8 - 1362.2	Silty shale, minor fine sand. Minor lignite from 1347.9 - 1350.9,

1338.7 - 1341.8	Shale, with more fine sand than 1314.3 - 1338.7
1341.8 - 1362.2	Silty shale, minor fine sand. Minor lignite from 1347.9 - 1350.9, 1360.1 - 1362.2
1362.2 - 1693.0 (T.D.)	Metavolcanic basement rock

TABLE A-3. Geologic Formation Boundaries, DGT-1

Formation/Stage	Depth (m)	Thickness(m)
Yorktown	? - 76.2	?
St. Marys	76.2 - 106.7	30.5
Choptank	106.7 - 131.7	25.0
Calvert	131.7 - 238.4	106.7
Piney Point	238.4 - 259.7	21.3
Midway - Upper Cretaceous (undivided)	259.7 - 338.9	79.2
Magothy	338.9 - 360.3	21.4
Raritan	360.3 - 564.5?	204.2?
Patapsco	564.5? - 701.6	137.1?
Arundel	701.6 - 820.5	118.9
Patuxent	820.5 - 1286.9	466.4
"lower acoustical zone"	1286.9 - 1362.2	75.3

The Patuxent Formation, 466 m thick and extending from a depth of 821 m to 1287 m, unconformably overlies the lower acoustical unit and consists primarily of thick sand layers interbedded with thin layers of variegated shale. The quartzose and feldspathic sands range from fine to coarse, and are commonly gravelly in the basal 18 m. Clean but poorly sorted sands form thin beds within the larger sand bodies, and the majority of the sands contain some shale. Shell fragments, lignite, and mica occur in minor amounts throughout the formation. The upper contact at 821 m can be distinguished in the drill cuttings, and by prominent breaks in the gamma and electric logs (Figure A-1). The characteristic change from the Patuxent to the overlying Patapsco-Arundel group is indicated by the presence of thicker layers of shale. Gamma ray activity is generally higher above 821 m where the Arundel shale unconformably overlies the Patuxent (Figure A-1).

In the Arundel (702 m - 821 m) the sediments consist chiefly of dark colored clay, shale and sandy shale. However in two distinct intervals, from 729 m - 735 m and from 757 m - 766 m, the Arundel is primarily fine to coarse sand with minor shale. From 565 m to 702 m there are alternating beds of sand and varicolored shale typical of the Patapsco Formation. Although it is usually difficult to separate these units, the lithostratigraphic change, coupled with major breaks in the gamma and electric logs at 702 m, suggest that the Patapsco-Arundel contact occurs at this depth (Figure A-1). Similarly, the upper contact of the Patapsco is not easily recognized in the section. Fine sands and varicolored shales, particularly gray and red shales are reported from the upper portion of the Patapsco, and in the basal part of the overlying Raritan Formation in Maryland (Rasmussen and Slaughter, 1955). However, the Raritan Formation usually contains more abundant mica than the Patapsco. In DGT-1, there is a marked increase in mica content above 565 m. On this basis, a tentative Patapsco - Raritan boundary has been assigned at 565 m.

The Raritan is fine to medium sands intercalated with variegated shale and clay. Lignite and mica are common to abundant, and plant fragments are occasionally seen in the upper portion. The upper contact with the Magothy Formation is marked by a decrease in gamma ray activity and a break in the electric log at approximately 360 m (Figure A-1).

The top and bottom of the Magothy are defined by the vertical extent of fine-to-medium white and buff quartz sand with minor stringers of carbonaceous clay and lignite. This unit is clearly defined by prominent breaks in the gamma and electric logs at 339 m and 360 m (Figure A-1). A similar pattern for the Magothy is seen in logs from the Janes Island well at a shallower depth (Hansen, 1967).

Above the Magothy, and extending from 260 m to 339 m are rocks of Midway age and the Upper Cretaceous (undivided) section; these are inseparable by lithology alone. This interval consists of alternating thin beds of fine to medium quartz sand and gray clay. Glauconite becomes a common constituent for the first time in the Atlantic Coastal Plain section; the sediments reflect a change from a marginal marine to a marine depositional environment. In the upper portion, between 260 m and 290 m, the cuttings are mainly glauconitic clay. This lithology is consistent with the gamma and resistivity trends (Figure A-1). The equivalent section from the Janes Island well (244 m - 325 m) is lithologically very similar to DGT-1; there is glauconitic clay in the upper 37 m (Hansen, 1967).

The boundaries of the overlying Piney Point Formation are easily distinguished from logs and cuttings. This unit is typically highly glauconitic, clayey, fine-to-medium quartz sand. Gamma logs from DGT-1 and Janes Island show a high, although variable, rate of activity between 241 m and 262 m (Figure A-1). This is unusual for sand bodies but it may be explained by the high concentration of glauconite. The contact of the Piney Point with the overlying Calvert Formation is defined by a major electrical log break, and by abundant clay and silt above 238 m (Figure A-1). A regional disconformity between the two units represents a period of nondeposition or erosion during the Oligocene Epoch.

The Calvert, 107 m thick and extending from 132 m to 238 m, is predominantly diatomaceous gray clay and silt. In the basal 9 m, the sediments contain a small fraction of fine sand. A clayey shell bed exists from 152 to 158 m, and a few other intervals contain minor shell fragments. At approximately 132 m, both the gamma and electric log exhibit breaks that are correlative to the breaks seen in logs from the Janes Island well at 116 m (Figure A-1) (Hansen, 1967). These breaks, plus the appearance of abundant shells above the breaks, mark the Choptank-Calvert contact at approximately 132 m.

The Choptank Formation conformably overlies the Calvert and ranges in depth from 107 m to 132 m. The highly fossiliferous sediments are more sandy than clayey in the upper two thirds of the unit with a gradual downward increase in clay from 125 m to the base.

Overlying the Choptank is the St. Marys Formation (76 - 107 m) which is easily distinguishable by the appearance of gray clay and silt above 107 m. Minor amounts of shell fragments are present in all the samples from this unit. The upper contact with the Yorktown Formation is indicated by a negative "kick" in the gamma log at 76 m, and by a corresponding break in the self-potential and resistivity curves (Figure A-1). Sand content increases above 76 m, becoming coarse and granular from 59 m to 68 m.

The Yorktown - Columbia Group contact cannot be determined for DGT-1 due to difficulty in collecting samples during the first 46 m of drilling. In the Janes Island well, this boundary was picked at 12 m (Hansen, 1967); it is anticipated that the boundary in DGT-1 is within a few meters of that depth.

References

Brown, P. M., Miller, J. A., and Swain, F. M., 1972, Structural and stratigraphic framework and spatial distribution of permeability of the Atlantic Coastal Plain, North Carolina to New York: U.S. Geol. Survey Prof. Paper 796, 79 p.

Glaser, J. D., 1969, Petrology and origin of Potomac and Magothy (Cretaceous) sediments, Middle Atlantic Coastal Plain: Maryland Geological Survey, Report of Investigations No. 11, 101 p.

Hansen, H. J., 1967, Hydrogeologic data from the Janes Island State Park test well (1514 feet): Maryland Geological Survey Basic Data Report No. 3, 24 p.

Hansen, H. J., 1978, Upper Cretaceous (Senonian) and Paleocene (Danian) pinchouts on the south flank of the Salisbury Embayment, Maryland, and their relationships to antecedent basement structures: Maryland Geological Survey Report of Investigations No. 29, 34 p.

Onuschak, E. Jr., February 1972, Deep test in Accomack County, Virginia: Virginia Minerals Vol 18, No. 1, p. 1 - 4.

Rasmussen, W. C., and Slaughter, T. H., 1955, The water resources of Somerset, Wicomico, and Worcester Counties: Maryland Dept. Geol., Mines and Water Resources Bull. 16, p. 1 - 170.

Schlee, J., Behrendt, J. C., Grow, J. A., Robb, J. M., Mattick, R. E., Taylor, P. T., and Lawson, B. J., 1976, Regional geologic framework off northeastern United States: Amer. Assoc. Petroleum Geol. Bull. Vol. 60/6, p. 926 - 951.

Vokes, H. E., and Edwards, J. Jr., 1974, Geography and geology of Maryland: Maryland Geological Survey Bull. 19, 242 p.

Summary of Temperature Logging of
Crisfield, Maryland Geothermal Test Hole

Samuel S. Dashevsky and Wilson S. McClung

Drilling of the first geothermal test hole (DGT-1) on the east coast began at Crisfield, Md. on May 13, 1979. Throughout the drilling and testing phase the thermal regime was monitored as closely as possible by V.P.I.& S.U. Previous measurements from initial heat flow data at that site (Hole C32-A) indicated a gradient of 45.7°C/km and a temperature of 26.2°C at 294m (965 ft). Extrapolating this shallow gradient to a depth of 1280m (4200 ft) where acoustic basement was indicated by surface VIBROSEIS seismic data obtained during February, 1979, 71°C was indicated as a maximum possible temperature at that depth.

During the drilling of DGT-1 the discharge mud temperature was monitored to test its application as a method to determine downhole formation temperatures. The data have been plotted as drilling depth vs temperature of discharge mud (Figure A-2). (All depths cited in this section are referenced to land surface.) During drilling to 1375m (4508 ft) the discharge temperature rose from 23°C to 37.5°C. The temperature rose during periods of continuous drilling. How much of this is to be attributed to the geothermal gradient and how much to frictional heat of the rotating bit and drill stem is not clear. Pauses in the drilling operation for coring, equipment failure, or lost circulation allows the standing column of mud to cool, and the temperature intervals become redundant. Variation in the mud intake temperature due to weather conditions and mixing of fresh water at the surface further complicates the data. At present this is not a useful technique, but similar monitoring on future holes is recommended. Useful trends and important differences may become apparent. This is a technique which has been shown to be valid in wells deeper than 1500 meters in Montana and along the Gulf Coast (Edwardson _et al_., 1962)

The base of the Coastal Plain sediments (base of "lower acoustic zone") was reached at 1362m (4469 ft); an additional 46 meters was drilled into basement (metavolcanics). The Schlumberger logging program in the sediments consisted of the following:

- Dual induction electric
- Spherically focused electric
- Self potential electric
- Borehole compensated sonic
- Three-arm caliper
- Gamma ray
- Formation density
- Cement bond

Temperature was logged by VPI&SU (Figure A-3).

Two maximum reading mercury thermometers were sent down on two of the logging runs. One thermometer strapped to the top of the logging

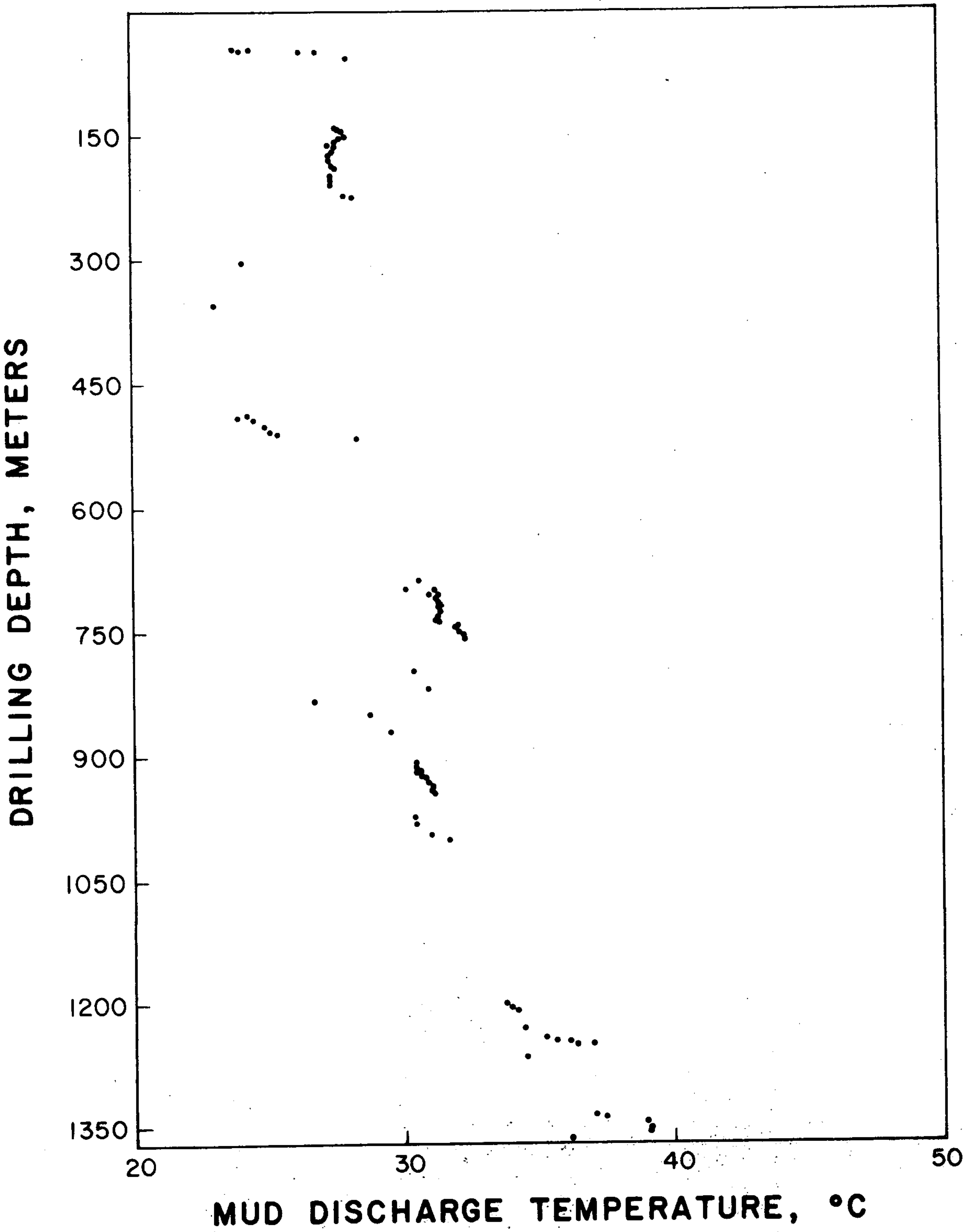


Figure A-2. Temperature of drilling mud discharged at surface plotted against depth of drilling at the time of measurement tools was run to a depth of 1398m (4586 ft). The second thermometer was strapped 61m (200 ft) further up the logging cable and was run to a depth of 1337m (4386 ft). The temperature recorded from each maximum thermometer is assumed to represent the temperature at the deepest point reached by that thermometer. The first set of thermometers reached their maximum depth 4.25 hours after circulation in the hole had ceased. At 1398m, 47.8°C (118°F) was recorded, 44.4°C (112°F) was recorded at 1337m. The total depth on the second run in the hole was 2 meters shallower than on the first run because debris had accumulated in the hole. On the second run, the thermometers reached their total depth 12.5 hours after circulation in the hole had ceased. The lower thermometer from 1396m recorded 54.4°C (130°F) a rise of 6.6°C in 8.25 hours, while the the upper thermometer from 1335m came up broken.

After the open-hole logs were completed a temperature log was run by VPI&SU. To minimize the time spent in the open hole , the log began at 50m and consists of temperature readings through ten meter intervals at spacings of 100 meters. In the bottom portion of the hole, measurements were taken every 0.5m through the lower three aquifer zones (1156m - 1287m), the indurated sediments (1287m - 1362m) and the metamorphic basement (1362m - 1406m). Detailed measurements also were made through the cored intervals. The resultant log is designated DGT-1A (Fig. A-3).

Following the casing and cementing of the 1406m (4620 ft) hole, the hole was turned over to the Los Alamos Scientific Laboratory (LASL) for further drilling and hydraulic fracturing. The hole was deepened to 1693m (5554 ft) and three cores were cut (see Gleason, this report).

Prior to and after fracturing the following suite of logs (with the exception of the Spectral Gamma Log) was run by Birdwell:

Pre-fracture logs	Post-fracture logs
Spontaneous potential	Spontaneous potential
16 " and 64 " normal electric	16 " and 64 " normal electric
6 arm caliper	6 arm caliper
3-dimensional velocity	3-dimensional velocity
Temperature	Temperature
Borehole televiewer	Borehole televiewer
Nuclear cement temp. locator	Temperature - VPI&SU
Neution borehole compensated	Bottom hole temperature-VPI&SU
Density borehold compensated	
Spectral gamma log (K,U,Th) by Dresser Atlas	
Temperature - VPI&SU	

The pre-fracture temperature log (DGT-1B, Fig. A-3) obtained by VPI&SU began at 1225m (4019 ft) and reached a total depth of 1693m (5554 ft). The log was run 43 hours after the last episode of circulation in the hole, and measured a bottom hole temperature of 66.3°C. This temperature (which is not an equilibrium value) is the highest temperature that was recorded at that depth and is the measured value

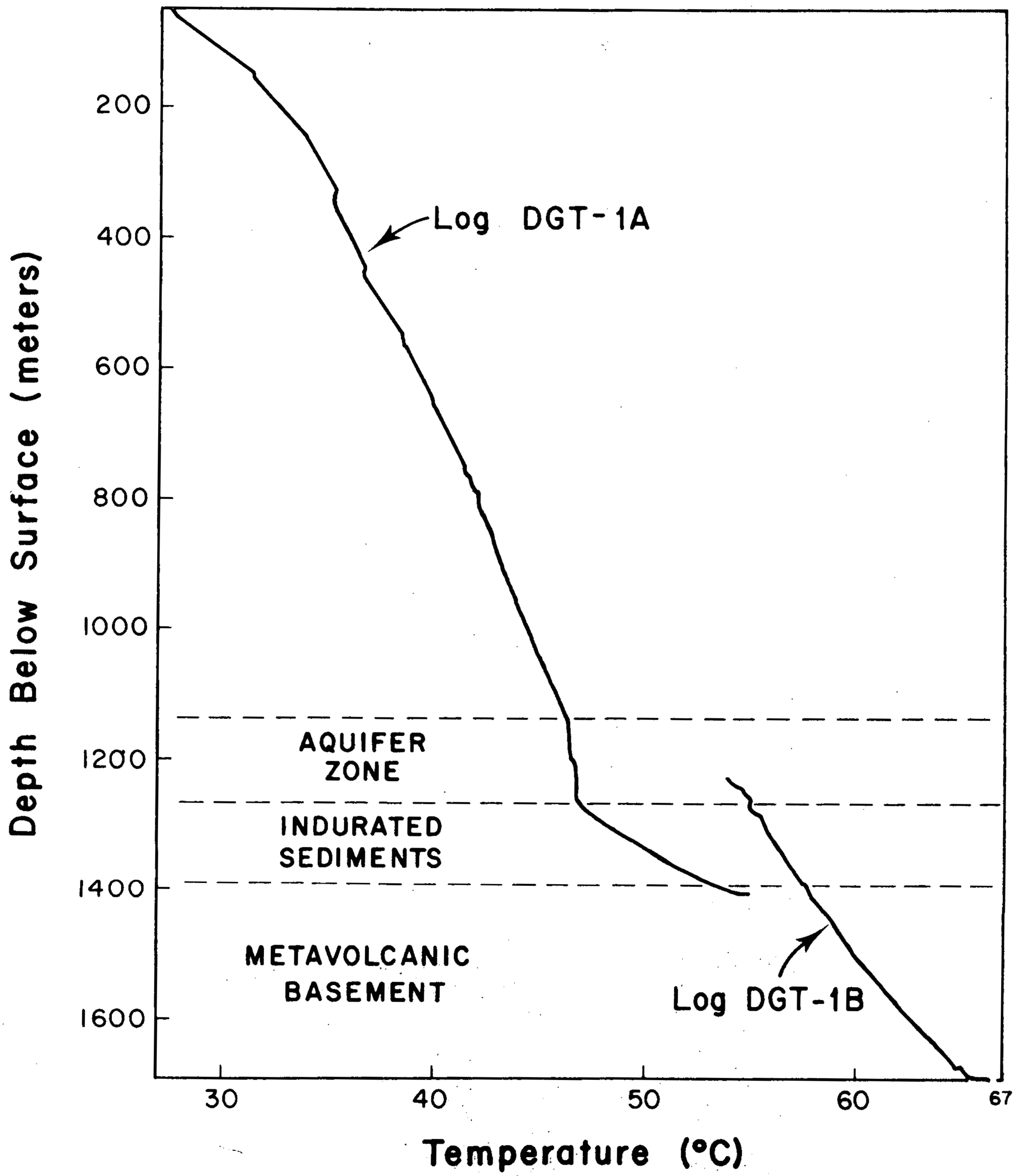


Figure A-3. Open hole temperature log of Coastal Plain sediments (DGT-1A) 16.5 hours after circulation stopped on 6/4/79. Open hole temperature log (DGT-1B) of lower sediments and basement 43 hours after circulation stopped on 6/15/79.

that is closest to equilibrium. Nine hours after circulation, a maximum reading mercury thermometer recorded 62°C at 1693 m, and 34.5 hours after circulaton the bottom-hole temperature recorded was 65°C.

After completion of all testing and contract logging in the basement part of the hole, another temperature log (DGT-1C) was obtained by VPI&SU from 1186m - 1693m. Three days had elapsed since the last temperature measurement, and in that time considerable temperature disturbance had occurred in the hole. A hydraulic fracture had been initiated and propogated by pumping large volumes of surface water into the hole. The fracture was propped open with sand, and excess sand was circulated out of the hole. Sixteen and one-half hours after that last circulation, temperature log DGT-1C was obtained (Fig. A-4). The fractured zone is apparent as a cooled interval between 1647m and 1690m where large volumes of surface waters absorbed heat from the fractured rock. The bottom hole temperature had dropped to 65.1°C due to the continued circulation of water.

After reaching the maximum depth of 1693m for log DGT-1C the probe was left on bottom for the next 10 hours at the request of LASL. Temperature measurements were made every minute to define the bottom-hole thermal equilibration curve in order to estimate the equilibrium temperature. Following this, a final temperatuare log (DGT-1E) was run (Figure A-4). In Figure A-5 bottom-hole temperature is plotted against time from 1200 hr to 2200 hr on June 19, 1979. During the 10-hour span of the survey the temperature rose 0.53°C from 65.37 to 65.90°C, an average of 0.05°C/hour. Most of the thermal equilibration had occurred in the preceeding 19 hours since circulation ceased. In the 10 hours monitored, the asymptotic portion of the curve was observed to approach a maximum of 67°C. Using the bottom-hole temperature measured in DGT-1B (pre-fracture log) as a minimum value, the temperature at 1693m can be bracketed in the range 66.3°C - 67°C. During the aquifer pump test of zone #1 directly above the indurated sediments (refer to figure 2) the temperature measured was 2°C warmer than that indicated by previous temperature log DGT-1B. If one accepts the temperature rise of 2°C to be valid also for the basement surface at the bottom of the indurated sediments then an equilibrium temperature can be assumed for the basement surface to be 58.8°C. This coupled with our value for the bottom of the hole of 66.3 - 67°C yields an average gradient between 22.6°C/km and 24.8°C/km. The mean thermal conductivity from the basement core samples is 3.20 $\pm$ 0.51 W/m-°C yielding a heat flow between 72 mW/m^2 and 79 mW/m^2. Incorporating this with three heat flow determinations in the sedimentary section of the hole (Table A-4), yields an average value of 72 mW/m^2 at the test well site.

With testing in the basement section completed, a bridge plug was set at 1400m (4595 ft) and the Gruy Federal aquifer testing program began. Three zones between 1156m and 1287m (3792 ft - 4224 ft) were perforated and pumped individually under the direction of Gruy Federal Inc. Drawdown was measured with a down-hole quartz pressure cell and each zone was pumped sufficiently to reach a static drawdown for the discharge rate established. After pumping, the head buildup was moni-

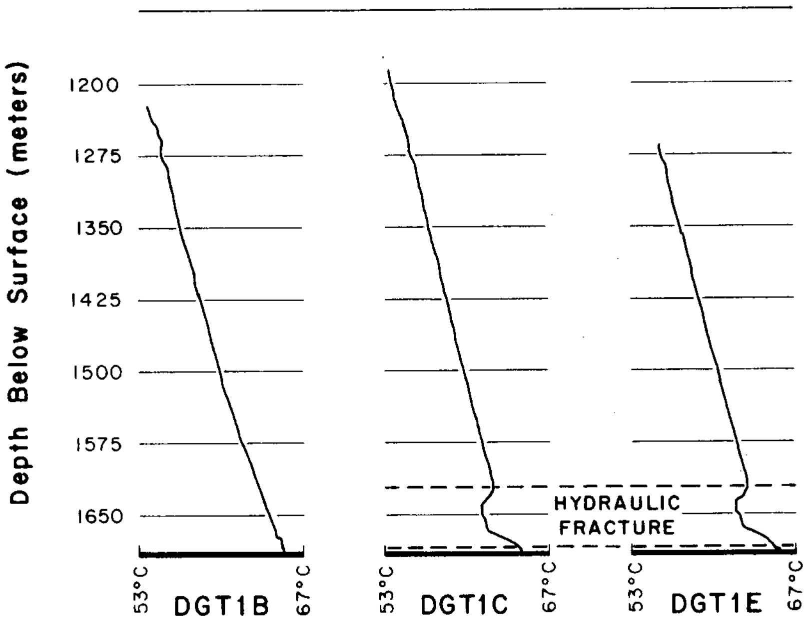


Figure A-4. Pre-hydrofracture temperature log DGT-1B 43 hours after circulation 6/15/79, and post-fracture logs DGT-1C 17 hours after circulation 6/18/79, and DGT-1E 30 hours after circulation 6/19/79.

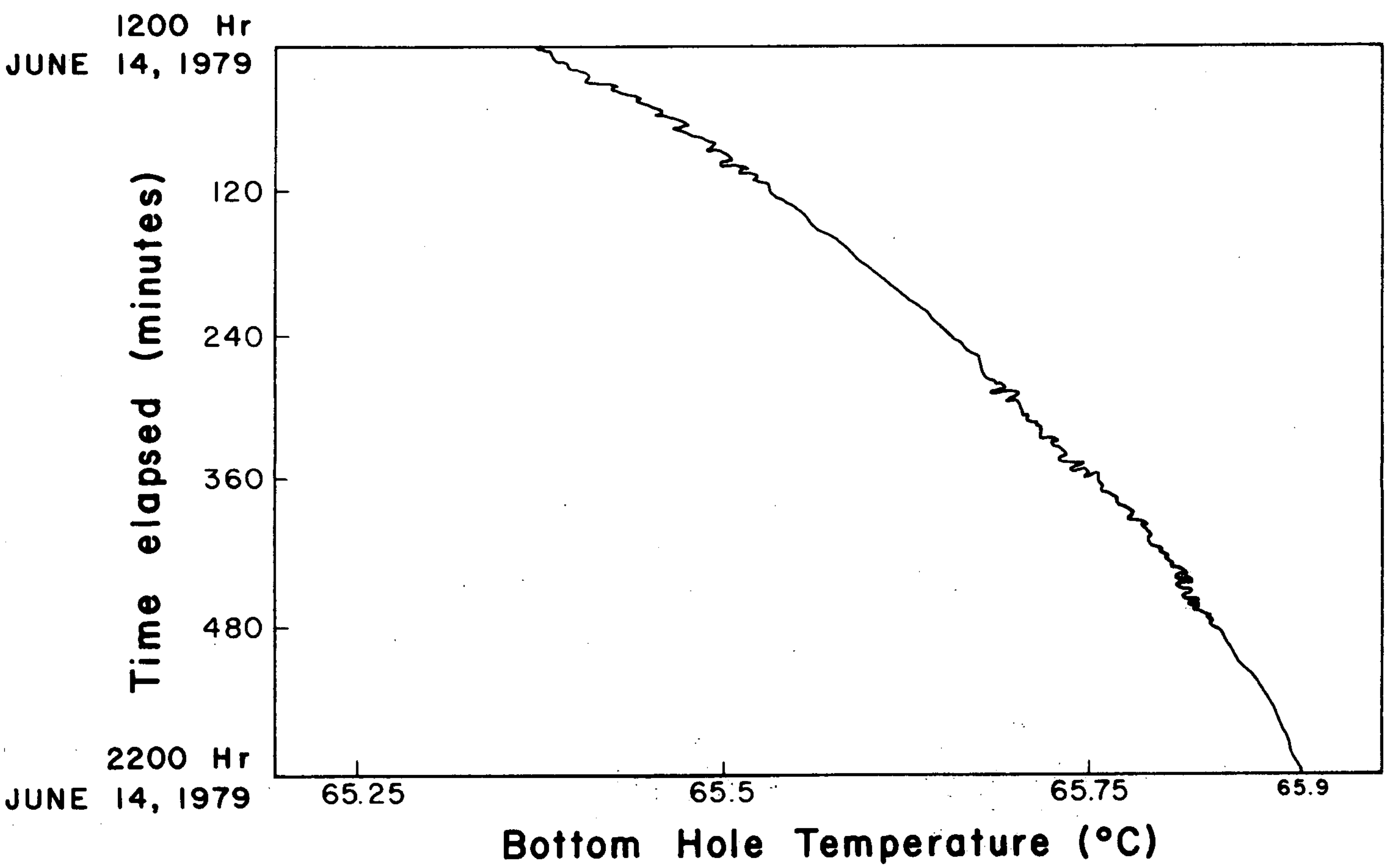


Figure A-5. Ten hour survey of bottom hole temperature at 1693m in metavolcanic basement.

tored until static level was regained in all three zones. Details of the aquifer test are forthcoming from Gruy Federal Inc.

Zone #1 was perforated between 1262m and 1285m (4142 ft - 4217 ft) A down-hole centrifugal pump set at 180m (600 ft) pumped the water level down below it in 8 minutes at a rate of 150 gallons/minute. It is not clear whether or not all perforations in this zone were effective in allowing water to enter the well bore unimpeded. A smaller pump capable of maintaining 10 g.p.m. was then set at 180m and pumped for 24 hours at an average rate of 14 g.p.m. The static drawdown at this discharge was approximately 4.6m (15ft). The temperature of the water flowing from the perforated zone was 57.2°C (135°F) at the level of perforation. Pumped at the low discharge of 14 g.p.m., the discharge temperature at the surface was only 38°C (100°F).

Zone #2 was perforated from 1187m to 1227m (3895 ft - 4026 ft) and the large volume pump was set at 210m (700 ft) depth. This horizon was indicated by logs and cuttings to be a much cleaner continuous sand unit than Zone #1. Water was produced for 48 hours at an average rate of 119 g.p.m. drawing the static head down 84m (275 ft). The temperature of the water at the level of perforation was 56°C (133°F) and at the surface the discharge temperature was 51°C (124°F). This surface temperature was considerably higher than that measured during pump tests of the deeper Zone #1 due to the substantially larger thermal mass being brought to the surface at a higher velocity by the larger pump in Zone #2.

During each pump test, surface temperature was seen to rise continually. Under high production for an extended period of time it is expected that the difference between the well head and perforation temperature would be less.

Following tests of Zone #2, a cement retainer was set at 1181m (3874 ft) and the perforations of Zones #1 and #2 were squeezed with cement. As much as 10 meters of cement can be expected on top of the retainer.

Zone #3 was perforated between 1155m and 1170m (3792 ft - 3840 ft). Logs and cuttings indicated this zone to be a clean sand within a thick shale horizon. The small, low-volume pump was set at 125m (410 ft) and produced at an average discharge of 32 g.p.m. for 36 hours reaching a static drawdown of 30m (98 ft). Down-hole water temperature was 54°C (129°F) and surface discharge temperature reached 35°C (95°F).

With the completion of Zone #3 testing, a cement retainer was set at 1140m (3742 ft) and Zone #3 perforations were squeezed with cement.

Twenty days later temperature log DGT-1F was run and cement was encountered at 1110m. Comparison with log DGT-1G run three days later indicates continuing dissipation of heat generated from cementing particularly in the upper 300m (see Report # VPI&SU-5648-4). Above this during drilling and these become large pockets of cement when casing is grouted in place. Figure A-6 shows the most recent temperature log DGT-1J (which is nearing equilibrium) in relation to the first temperature log DGT-1A in the Coastal Plain sediments, and DGT-1B the best representative temperature log in the basement. The overall least-square gradient from 20m to 1080m is 34°C/km. The gradient from 60m to 295m of DGT-1J is 43.9°C/km as compared to 45.8°C/km measured in the original heat flow hole C32A. This indicates the latest gradient is within 5% of thermal equilibrium.

Table A-4 summarizes the depths of the different horizons and zones of interest in DGT-1.

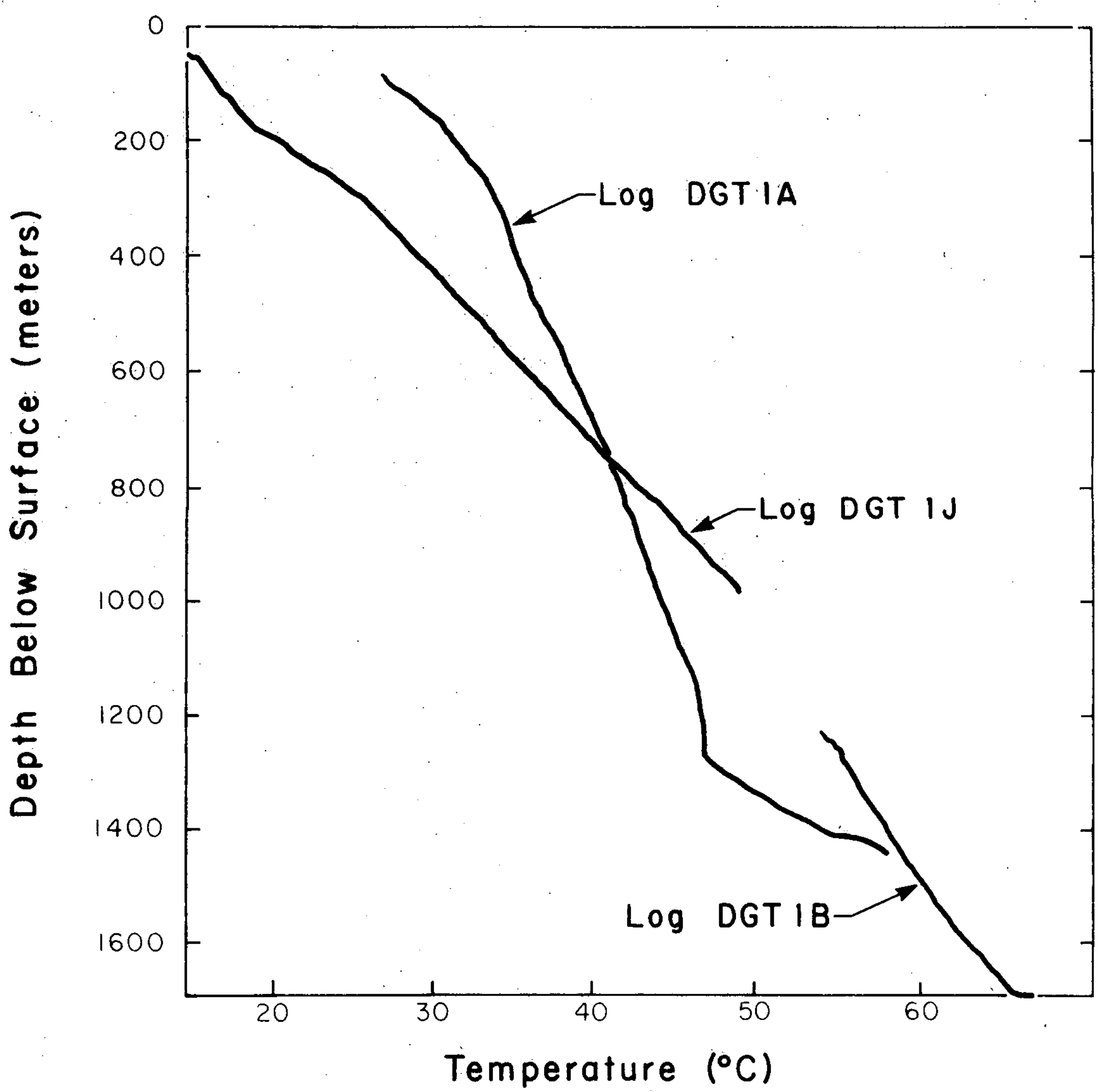


Figure A-6. DGT-1A, open hole temperature log of Coastal Plain sediments 16.5 hours post circulation. DGT-1B, open hole temperature log of lower Coastal Plain and basement section 43 hours post circulation. DGT-1J, cased hole temperature log of Coastal Plain sediments to depth of cement plug, 65 days post-completion.

TABLE A-4

Deep Geothermal Test - 1 (DGT-1) Total depth 1693 m (5554 ft)

Zone	Depth (ref. land surface) Meters	Feet	Thermal Conductivity W/m-°C	Thermal Gradient °C/km	Heat Flow mW/m^2
Unconsolidated Coastal Plain Sediments	0 - 1287	0 - 4224			
Cores 1 and 2	331 - 347	1089 - 1139	1.72 ± .14	36.4 ± .42	63 ± 6
Cores 4, 5, and 6	793 - 821	2603 - 2693	2.16 ± .3	36.2 ± .18	78 ± 11
Core 7	946 - 956	3106 - 3136	2.15 ± .07	34.8 ± .24	75 ± 3
Cores 8, 9, and 10	1250 - 1279	4104 - 4194	2.30 ± .49	29.2 ± .05	67 ± 15
Zone #3 perforation	1157 - 1172	3798 - 3846			
Zone #2 perforation	1189 - 1229	3901 - 4032			
Zone #1 perforation	1264 - 1287	4148 - 4223			
Indurated Coastal Plain Sediments	1287 - 1362	4222 - 4467			
Metavolcanic Basement	1362 - 1693	4467 - 5554			
Core 11	1418 - 1421	4652 - 4663			
Core 12	1528 - 1532	5012 - 5027	3.20 ± .51	22.6 ± 24.8	75 ±
Core 13	1688 - 1693	5539 - 5554			
Hydraulic fracture	1647 - 1693	5402 - 5554			

Comparison of Geothermal Gradients and Gamma Logs in Shallow Holes (300 m) in the Atlantic Coastal Plain

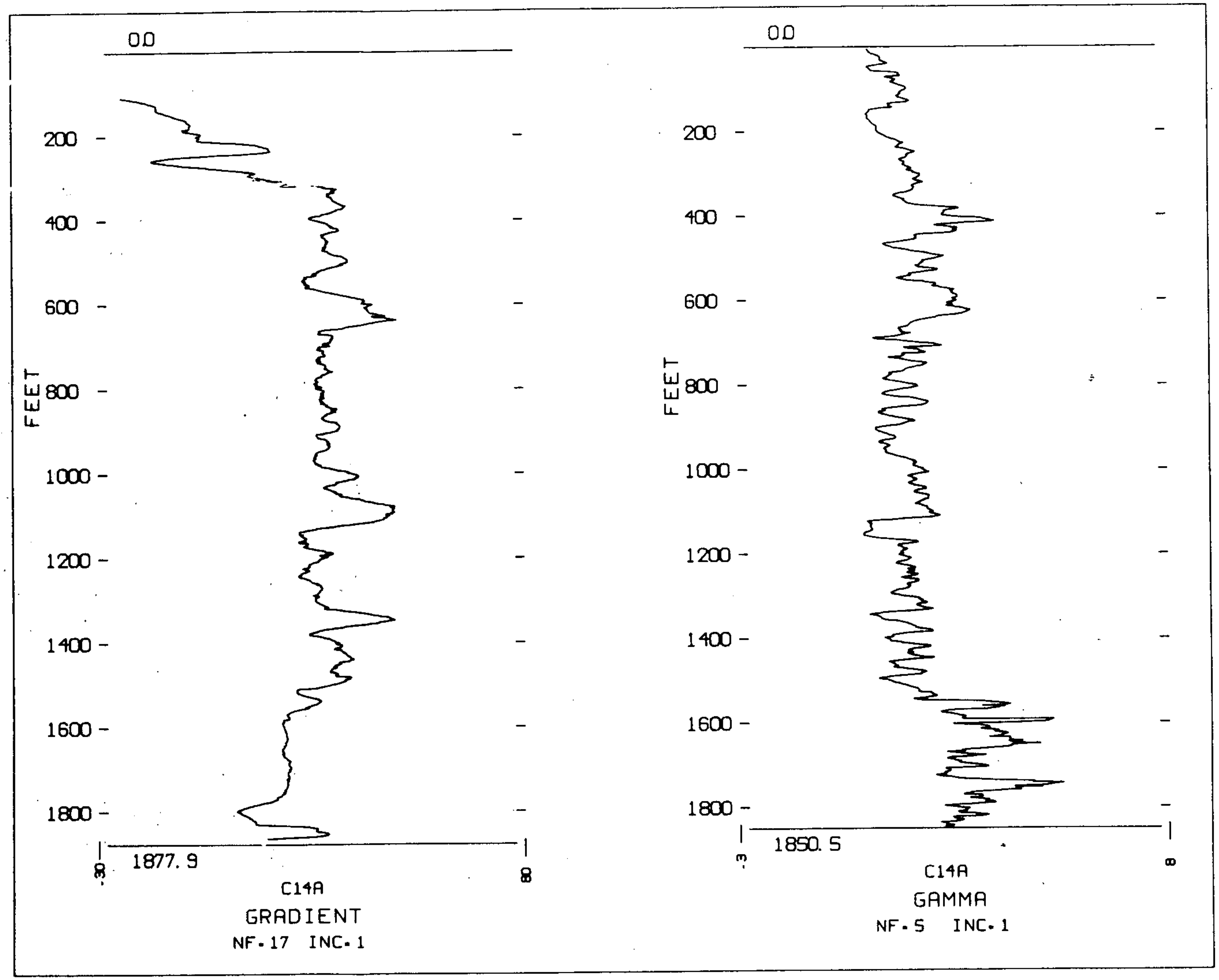
Wilson McClung, Samuel Dashevsky, and Brian Thoreson

Geothermal gradients in the shallow (300 m) Coastal Plain test holes are being compared with gamma logs from the same holes. The study should yield valuable information concerning the relationship between thermal conductivity, grain size and geothermal gradient. It is expected that the geothermal gradient and gamma log will have a similar shape because high gamma-producing units tend to be predominantly clay, and clays have a low thermal conductivity so that geothermal gradient is high. This trend is readily apparent in the comparative plots for 35 test holes that are presented on the following pages.

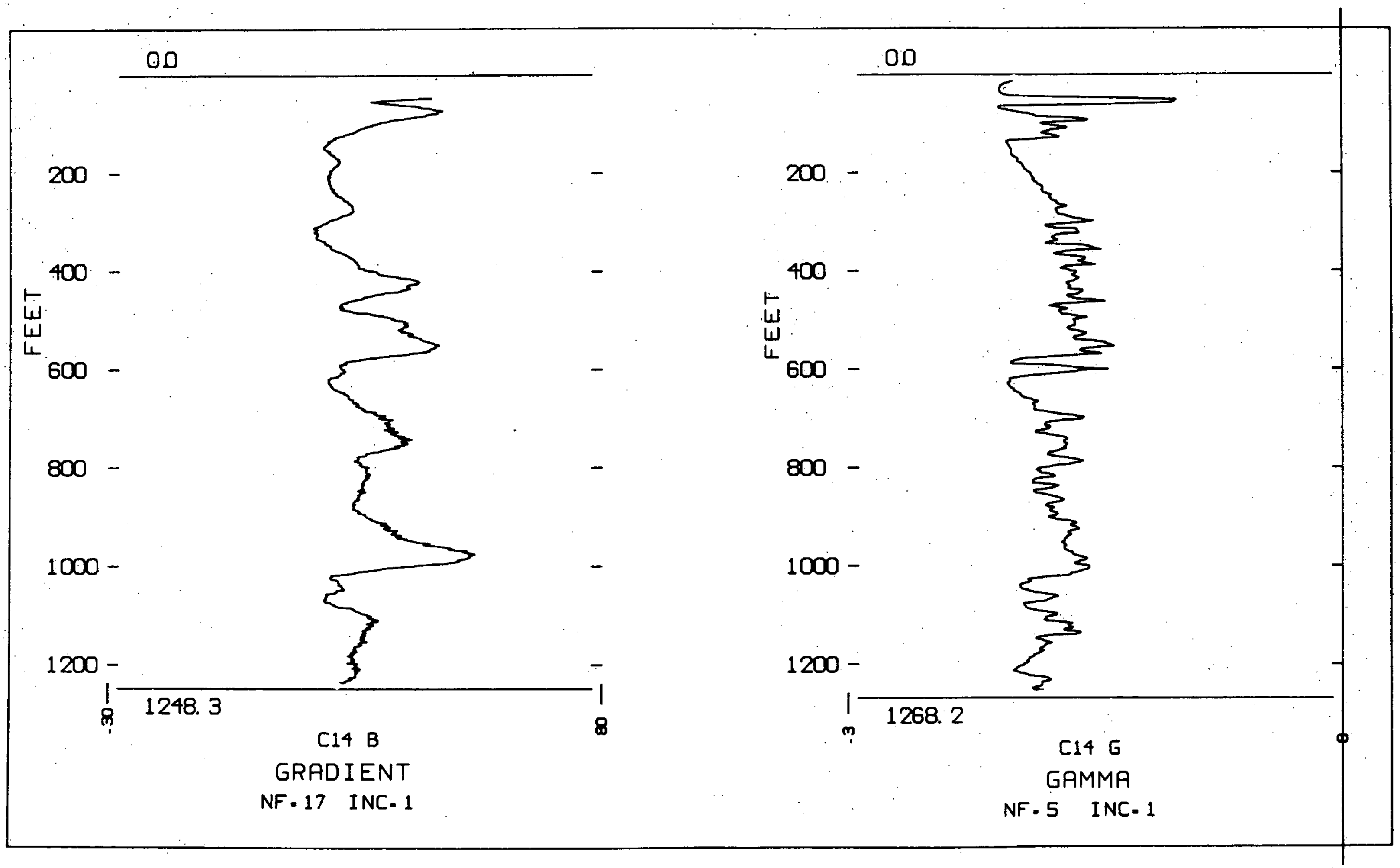
There are deviations from the trend described above. In some cases, high gamma values are associated with low geothermal gradients. Most likely, this is the result of a high-gamma producing thorium-rich sand or glauconitic sand with a relatively high thermal conductivity. Low gamma values associated with high geothermal gradients probably are caused by water-saturated rocks with low gamma production and low thermal conductivity.

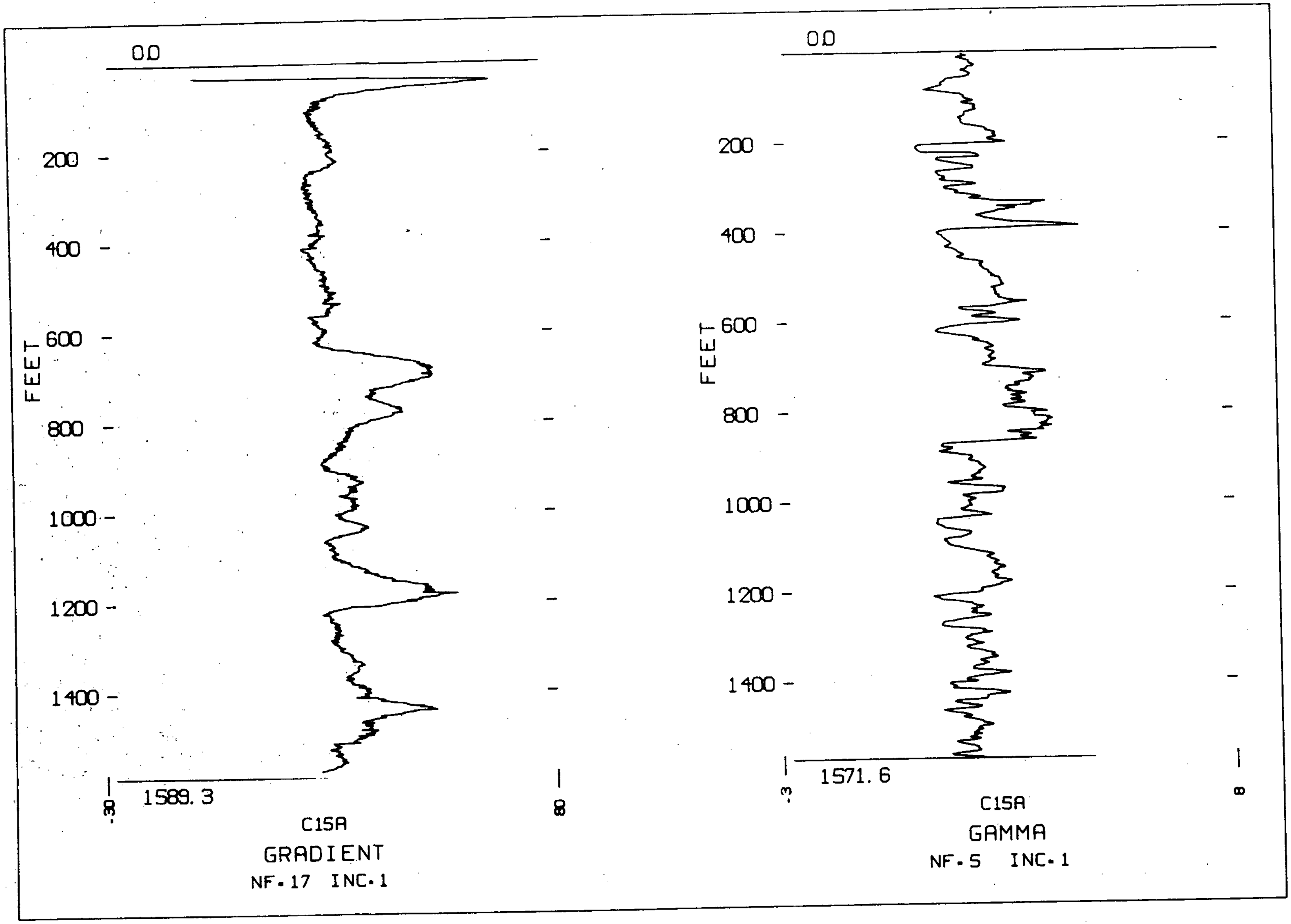
Occasional instances of water movement in or around the well bore have been observed to modify the thermal gradient independently of the thermal conductivity or gamma radiation of the lithology penetrated.

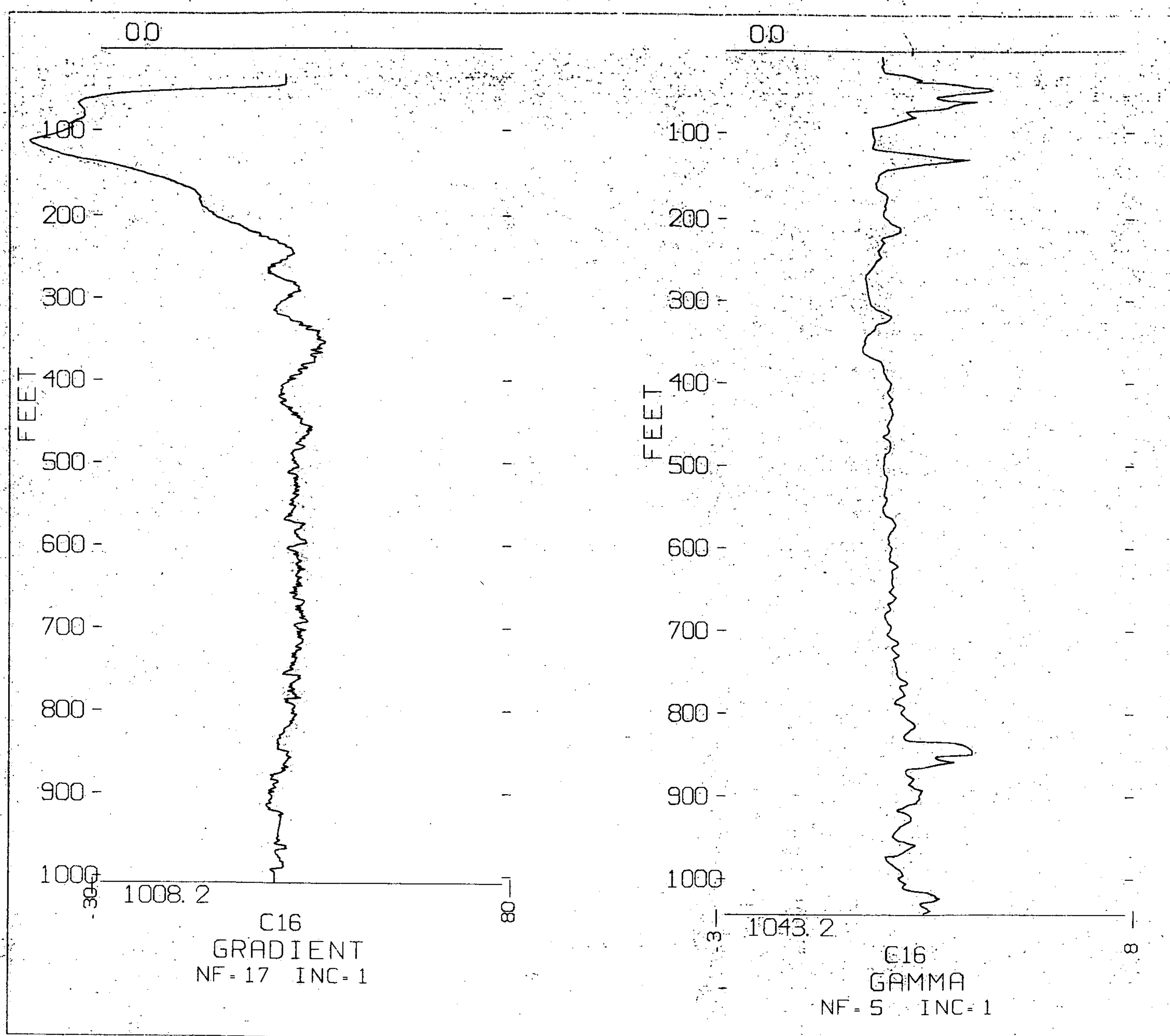
Detailed comparison of gamma logs and geothermal gradients is expected to contribute to an understanding of the hydrologic regime and potential aquifers, grain size and thermal conductivity. This study is in its initial stages.

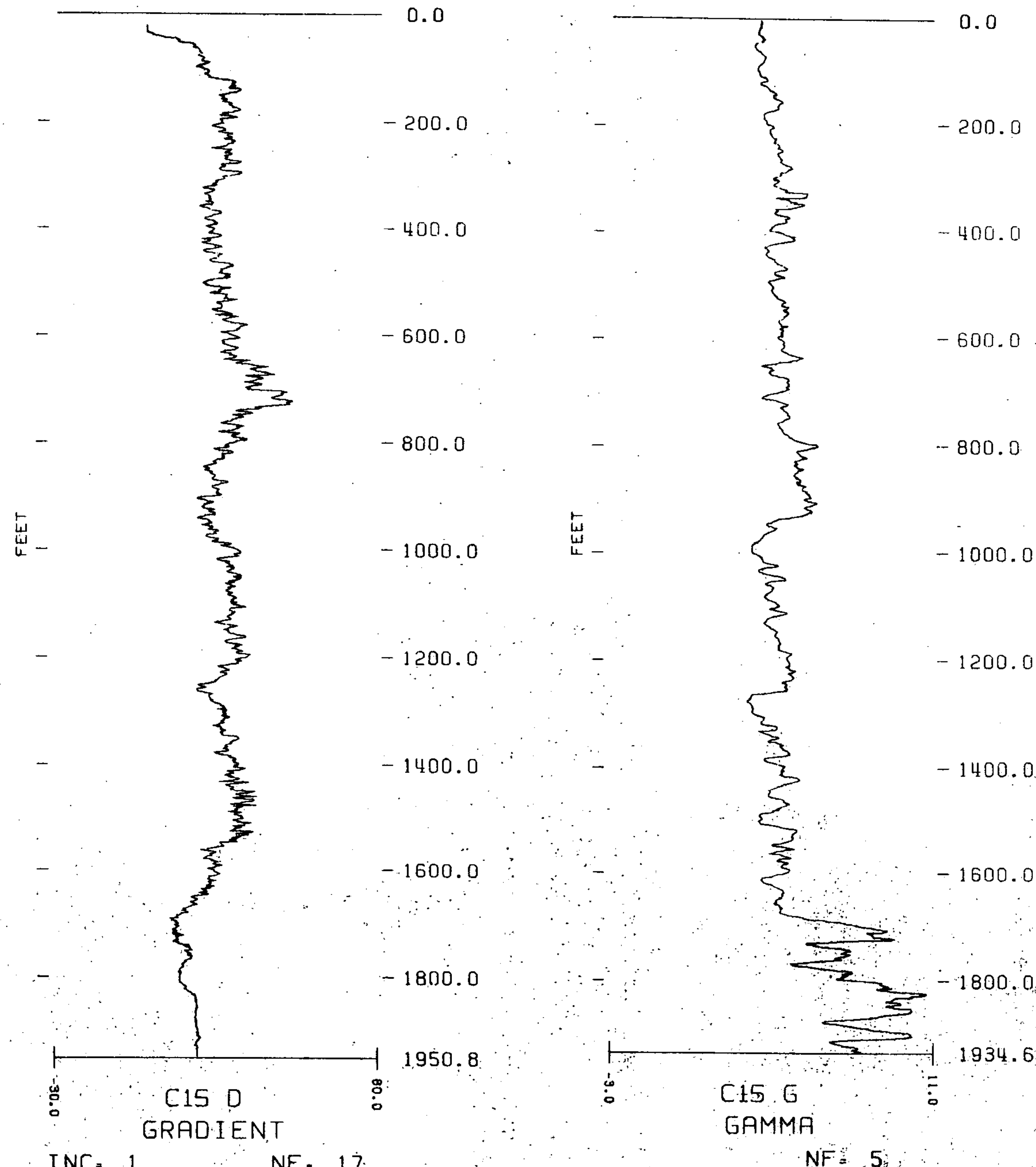


0.0
FEET
200
400
600
800
1000
1200
1400
1600
1800
1877.9
-30
80
C14A
GRADIENT
NF-17 INC-1
0.0
FEET
200
400
600
800
1000
1200
1400
1600
1800
1850.5
-3
8
C14A
GAMMA
NF-5 INC-1

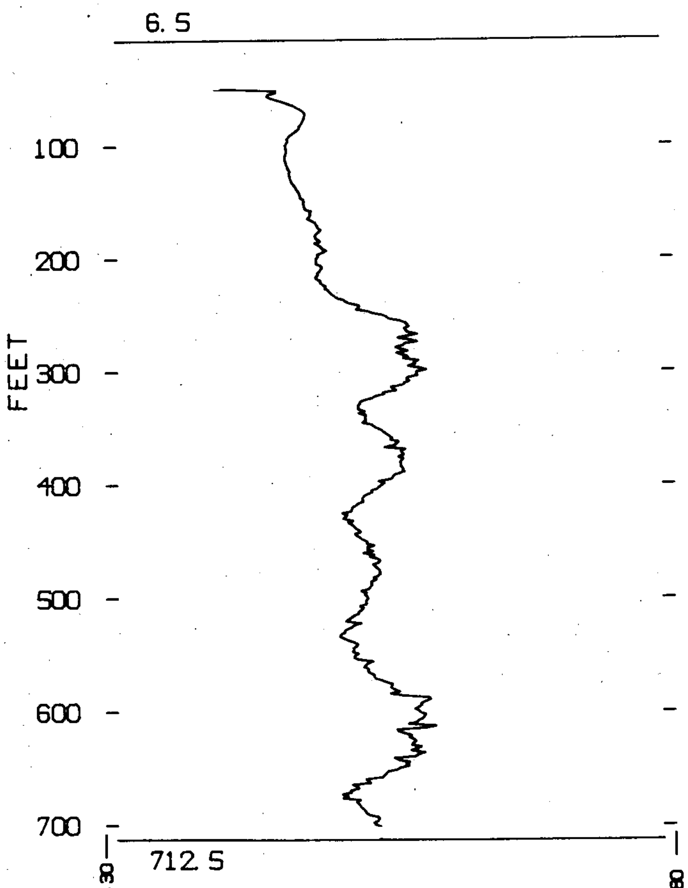

0.0
FEET
200
400
600
800
1000
1200
1248.3
-30
80
C14 B
GRADIENT
NF.17 INC.1
0.0
FEET
200
400
600
800
1000
1200
1268.2
-3
8
C14 G
GAMMA
NF.5 INC.1


0.0
200
400
600
800
1000
1200
1400
FEET
1589.3
-30
80
C15A
GRADIENT
NF-17 INC-1
0.0
200
400
600
800
1000
1200
1400
FEET
1571.6
-3
8
C15A
GAMMA
NF-5 INC-1

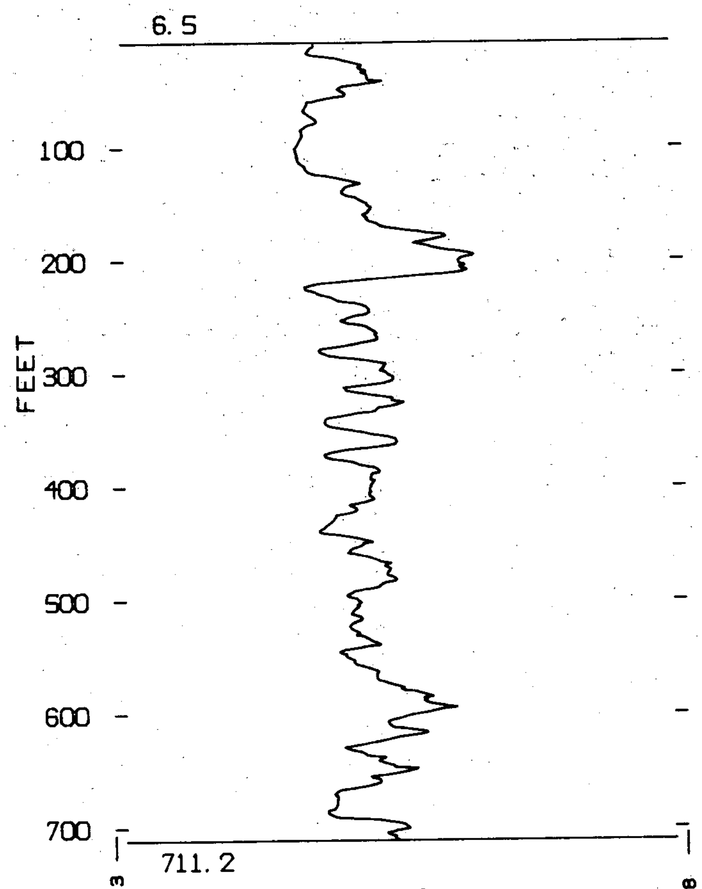

0.0
100
200
300
400
500
600
700
800
900
1000
FEET
1008.2
-30
80
C16
GRADIENT
NF = 17 INC = 1
0.0
100
200
300
400
500
600
700
800
900
1000
FEET
1043.2
3
8
C16
GAMMA
NF = 5 INC = 1



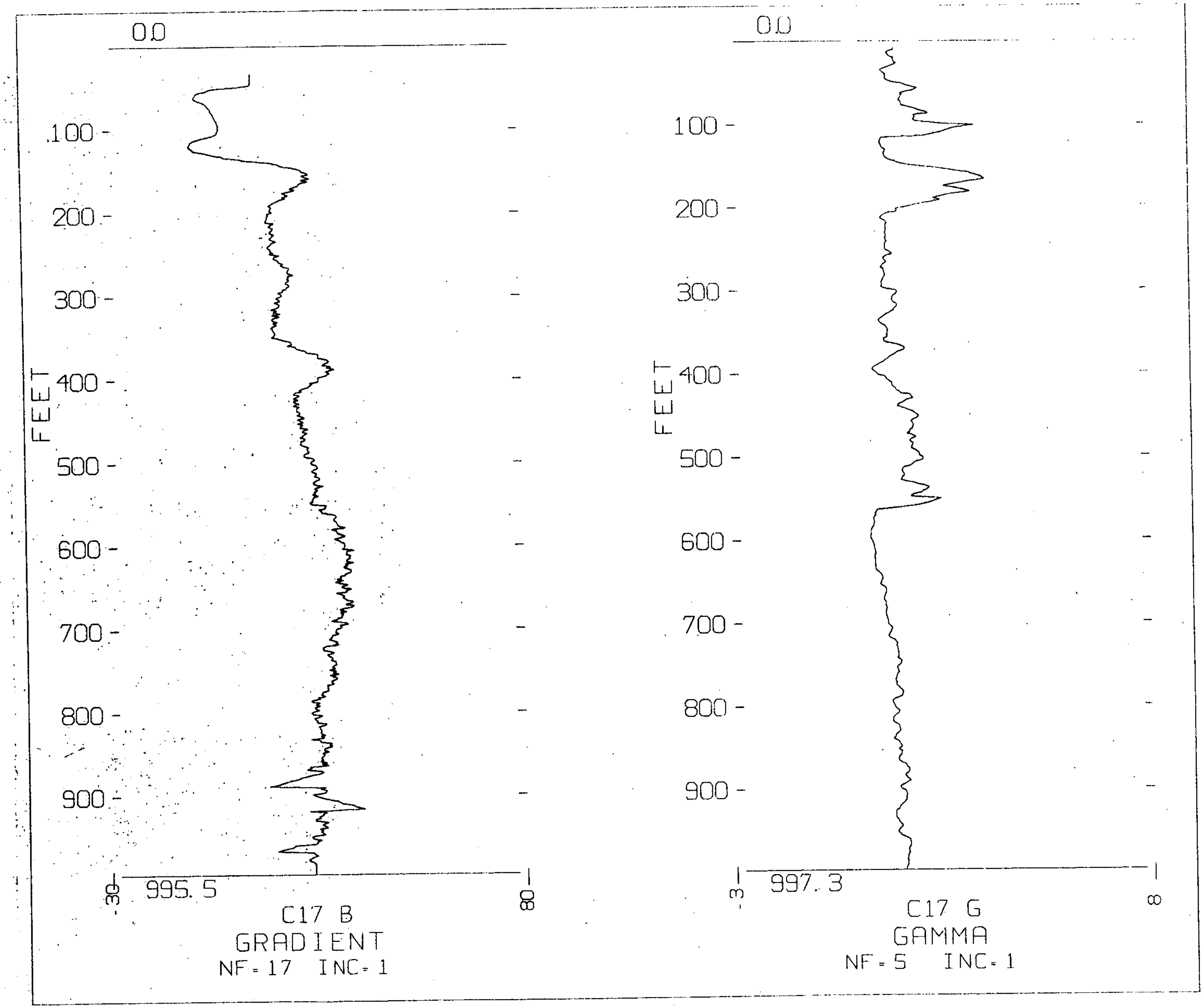
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
1950.8
FEET
-30.0
80.0
C15 D
GRADIENT
INC= 1
NF= 17
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
1934.6
FEET
-9.0
11.0
C15 G
GAMMA
NF= 5

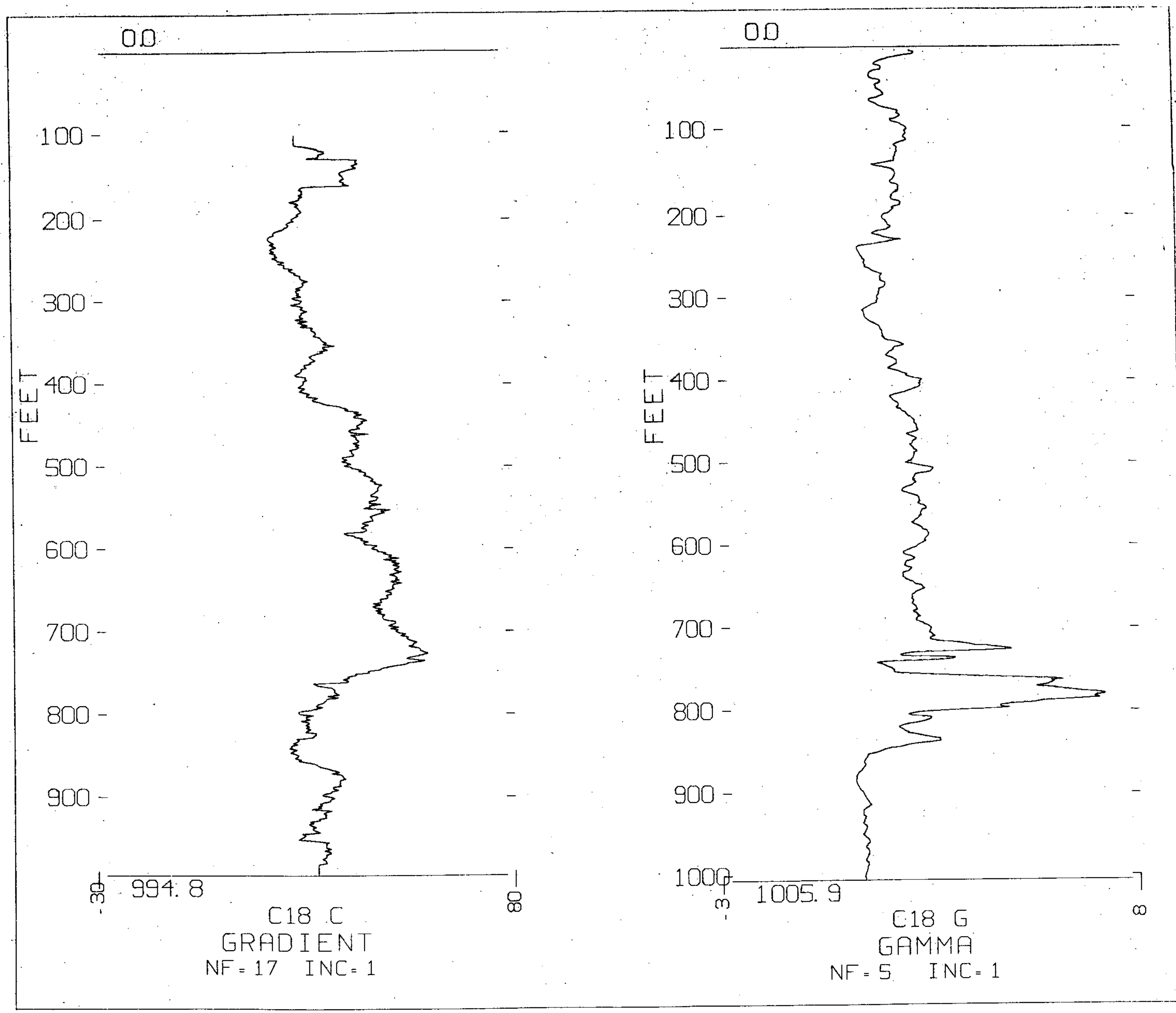


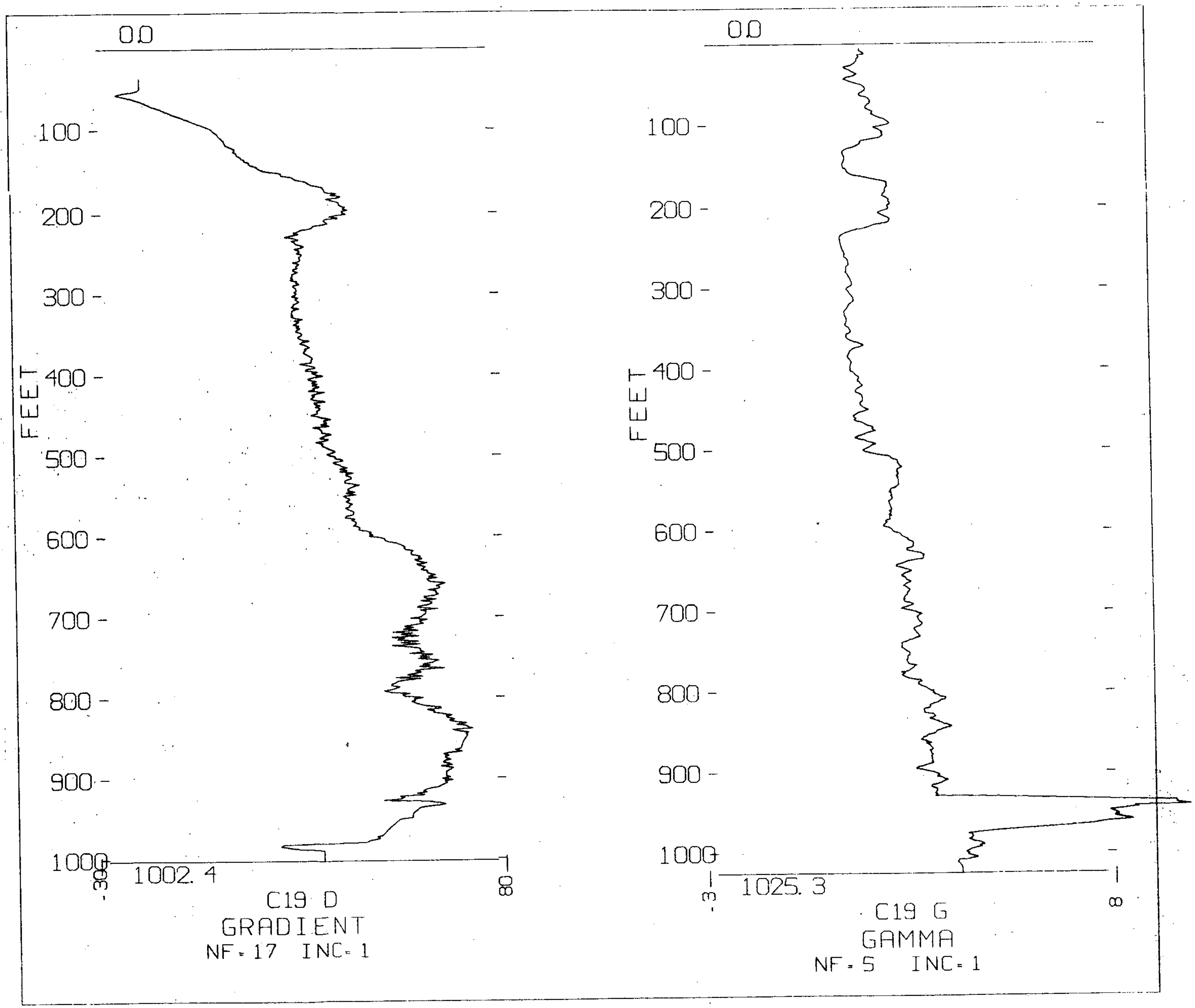
C16A
GRADIENT
NF-17 INC-1

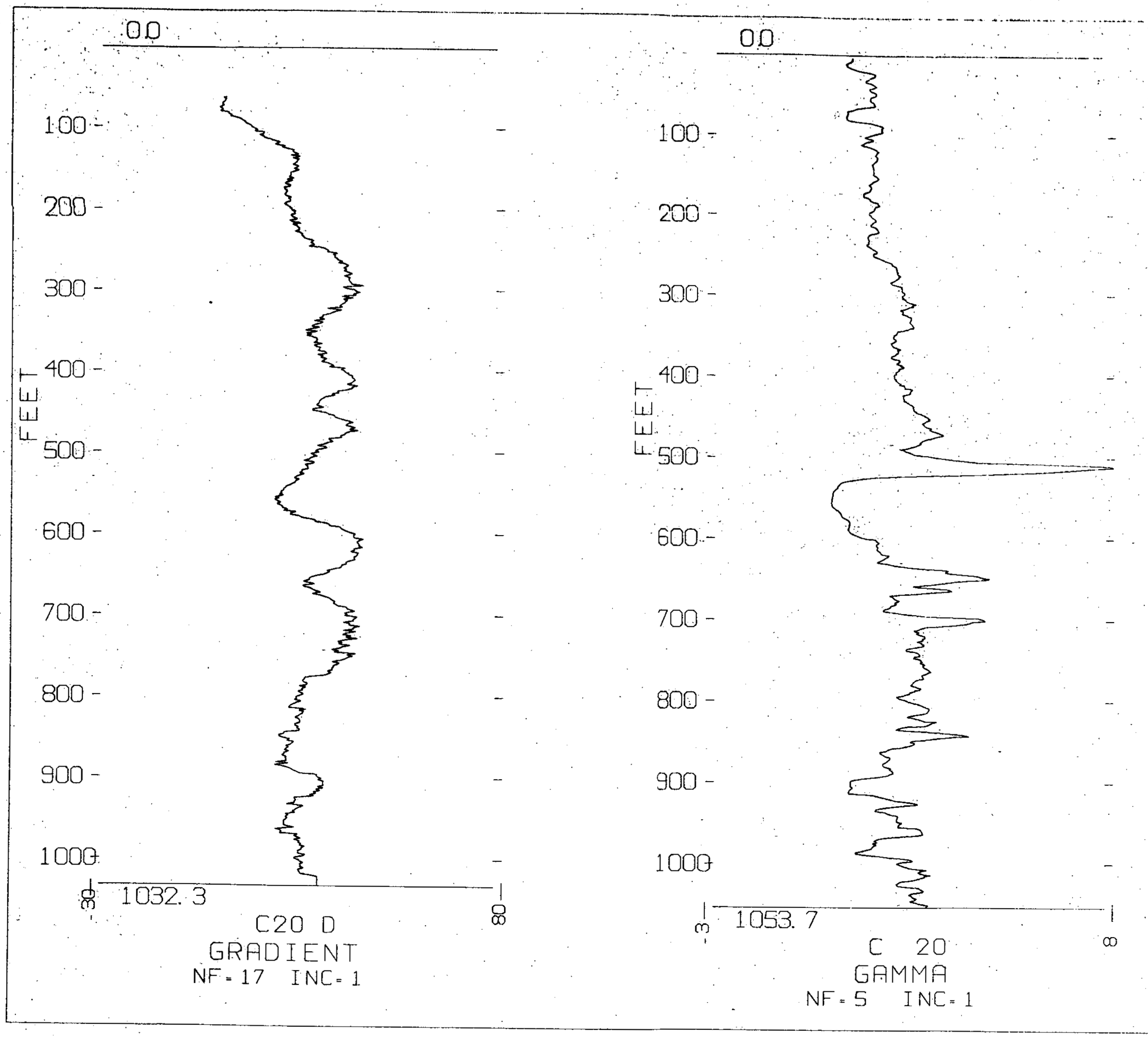


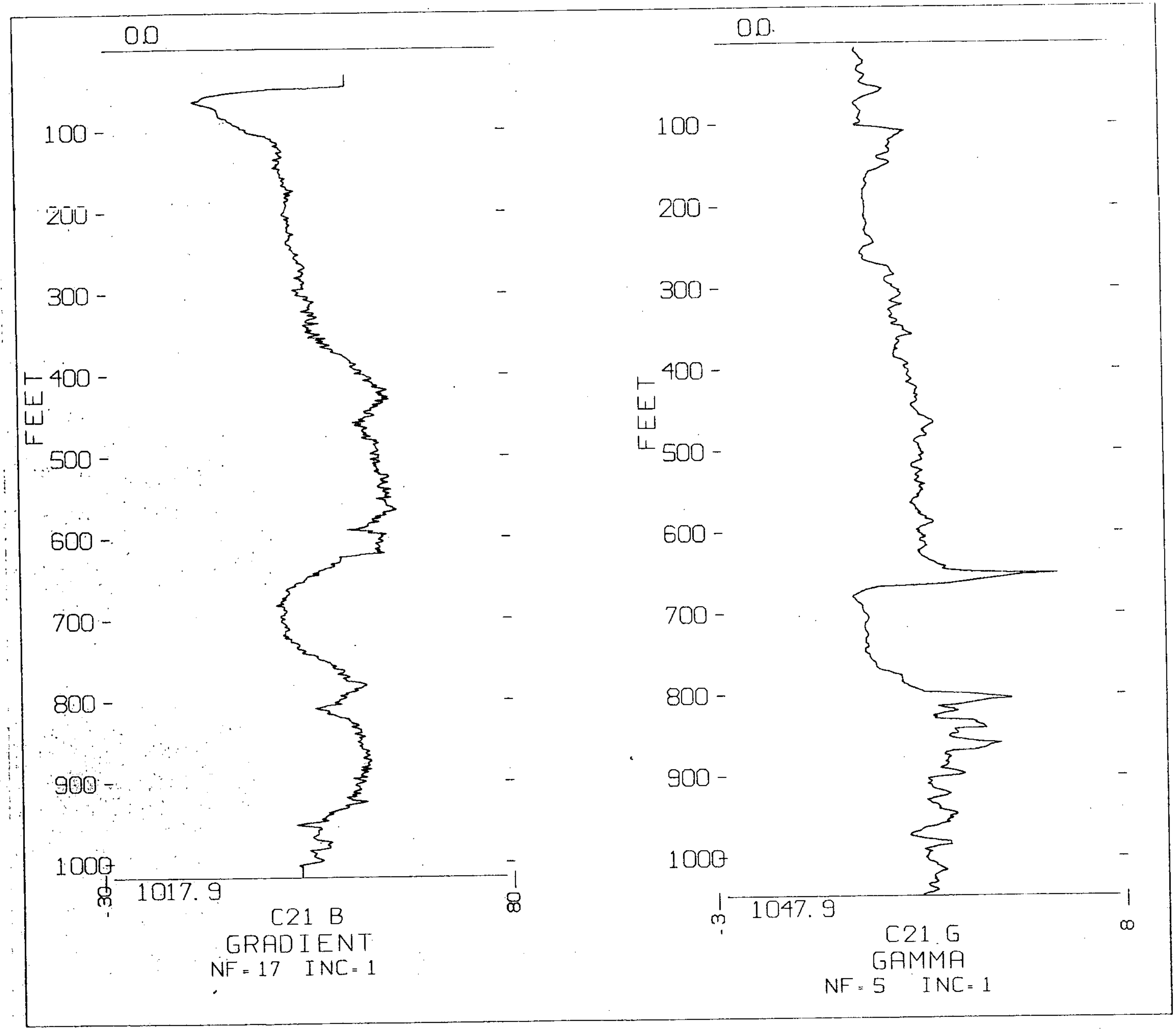
C 16
GAMMA
NF-5 INC-1

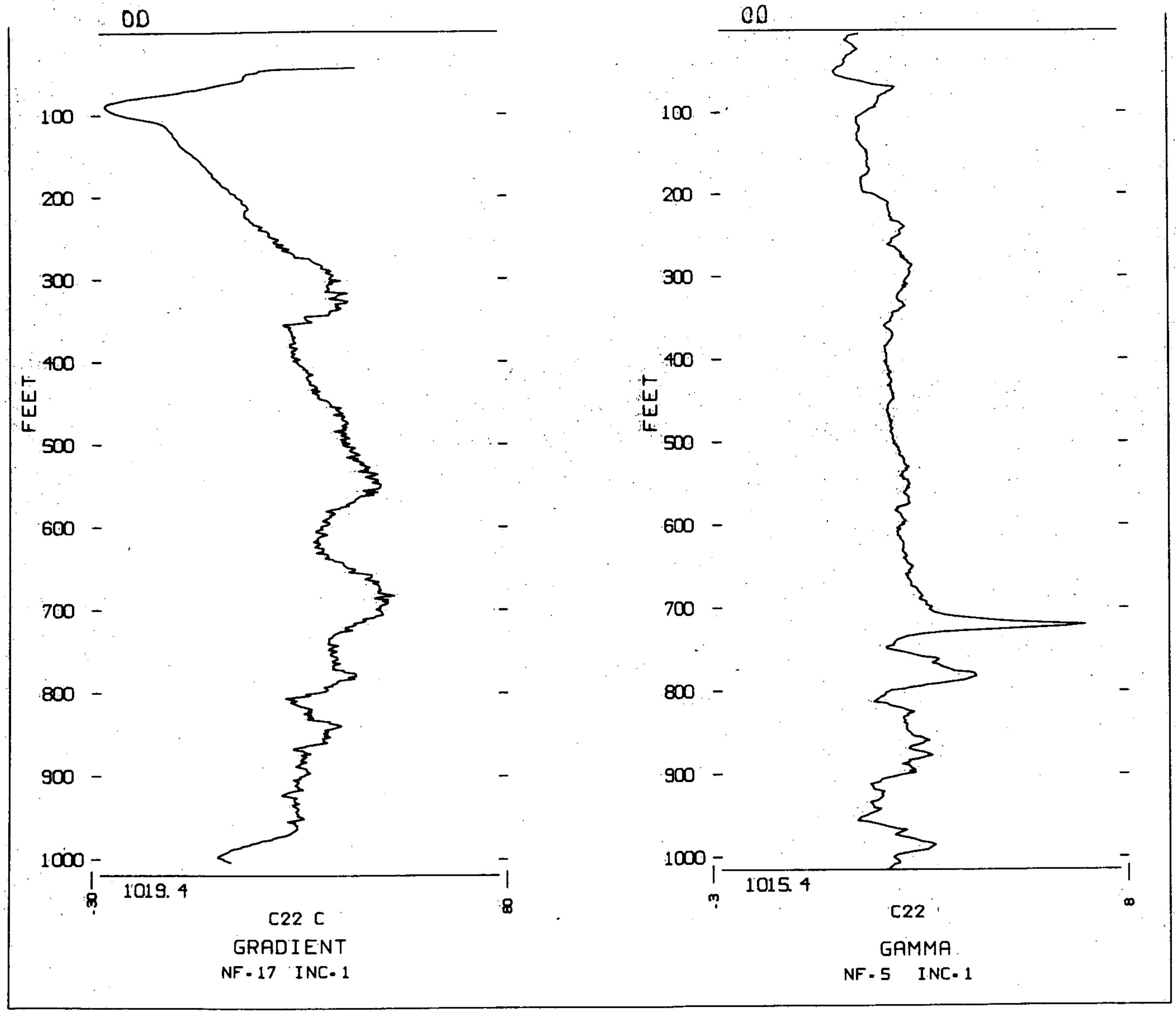

0.0
100
200
300
400
500
600
700
800
900
FEET
-30
995.5
80
C17 B
GRADIENT
NF = 17 INC = 1
0.0
100
200
300
400
500
600
700
800
900
FEET
-3
997.3
8
C17 G
GAMMA
NF = 5 INC = 1


0.0
FEET
100
200
300
400
500
600
700
800
900
-30
994.8
80
C18 C
GRADIENT
NF=17 INC=1
0.0
FEET
100
200
300
400
500
600
700
800
900
1000
-3
1005.9
8
C18 G
GAMMA
NF=5 INC=1

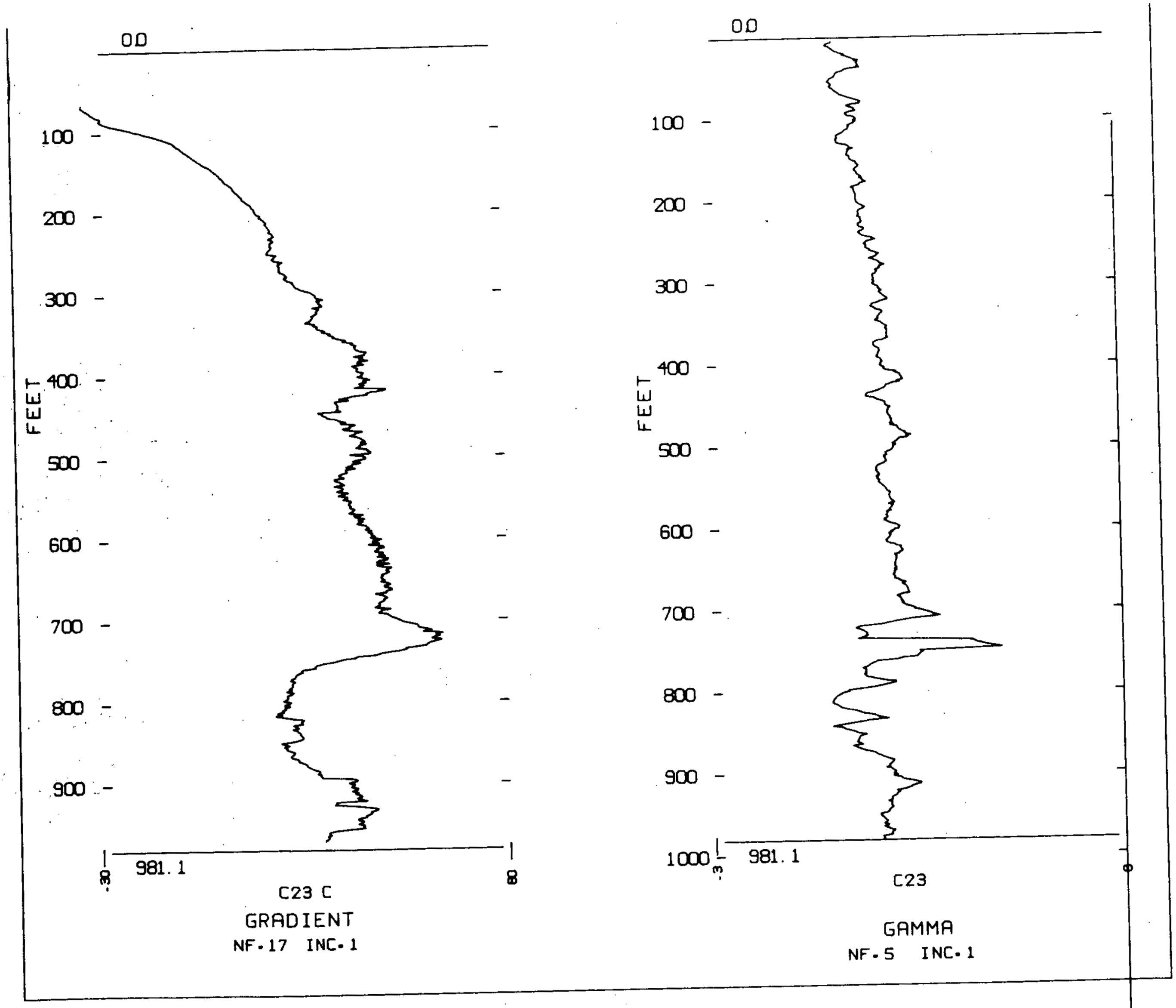

0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-30
1002.4
80
C19 D
GRADIENT
NF=17 INC=1
0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-3
1025.3
8
C19 G
GAMMA
NF=5 INC=1


0.0
FEET
100
200
300
400
500
600
700
800
900
1000
-30
1032.3
80
C20 D
GRADIENT
NF = 17 INC = 1
0.0
FEET
100
200
300
400
500
600
700
800
900
1000
-3
1053.7
8
C 20
GAMMA
NF = 5 INC = 1

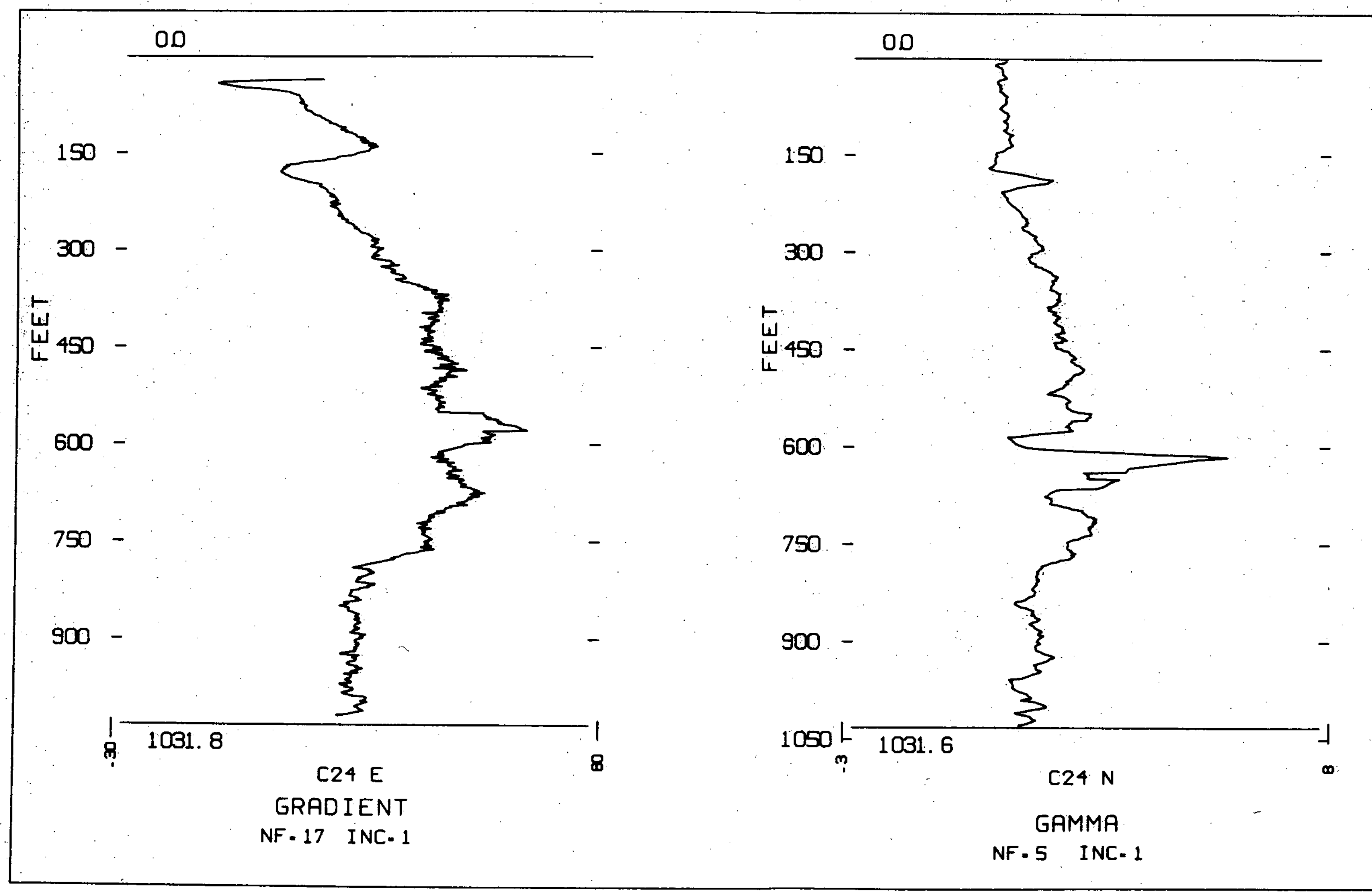

0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-30
80
1017.9
C21 B
GRADIENT
NF=17 INC=1
0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-3
8
1047.9
C21 G
GAMMA
NF=5 INC=1

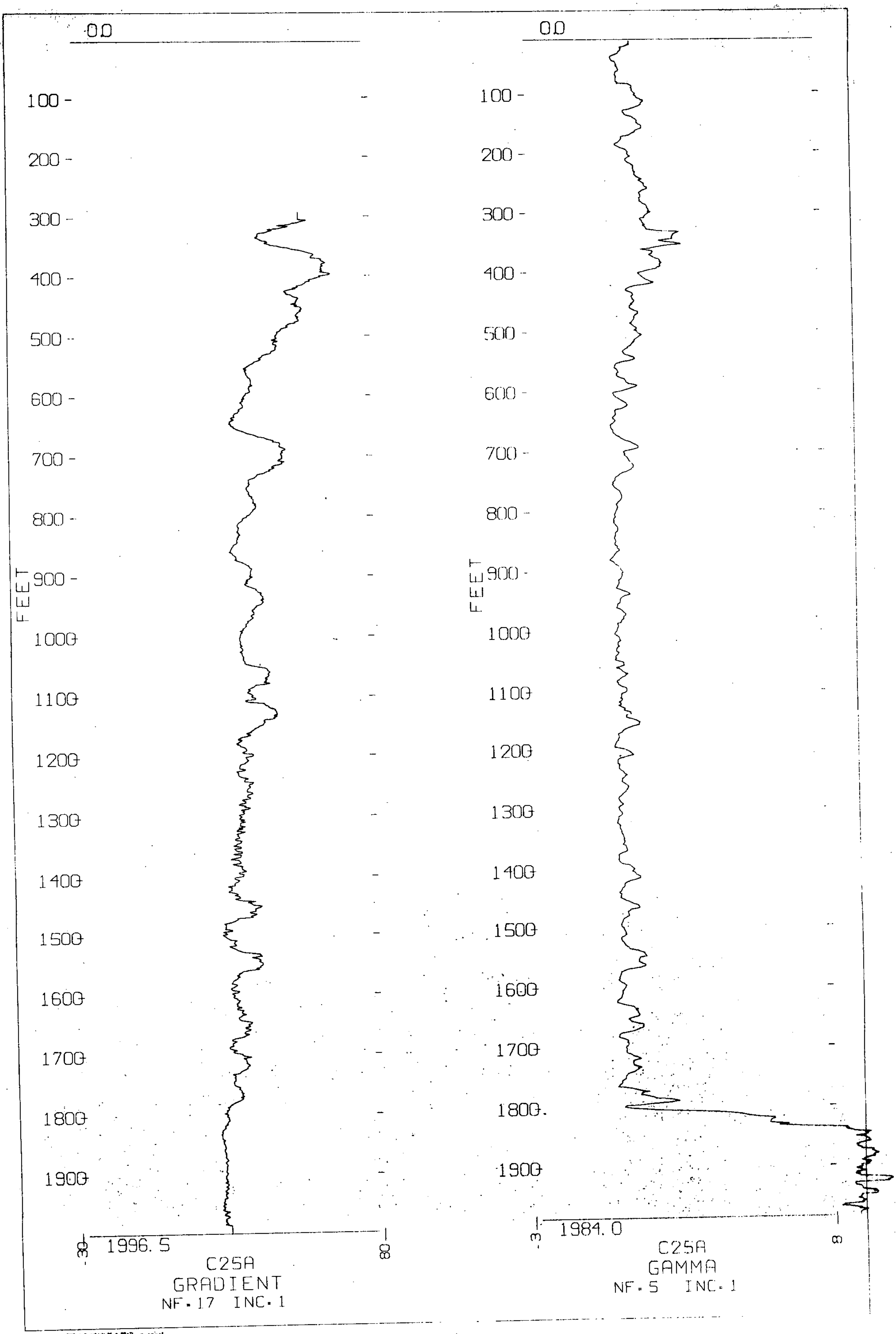


OD
FEET
100
200
300
400
500
600
700
800
900
1000
1019.4
-30
80
C22 C
GRADIENT
NF-17 INC-1
OD
FEET
100
200
300
400
500
600
700
800
900
1000
1015.4
-3
8
C22
GAMMA
NF-5 INC-1

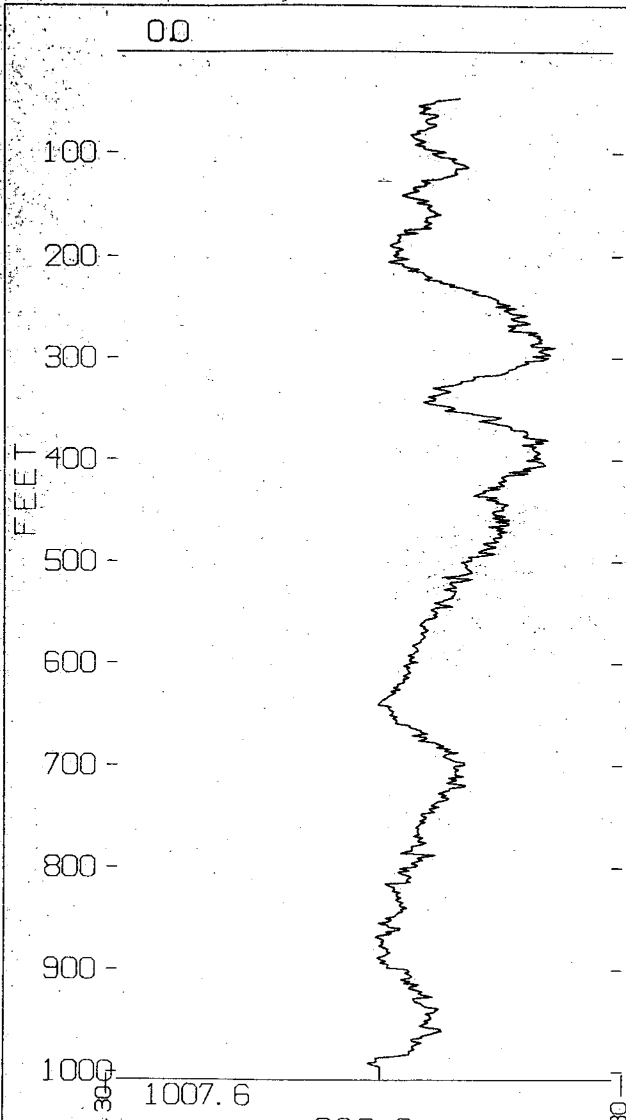


0.0
FEET
100
200
300
400
500
600
700
800
900
-30
981.1
80
C23 C
GRADIENT
NF-17 INC-1
0.0
FEET
100
200
300
400
500
600
700
800
900
1000
-3
981.1
C23
8
GAMMA
NF-5 INC-1

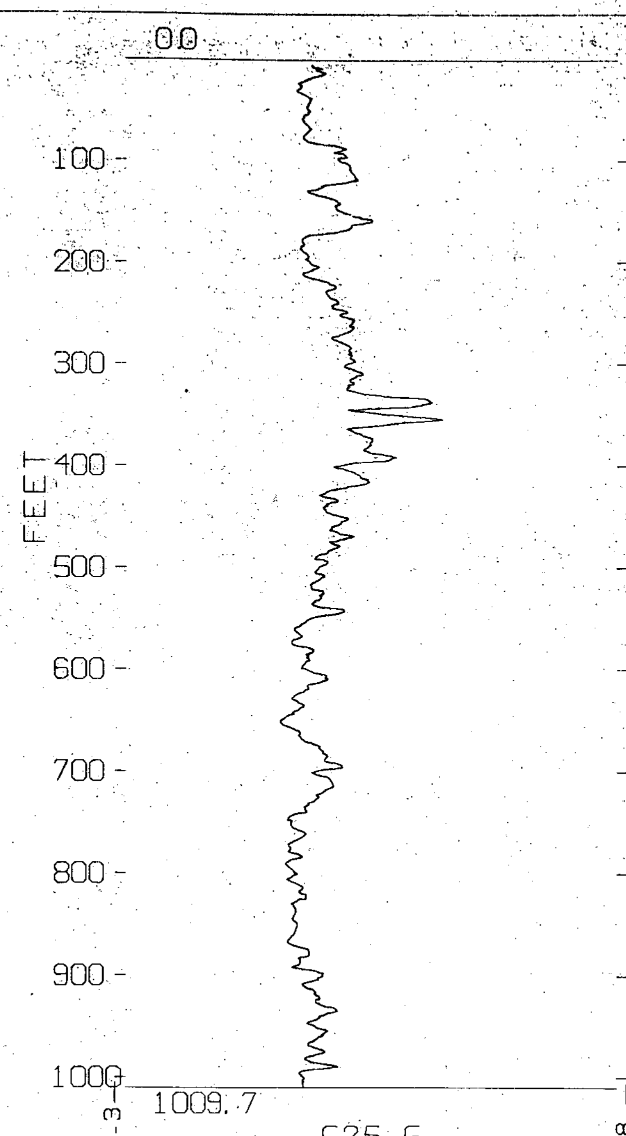

0.0
FEET
150
300
450
600
750
900
-30
1031.8
80
C24 E
GRADIENT
NF-17 INC-1
0.0
FEET
150
300
450
600
750
900
1050
-3
1031.6
8
C24 N
GAMMA
NF-5 INC-1



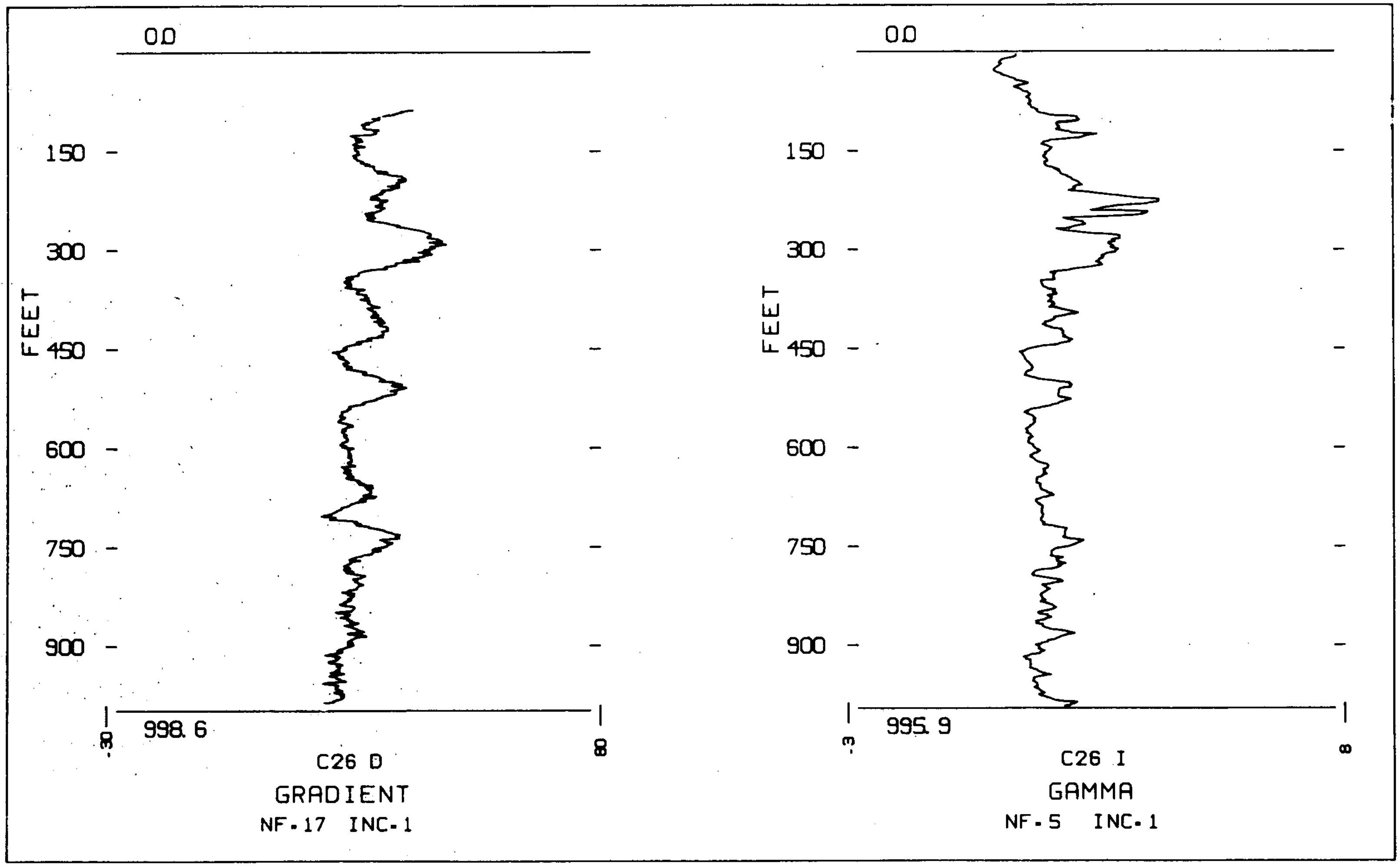
0.0
0.0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
FEET
-30
1996.5
80
C25A
GRADIENT
NF.17 INC.1
-3
1984.0
8
C25A
GAMMA
NF.5 INC.1



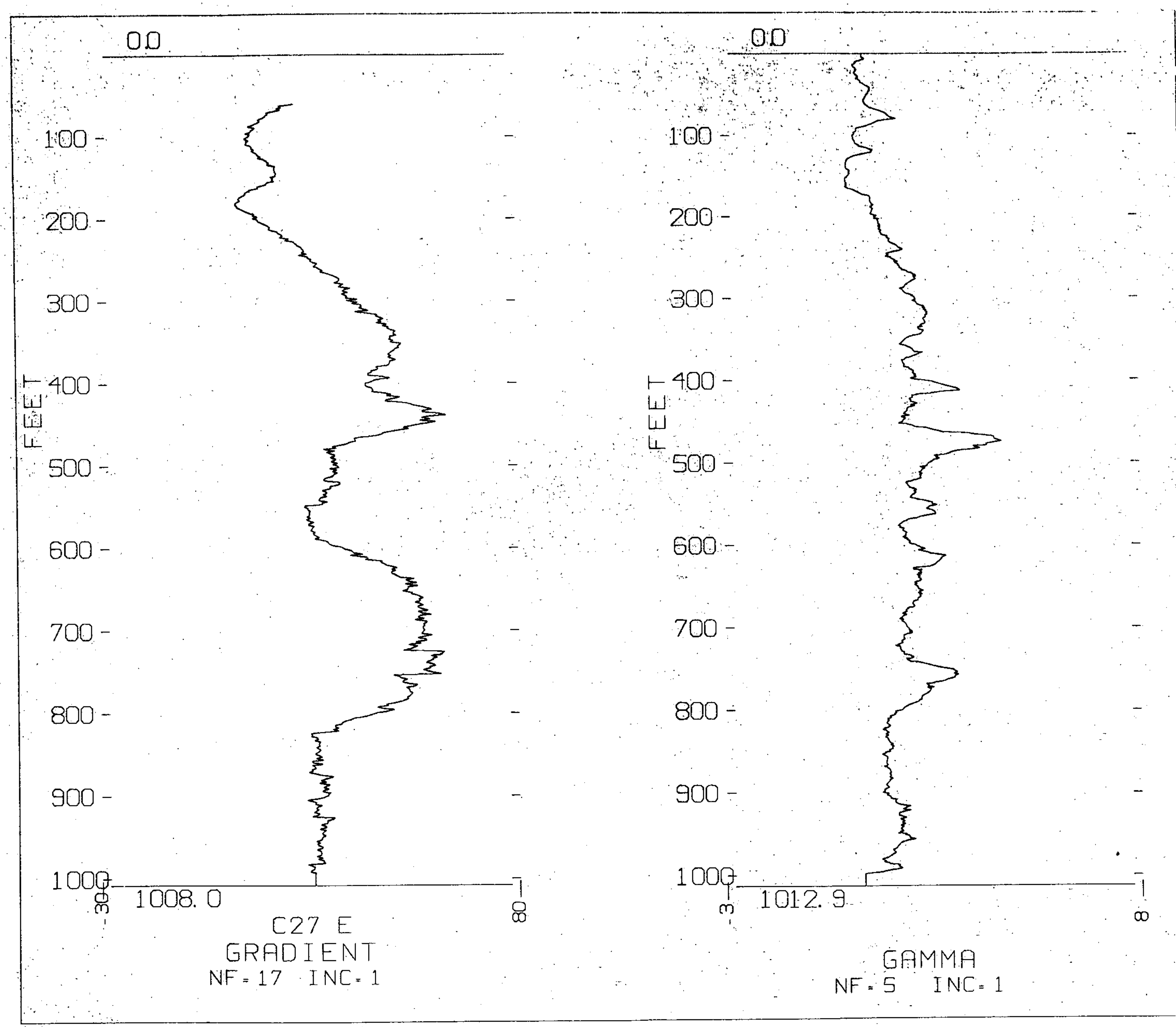
C25 D
GRADIENT
NF=17 INC=1



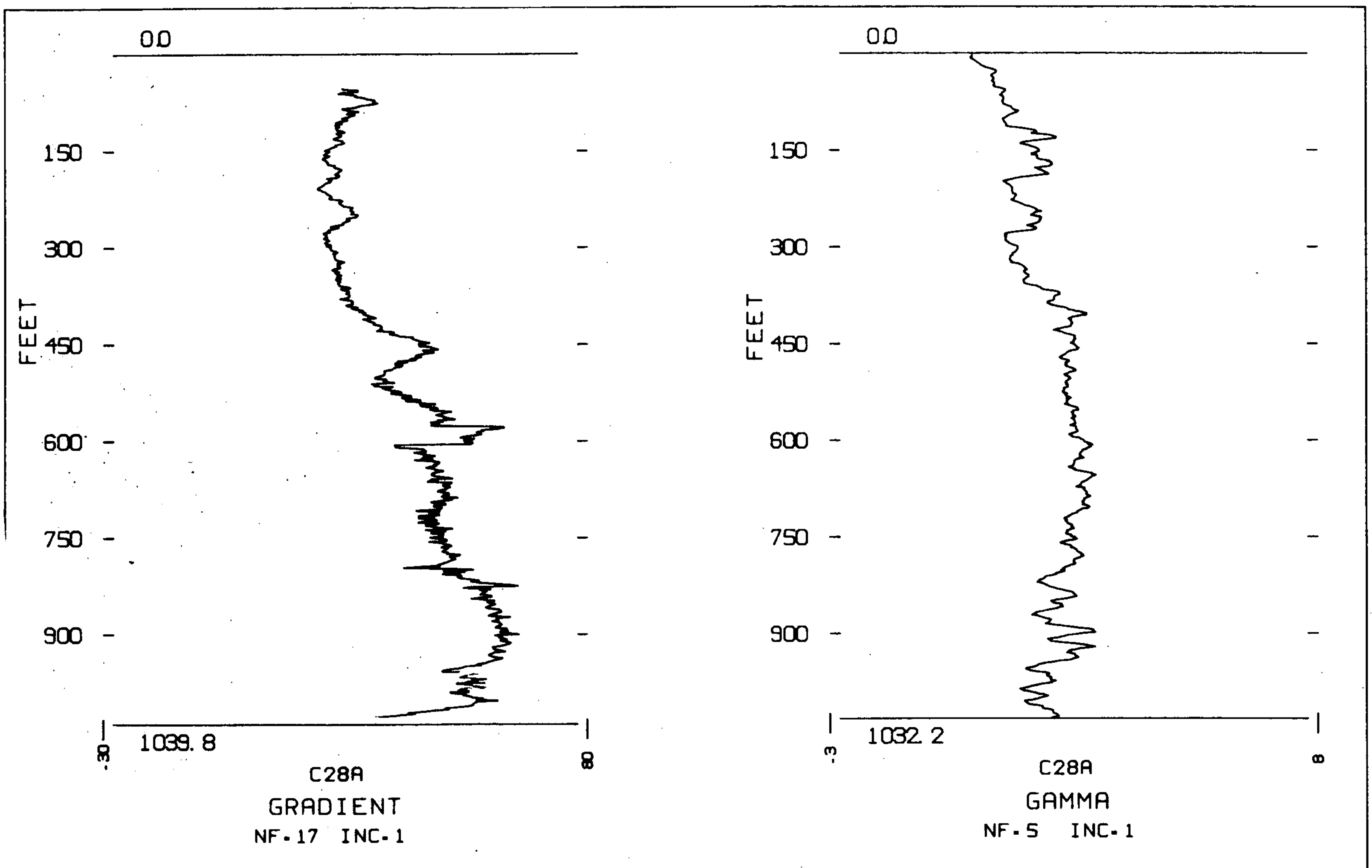
C25 G
GAMMA
NF=5 INC=1

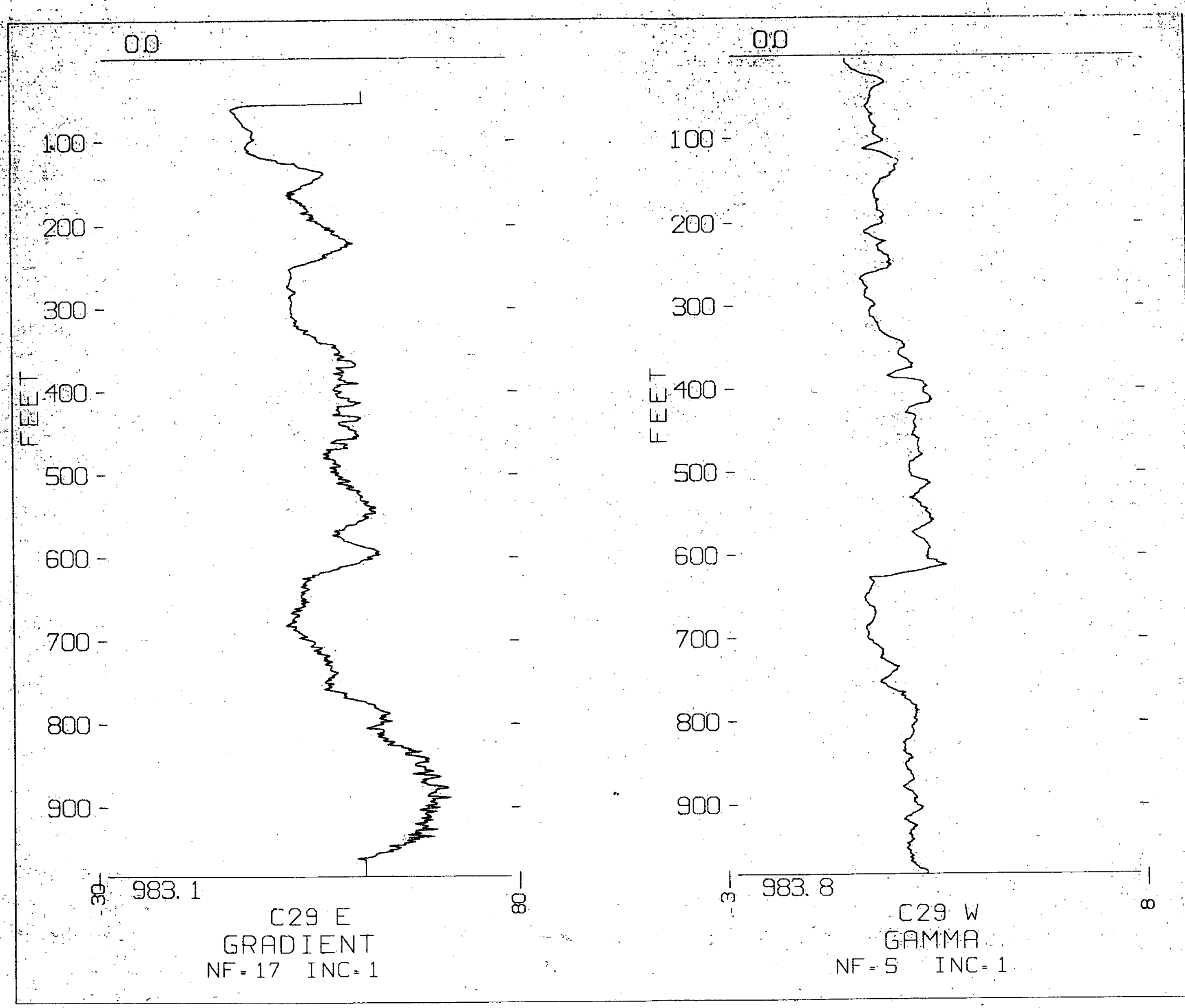


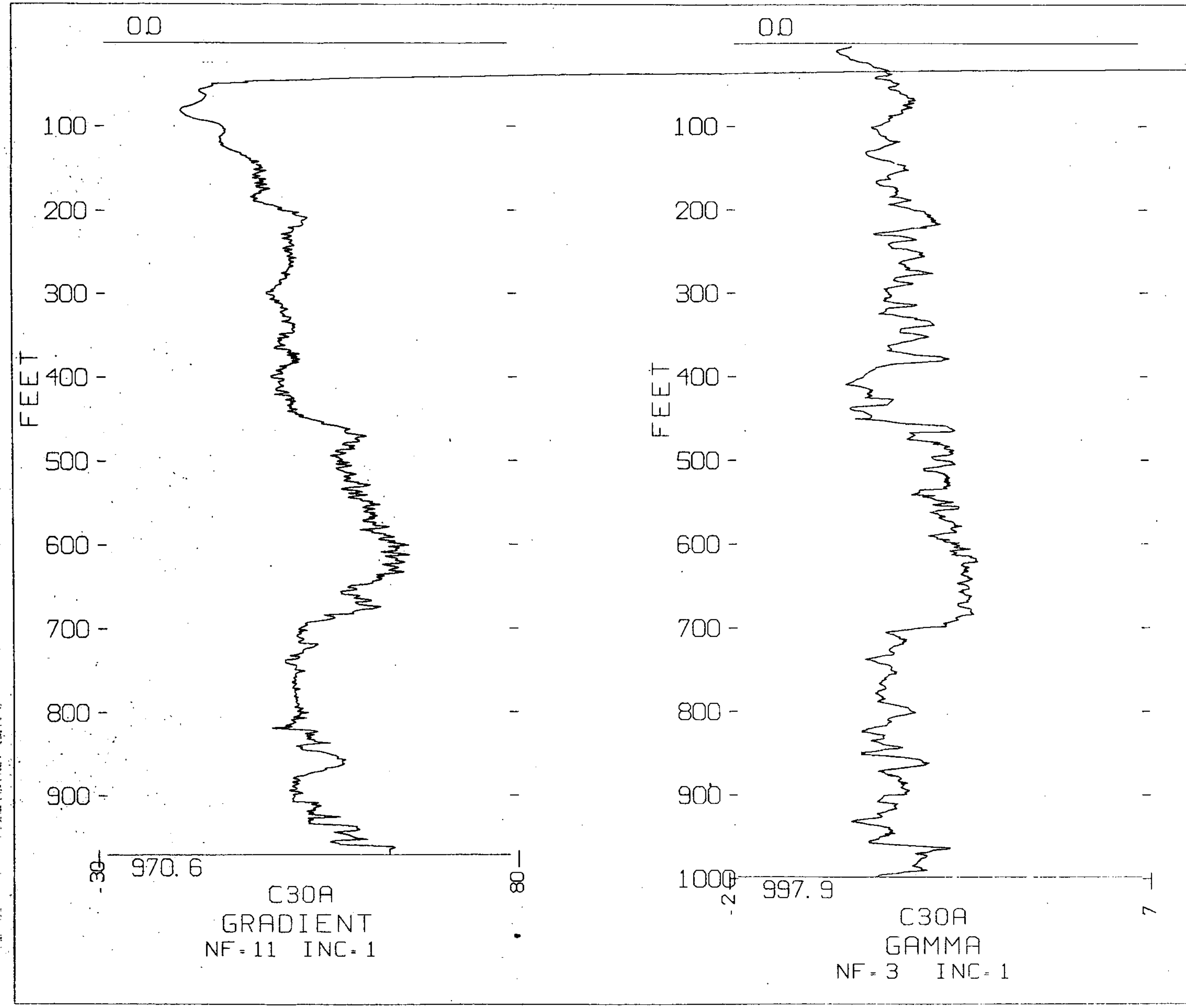
0.0
150
300
450
600
750
900
FEET
998.6
-30
80
C26 D
GRADIENT
NF-17 INC-1
0.0
150
300
450
600
750
900
FEET
995.9
-3
8
C26 I
GAMMA
NF-5 INC-1

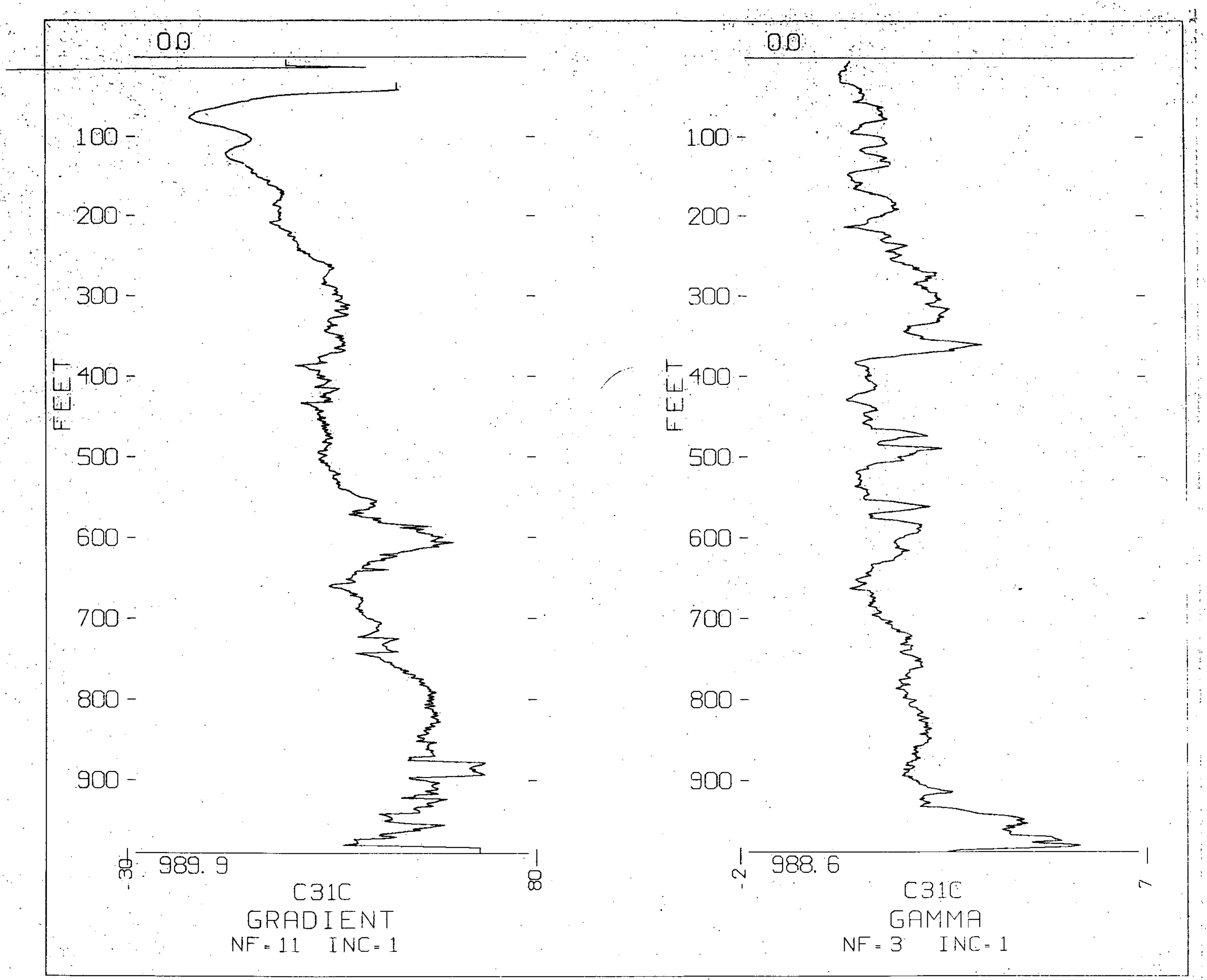


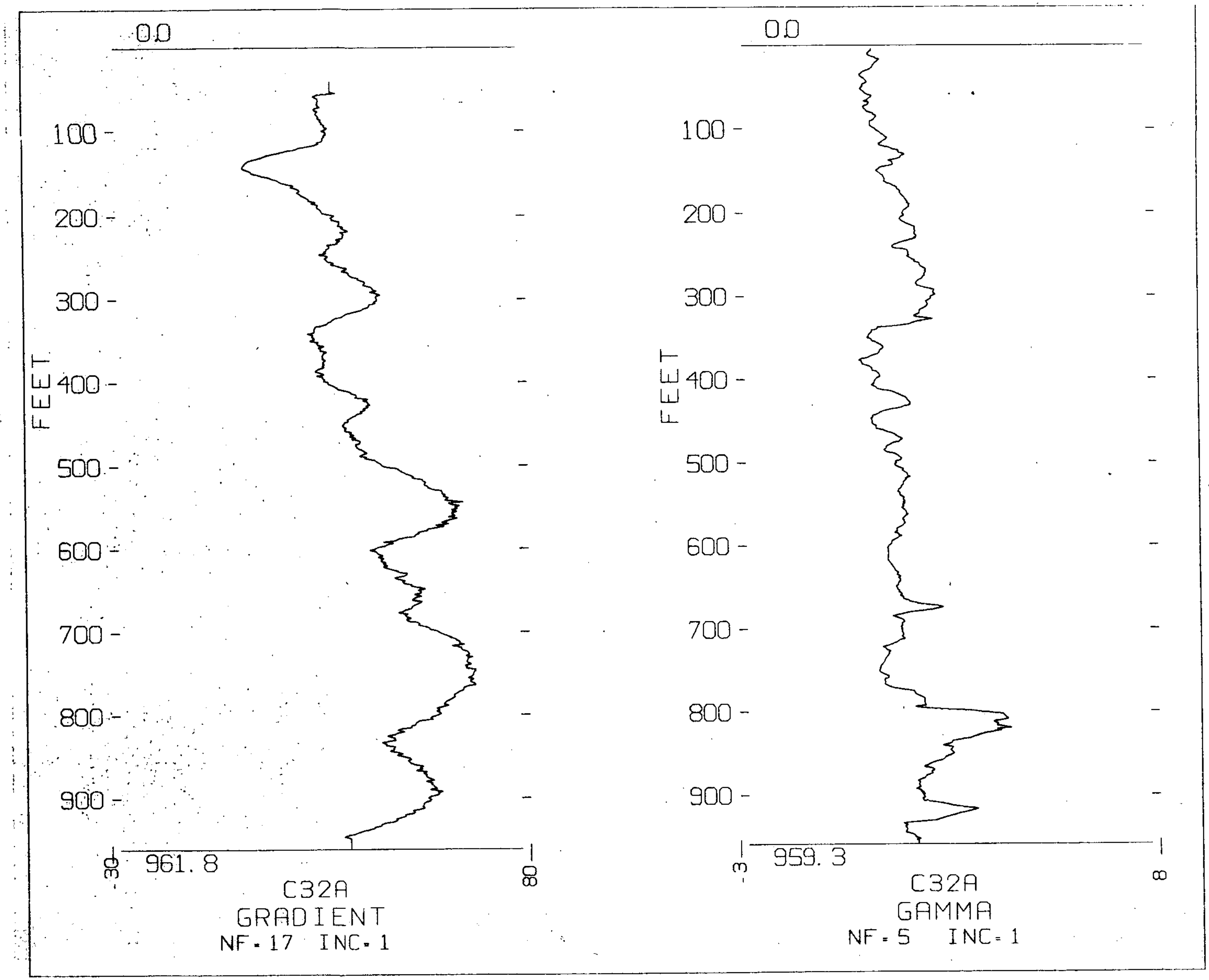
0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-30
1008.0
80
C27 E
GRADIENT
NF=17 INC=1
0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-3
1012.9
8
GAMMA
NF=5 INC=1

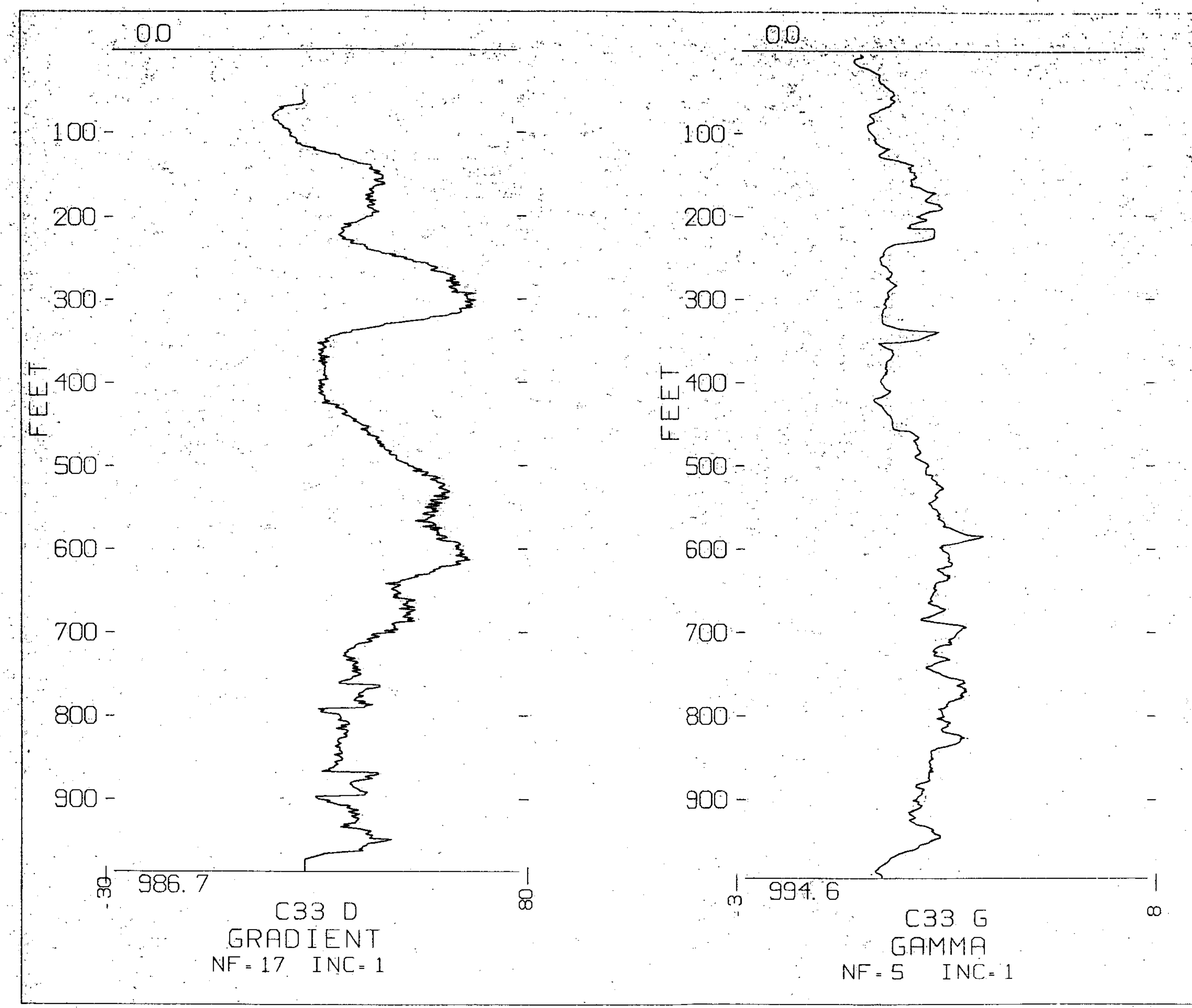

0.0
150
300
FEET
450
600
750
900
1039.8
-30
80
C28A
GRADIENT
NF-17 INC-1
0.0
150
300
FEET
450
600
750
900
1032.2
-3
8
C28A
GAMMA
NF-5 INC-1

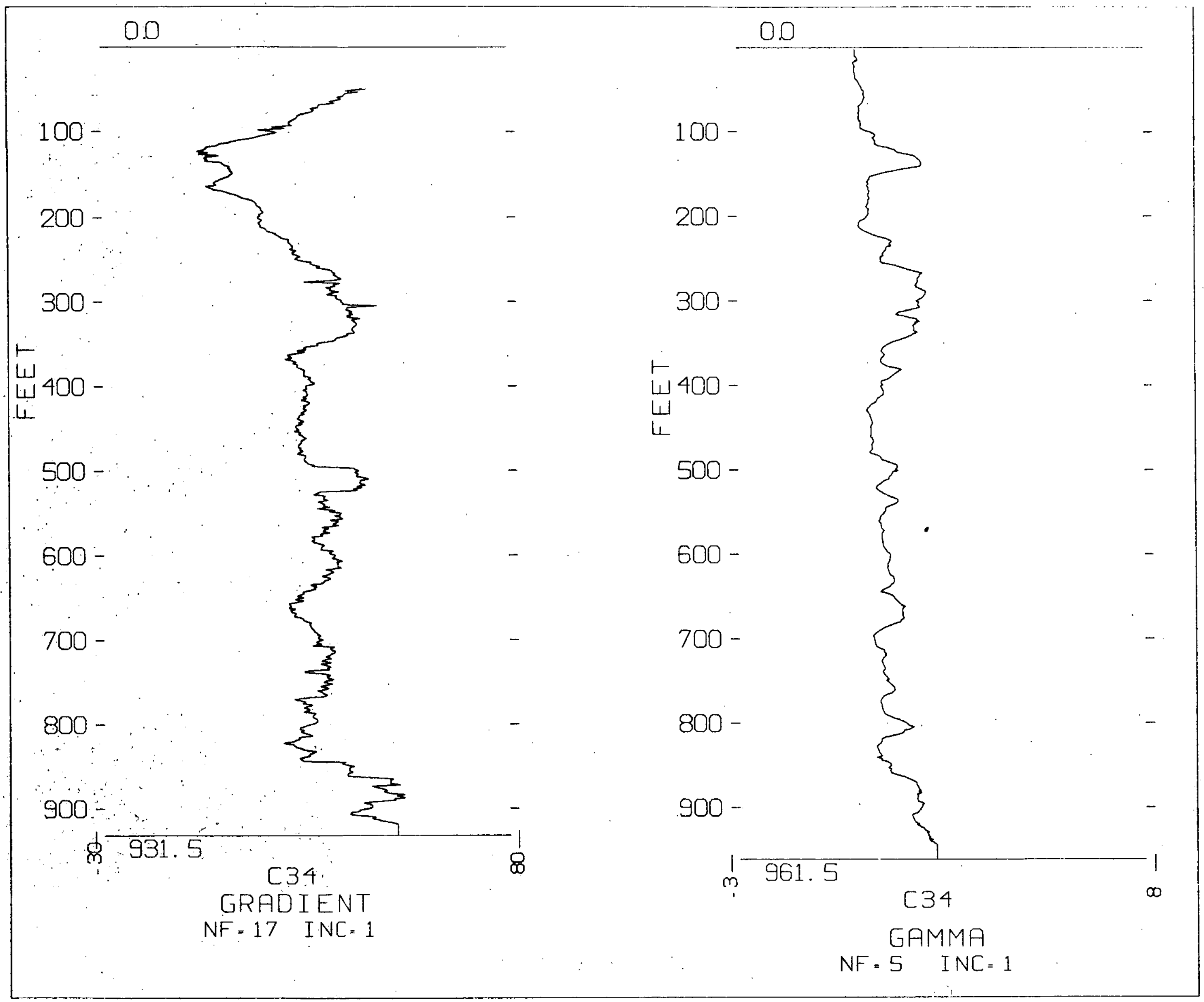

0.0
100
200
300
400
500
600
700
800
900
FEET
-30
983.1
80
C29 E
GRADIENT
NF=17 INC=1
0.0
100
200
300
400
500
600
700
800
900
FEET
-3
983.8
8
C29 W
GAMMA
NF=5 INC=1


0.0
100
200
300
400
500
600
700
800
900
FEET
-30
970.6
80
C30A
GRADIENT
NF=11 INC=1
0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-2
997.9
7
C30A
GAMMA
NF=3 INC=1

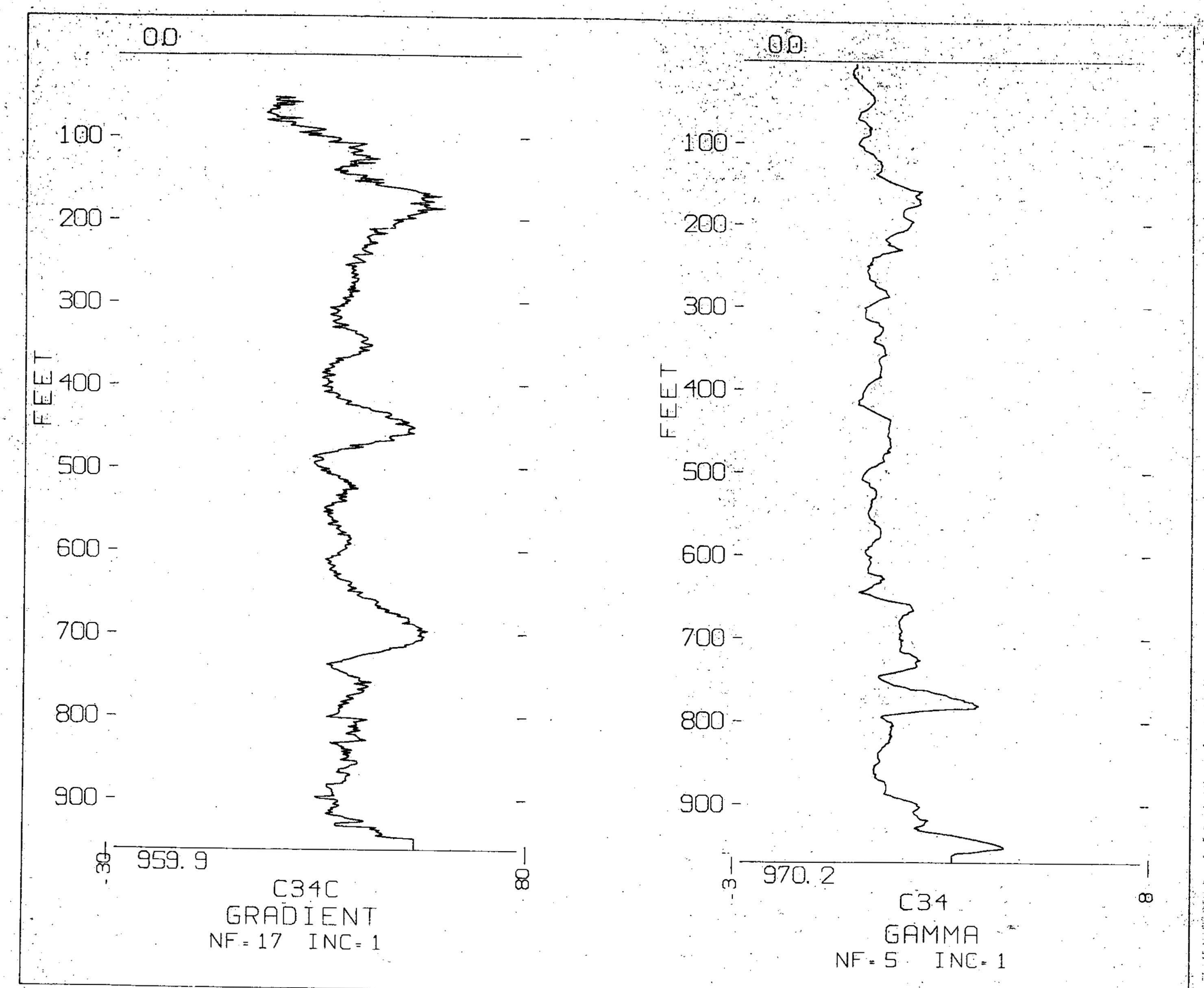

0.0
0.0
100
200
300
400
500
600
700
800
900
FEET
-30
989.9
80
C31C
GRADIENT
NF = 11 INC = 1
-2
988.6
7
C31C
GAMMA
NF = 3 INC = 1

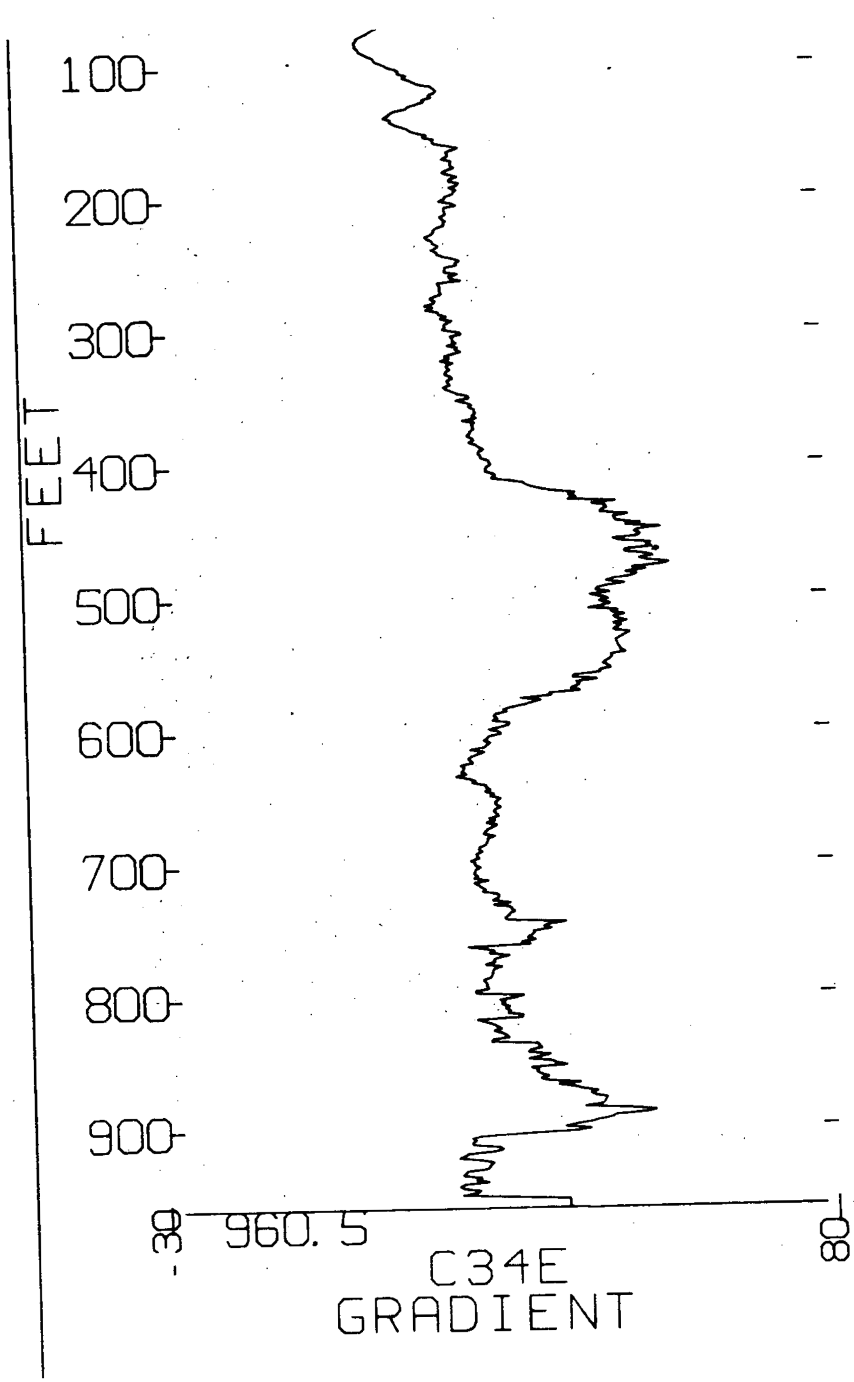

0.0
100
200
300
FEET
400
500
600
700
800
900
-30
961.8
80
C32A
GRADIENT
NF=17 INC=1
0.0
100
200
300
FEET
400
500
600
700
800
900
-3
959.3
8
C32A
GAMMA
NF=5 INC=1

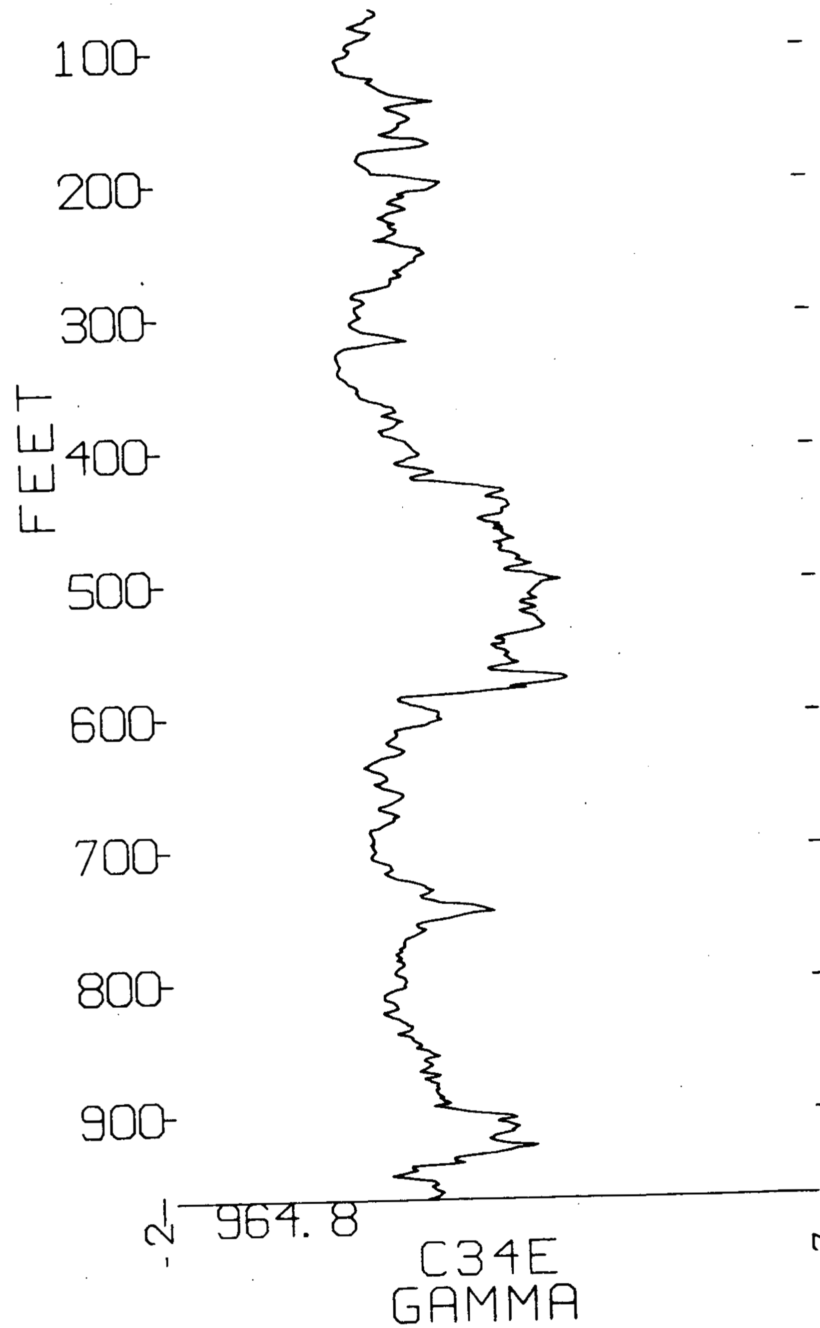

0.0
FEET
100
200
300
400
500
600
700
800
900
-30
986.7
80
C33 D
GRADIENT
NF=17 INC=1
0.0
FEET
100
200
300
400
500
600
700
800
900
-3
994.6
8
C33 G
GAMMA
NF=5 INC=1

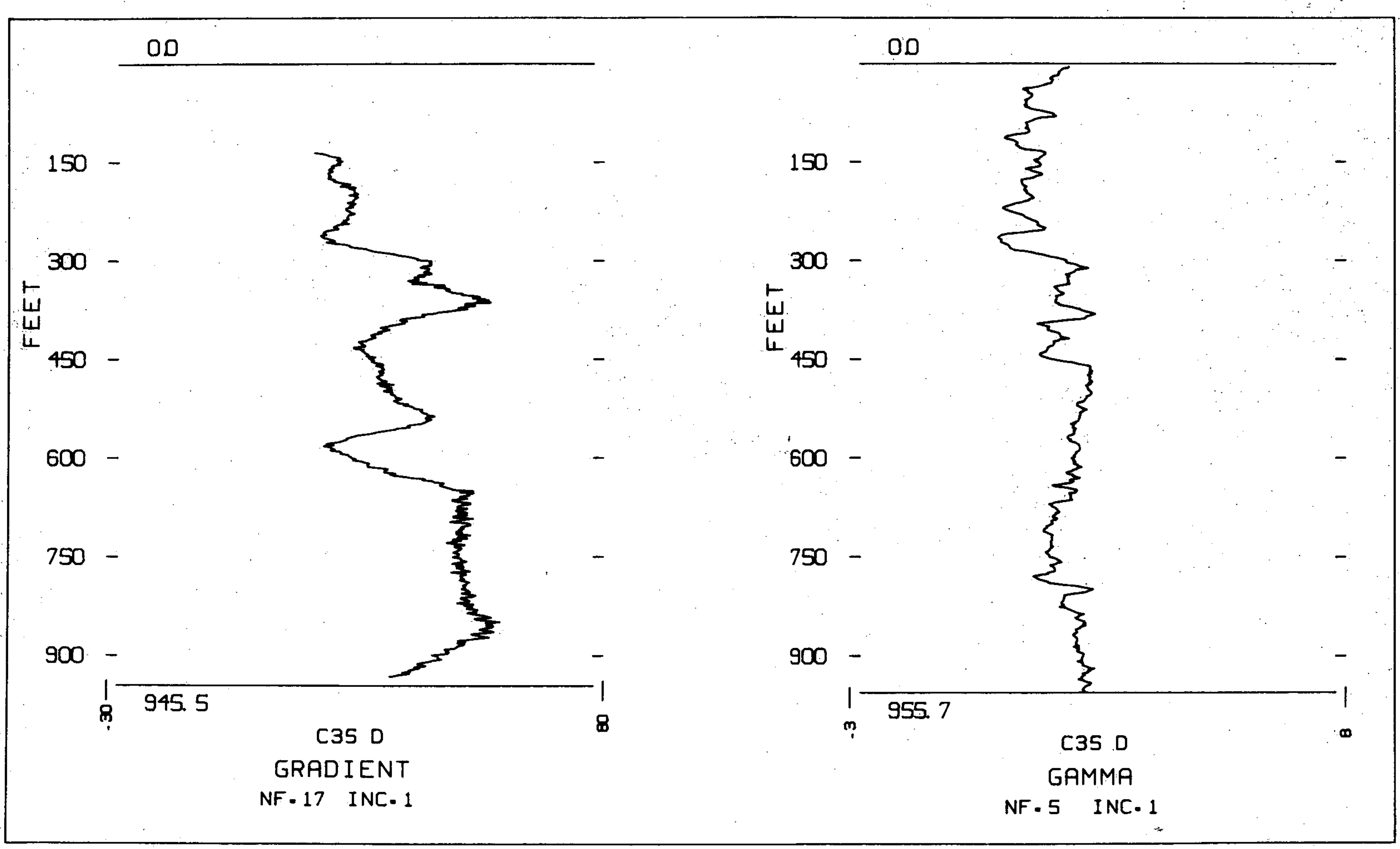


0.0
FEET
100
200
300
400
500
600
700
800
900
-30
80
931.5
C34
GRADIENT
NF=17 INC=1
0.0
FEET
100
200
300
400
500
600
700
800
900
-3
8
961.5
C34
GAMMA
NF=5 INC=1

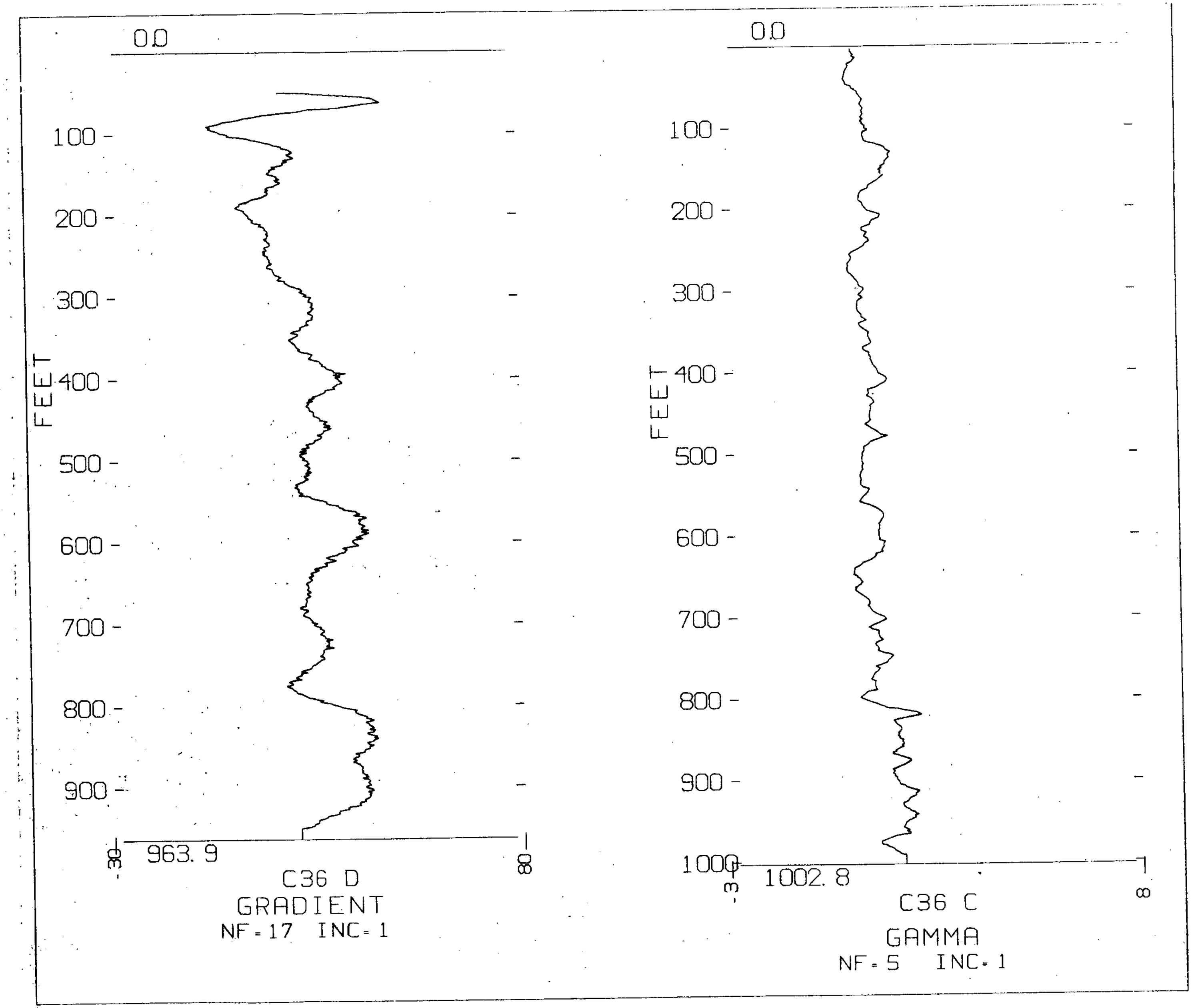

0.0
100
200
300
400
500
600
700
800
900
FEET
-30
959.9
80
C34C
GRADIENT
NF=17 INC=1
0.0
100
200
300
400
500
600
700
800
900
FEET
-3
970.2
8
C34
GAMMA
NF=5 INC=1


FEET
100
200
300
400
500
600
700
800
900
-30
960.5
80
C34E
GRADIENT

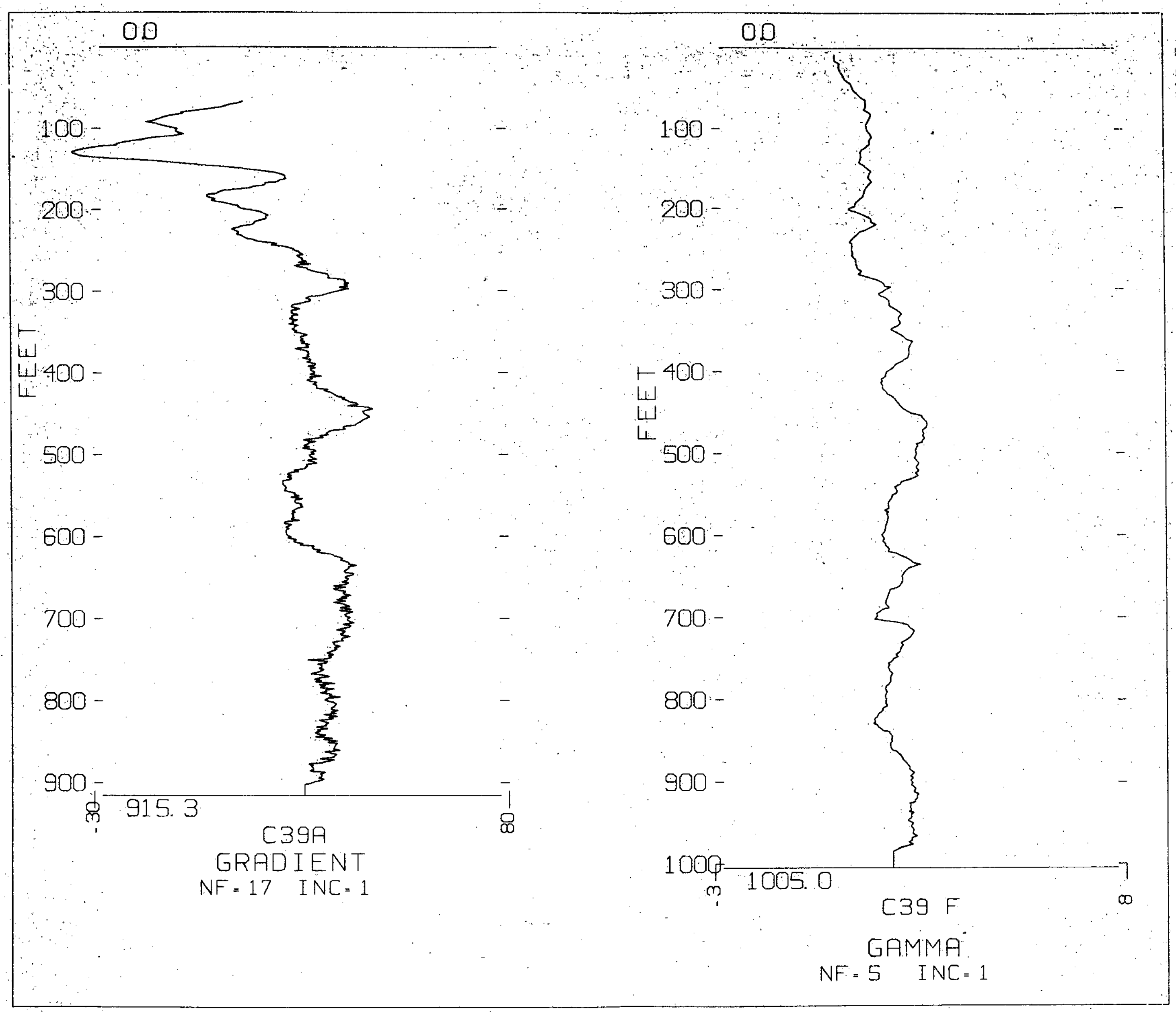

FEET
100
200
300
400
500
600
700
800
900
-2
964.8
7
C34E
GAMMA

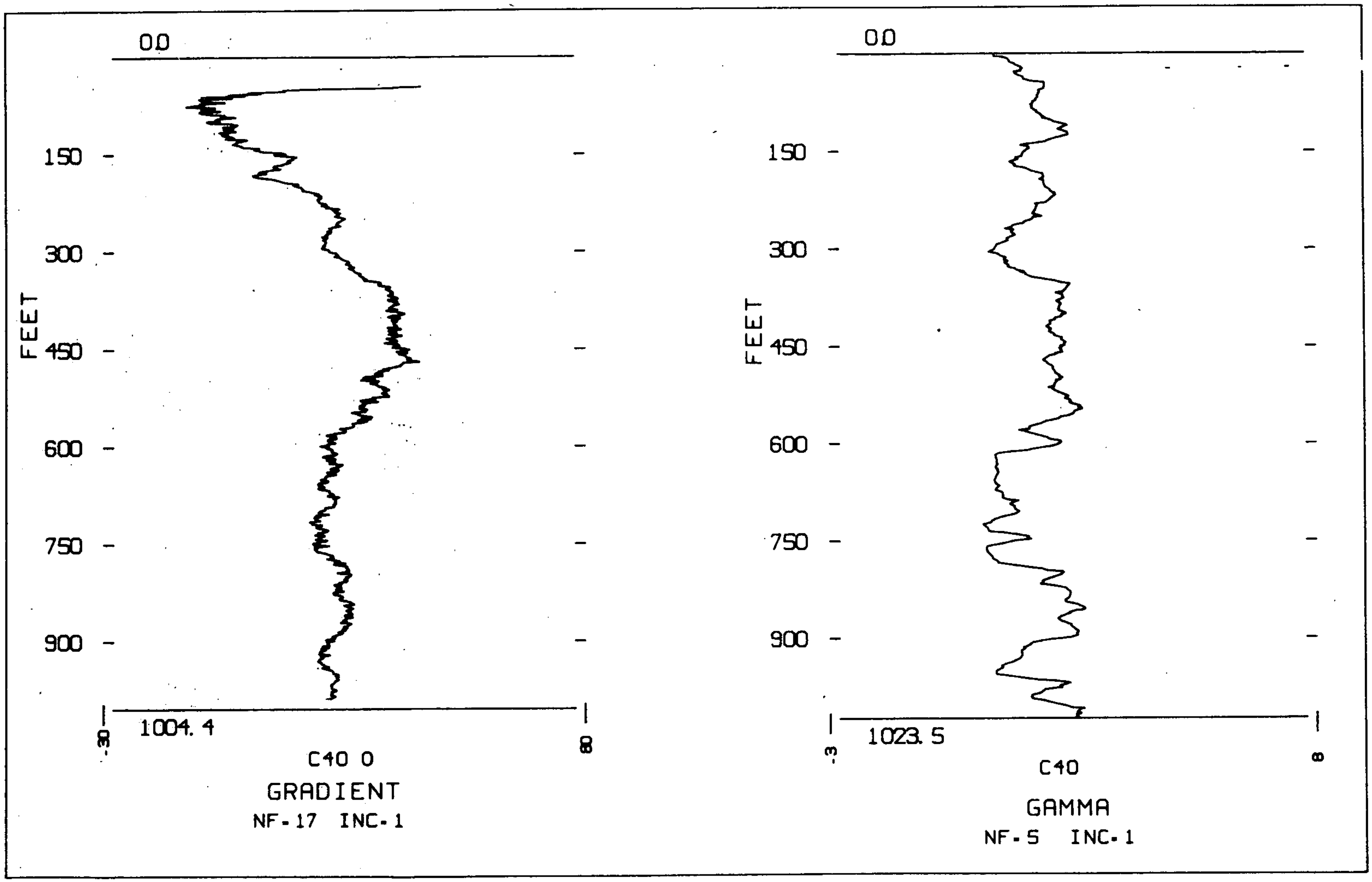


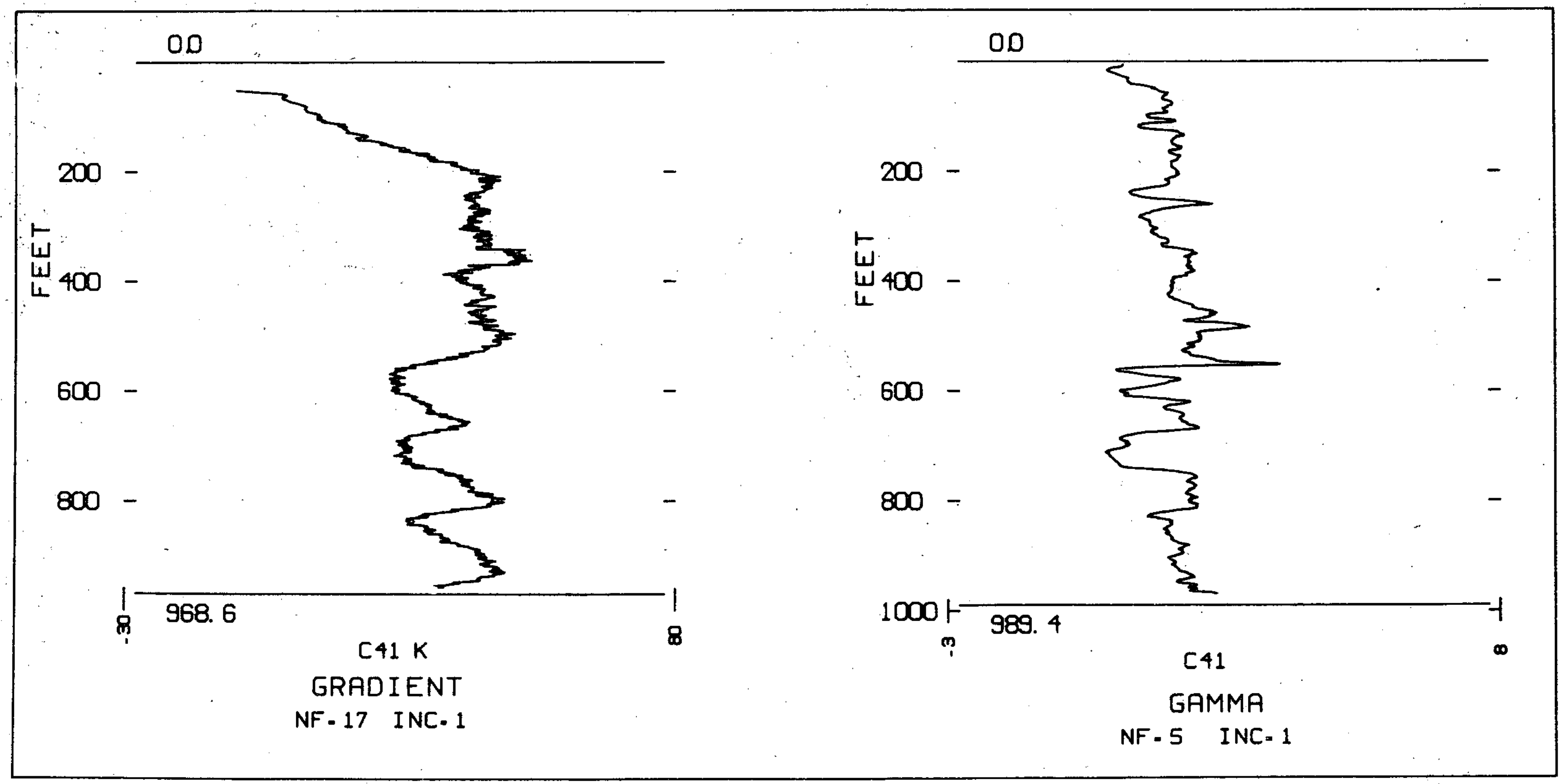
0.0
150
300
450
600
750
900
FEET
945.5
-30
80
C35 D
GRADIENT
NF•17 INC•1
0.0
150
300
450
600
750
900
FEET
955.7
-3
8
C35 D
GAMMA
NF•5 INC•1

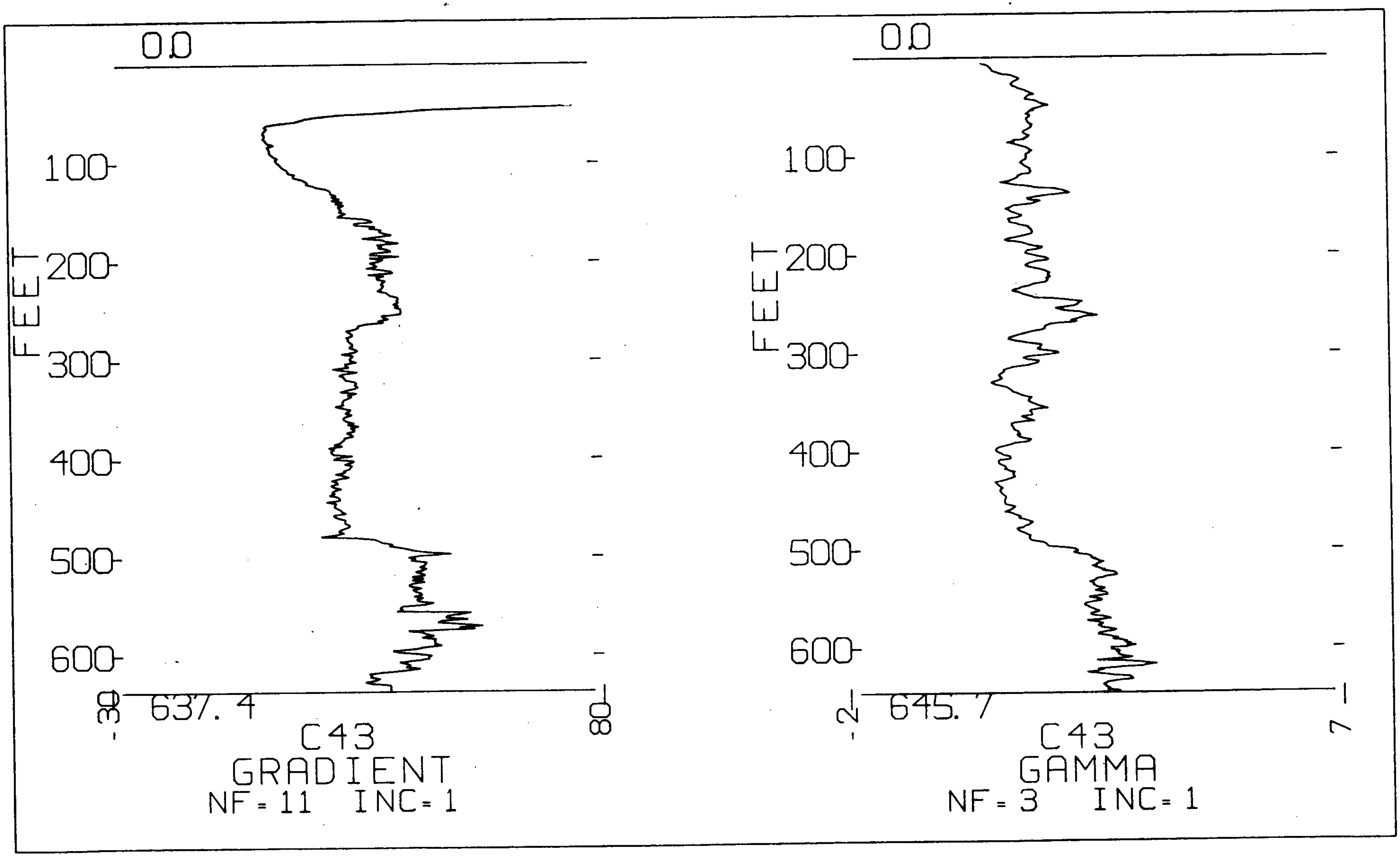


0.0
FEET
100
200
300
400
500
600
700
800
900
-30
963.9
80
C36 D
GRADIENT
NF = 17 INC = 1
0.0
FEET
100
200
300
400
500
600
700
800
900
1000
-3
1002.8
8
C36 C
GAMMA
NF = 5 INC = 1

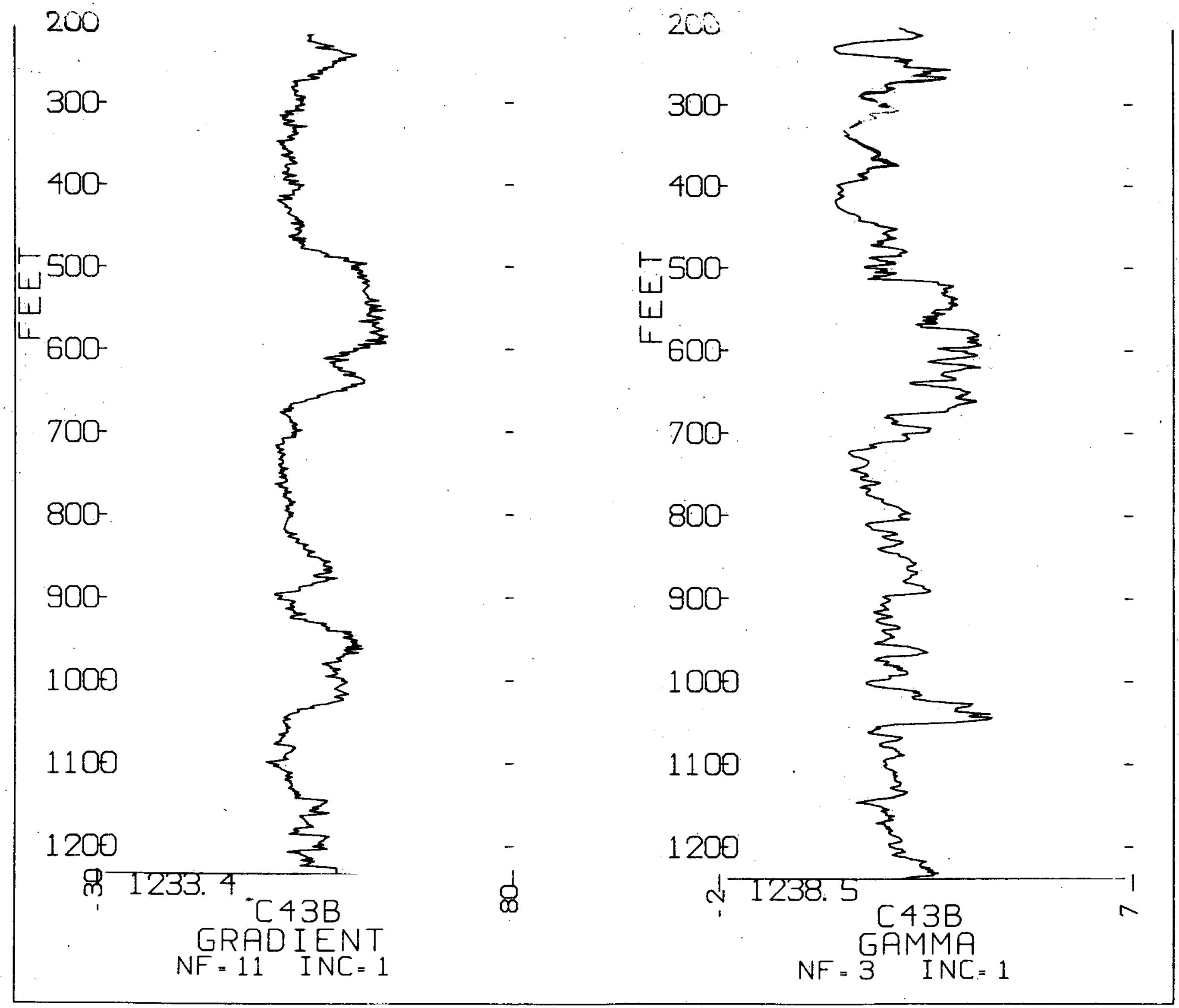

OD
FEET
100
200
300
400
500
600
700
800
900
-30
80
915.3
C39A
GRADIENT
NF=17 INC=1
OD
FEET
100
200
300
400
500
600
700
800
900
1000
-3
8
1005.0
C39 F
GAMMA
NF=5 INC=1

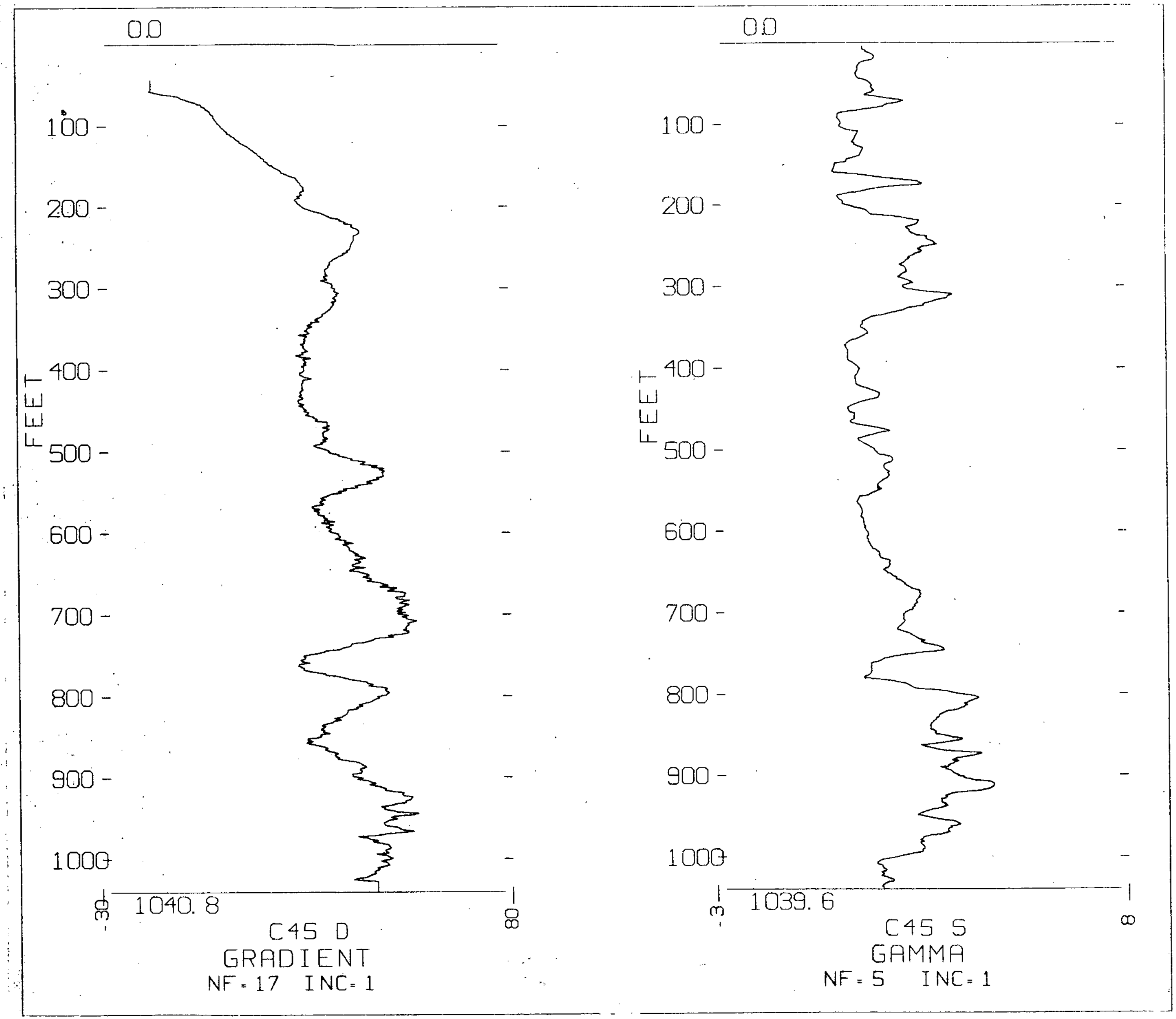

0.0
150
300
FEET
450
600
750
900
1004.4
-30
80
C40 0
GRADIENT
NF-17 INC-1
0.0
150
300
FEET
450
600
750
900
1023.5
-3
8
C40
GAMMA
NF-5 INC-1

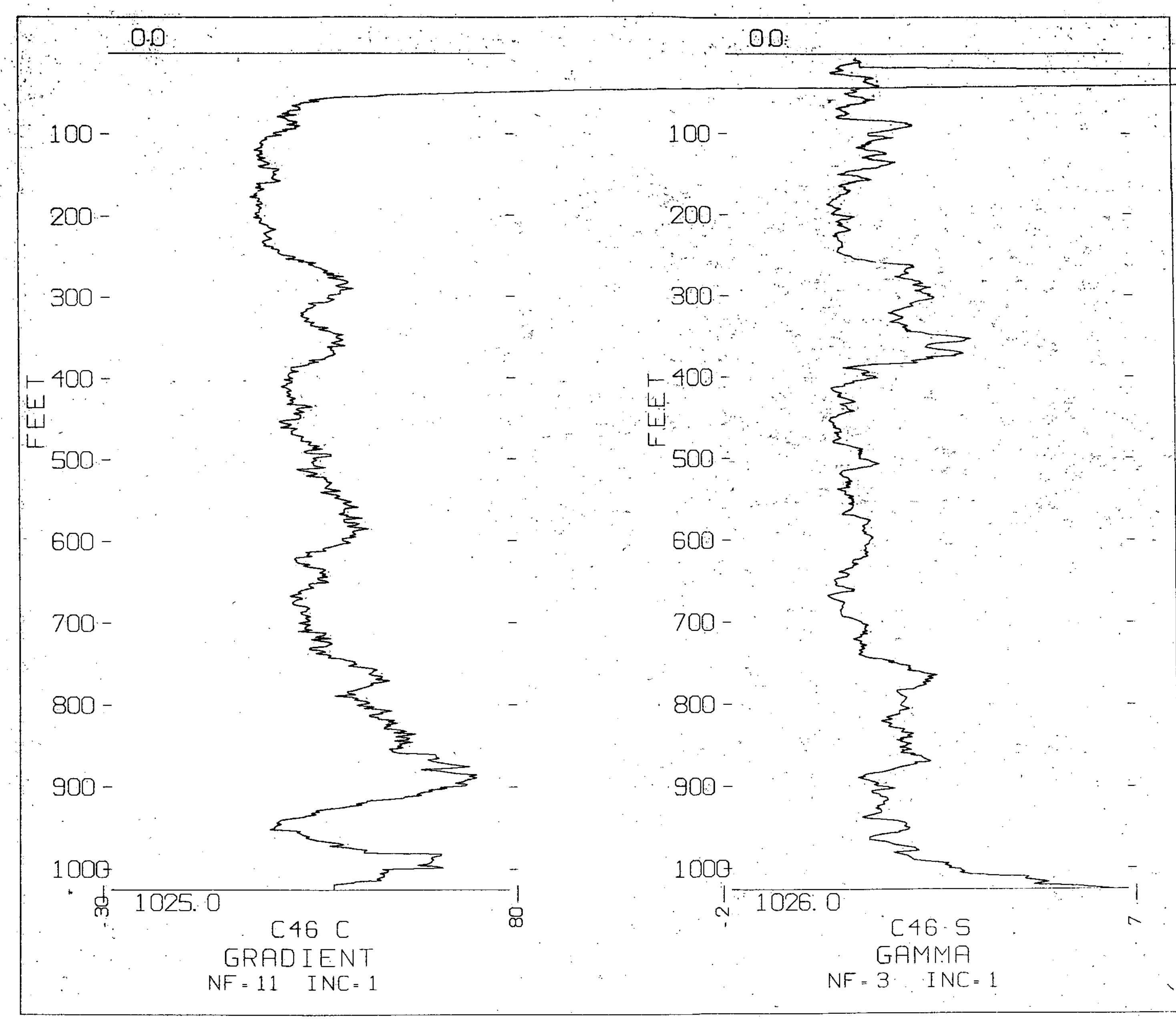

0.0
FEET
200
400
600
800
968.6
-30
80
C41 K
GRADIENT
NF-17 INC-1
0.0
FEET
200
400
600
800
1000
989.4
-3
8
C41
GAMMA
NF-5 INC-1

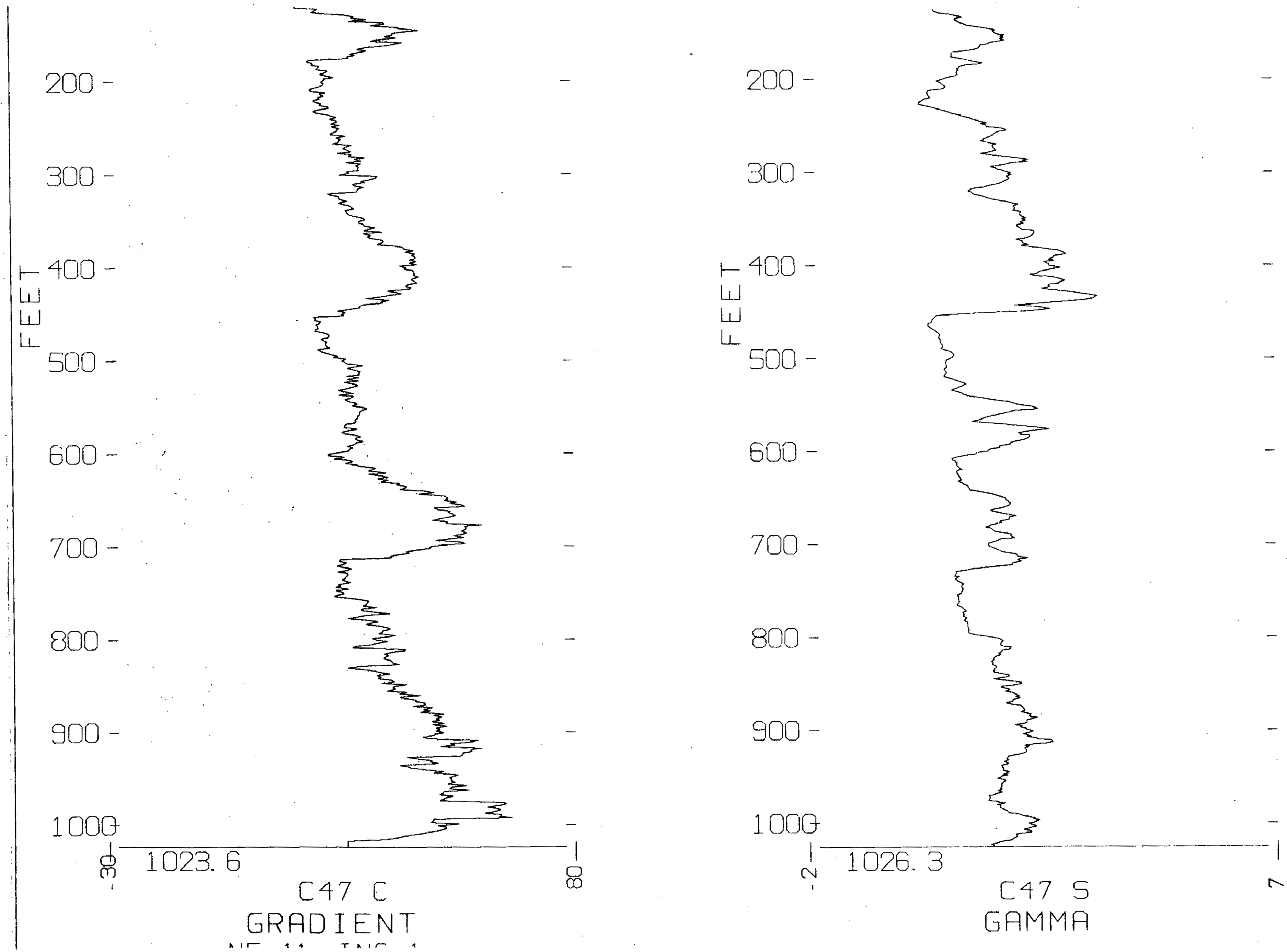


0.0
100
200
300
400
500
600
FEET
-30
637.4
80
C43
GRADIENT
NF = 11 INC = 1
0.0
100
200
300
400
500
600
FEET
-2
645.7
7
C43
GAMMA
NF = 3 INC = 1

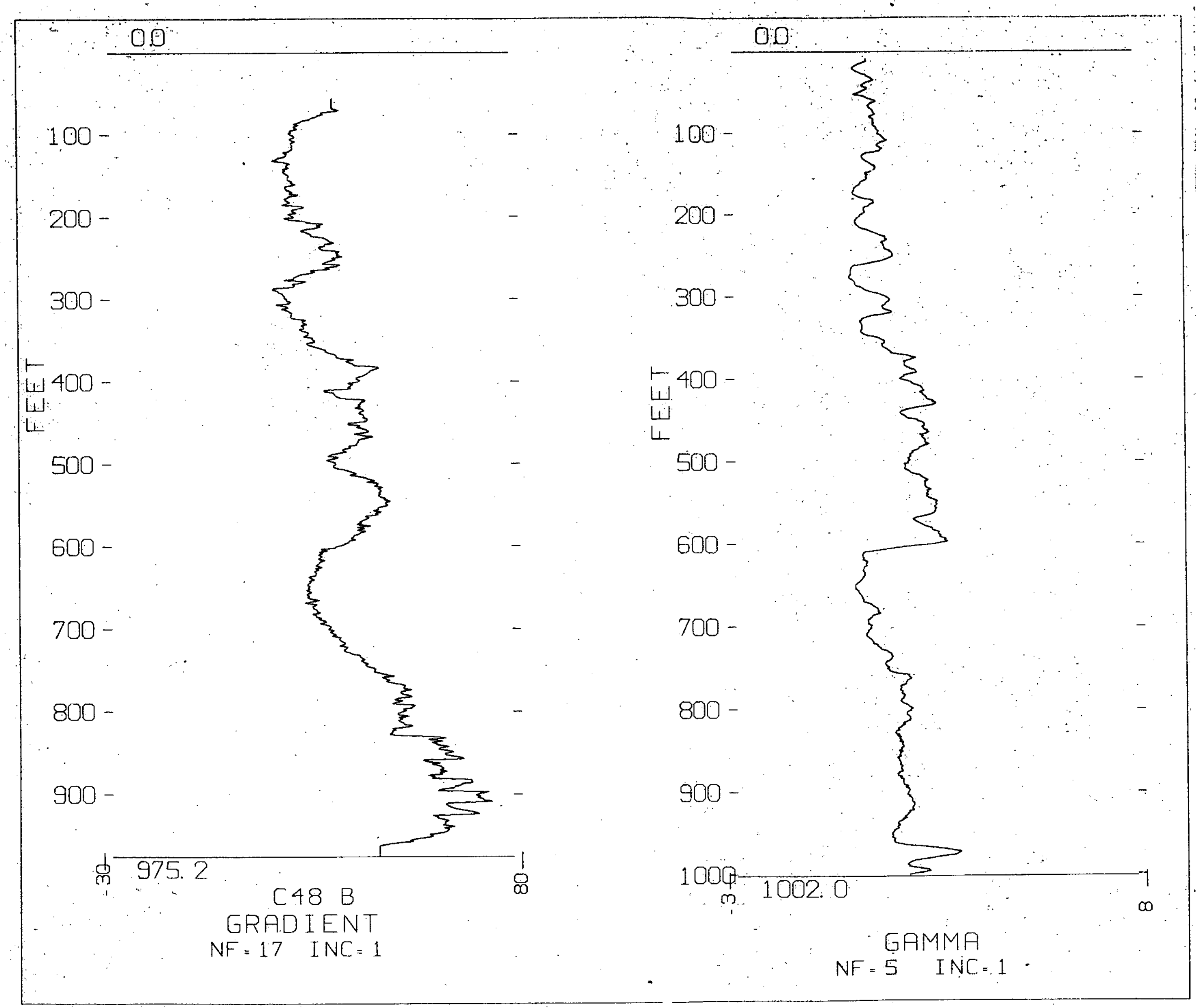

200
300
400
500
600
700
800
900
1000
1100
1200
FEET
-30
1233. 4
80
C43B
GRADIENT
NF = 11 INC = 1
200
300
400
500
600
700
800
900
1000
1100
1200
FEET
-2
1238. 5
7
C43B
GAMMA
NF = 3 INC = 1

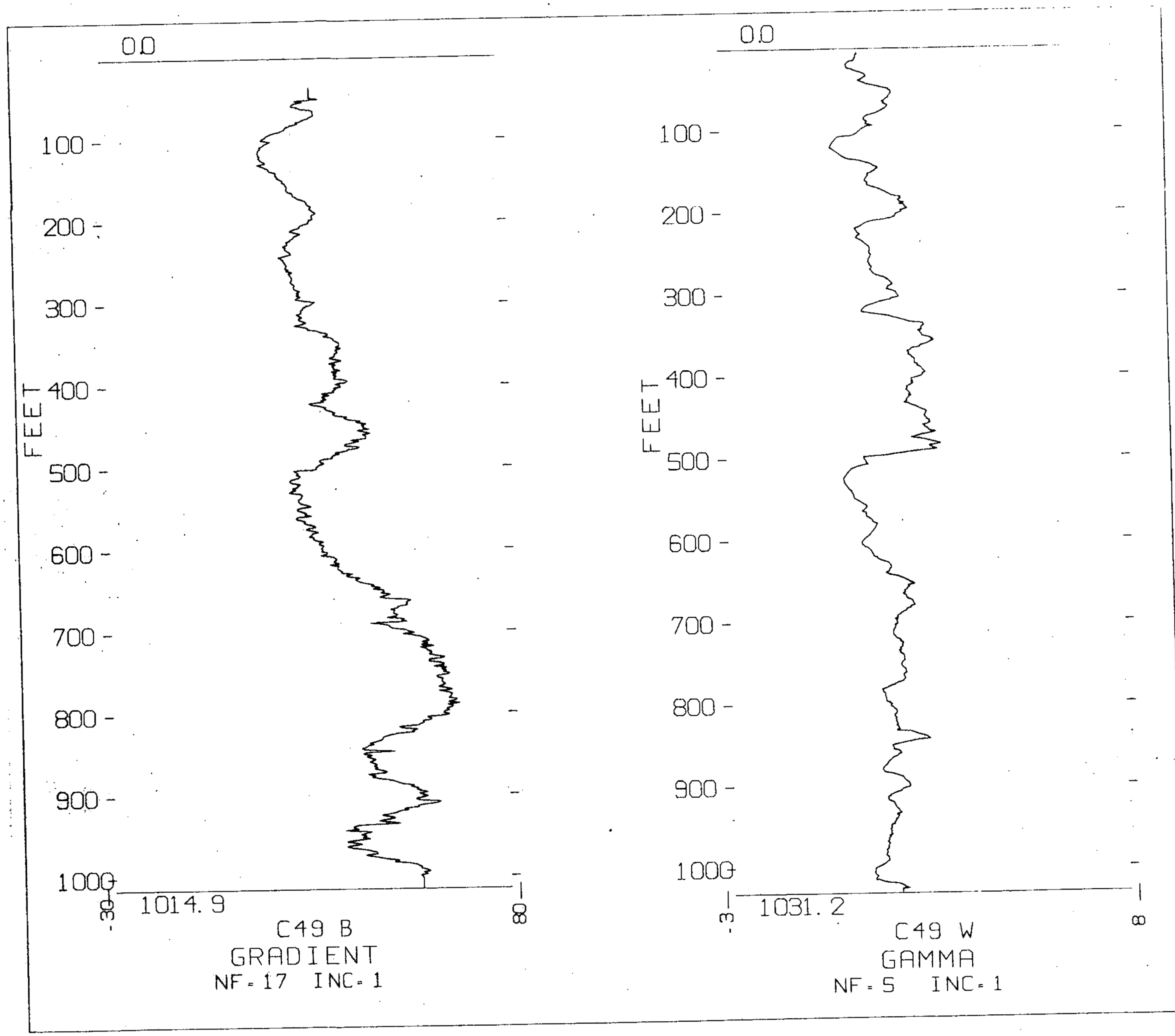

0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-30
1040.8
80
C45 D
GRADIENT
NF = 17 INC = 1
0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-3
1039.6
8
C45 S
GAMMA
NF = 5 INC = 1

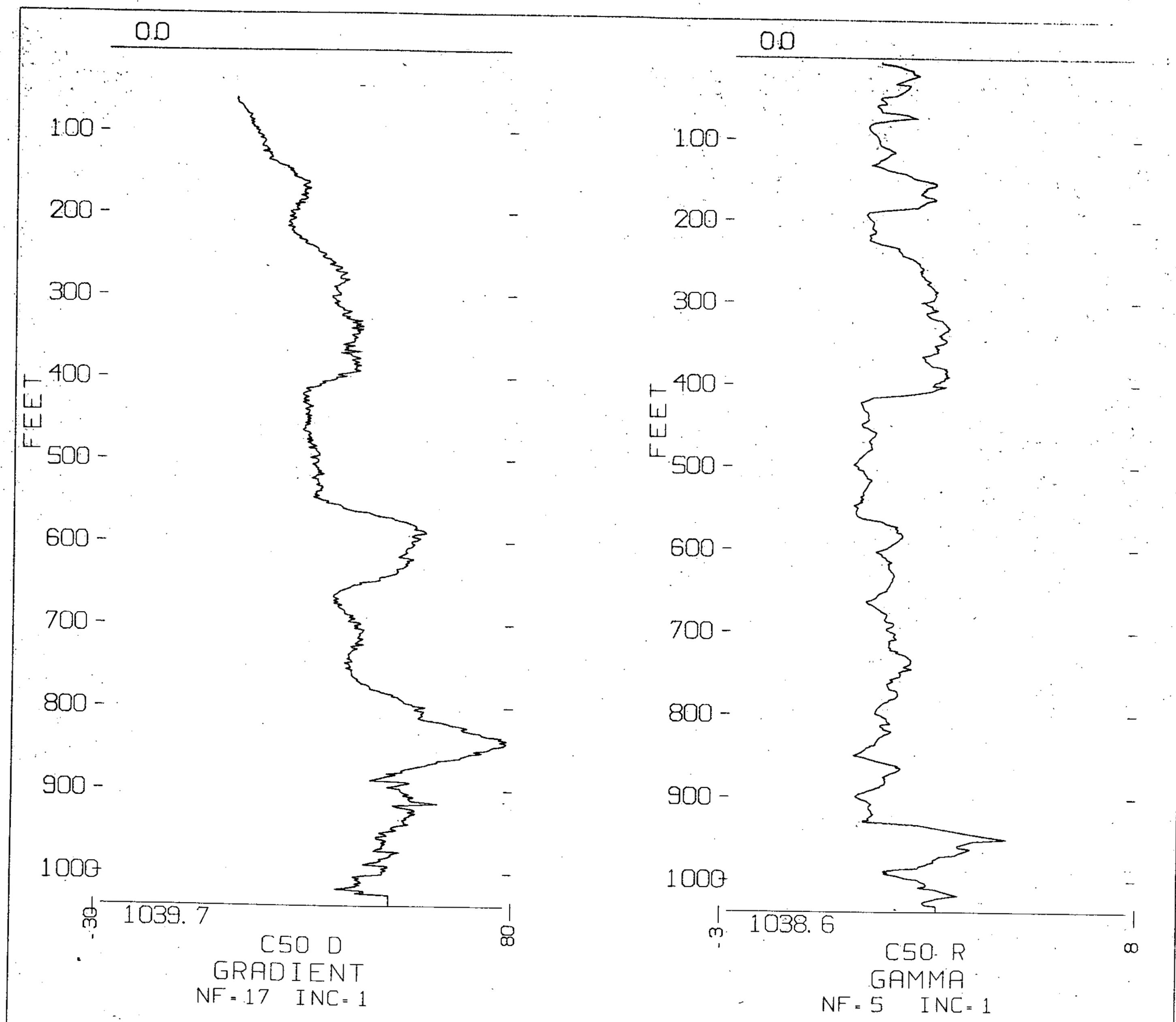

0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-30
1025.0
80
C46 C
GRADIENT
NF = 11 INC = 1
0.0
FEET
-2
1026.0
7
C46 S
GAMMA
NF = 3 INC = 1



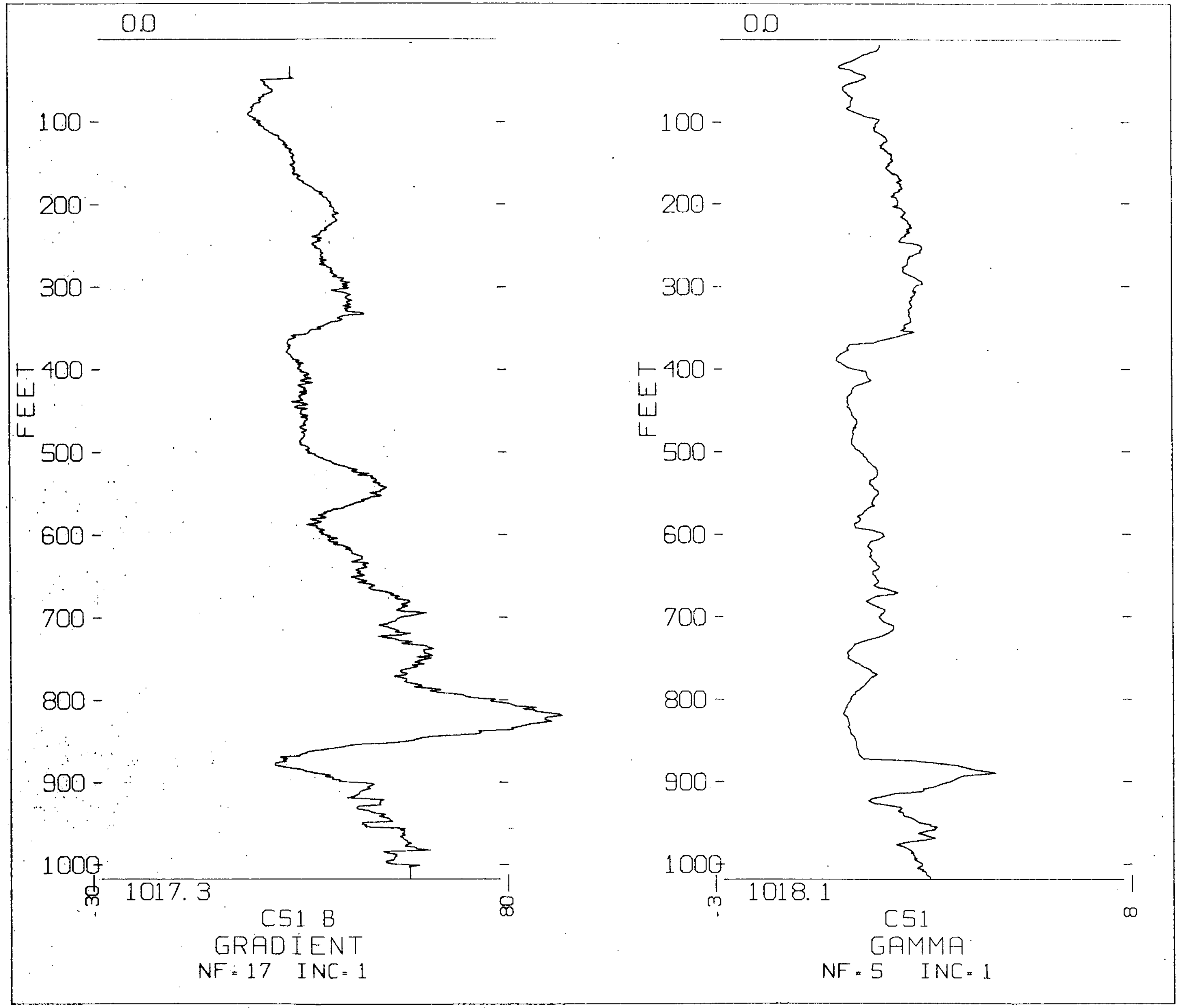
FEET
200
300
400
500
600
700
800
900
1000
-30
1023.6
80
C47 C
GRADIENT
FEET
200
300
400
500
600
700
800
900
1000
-2
1026.3
7
C47 S
GAMMA

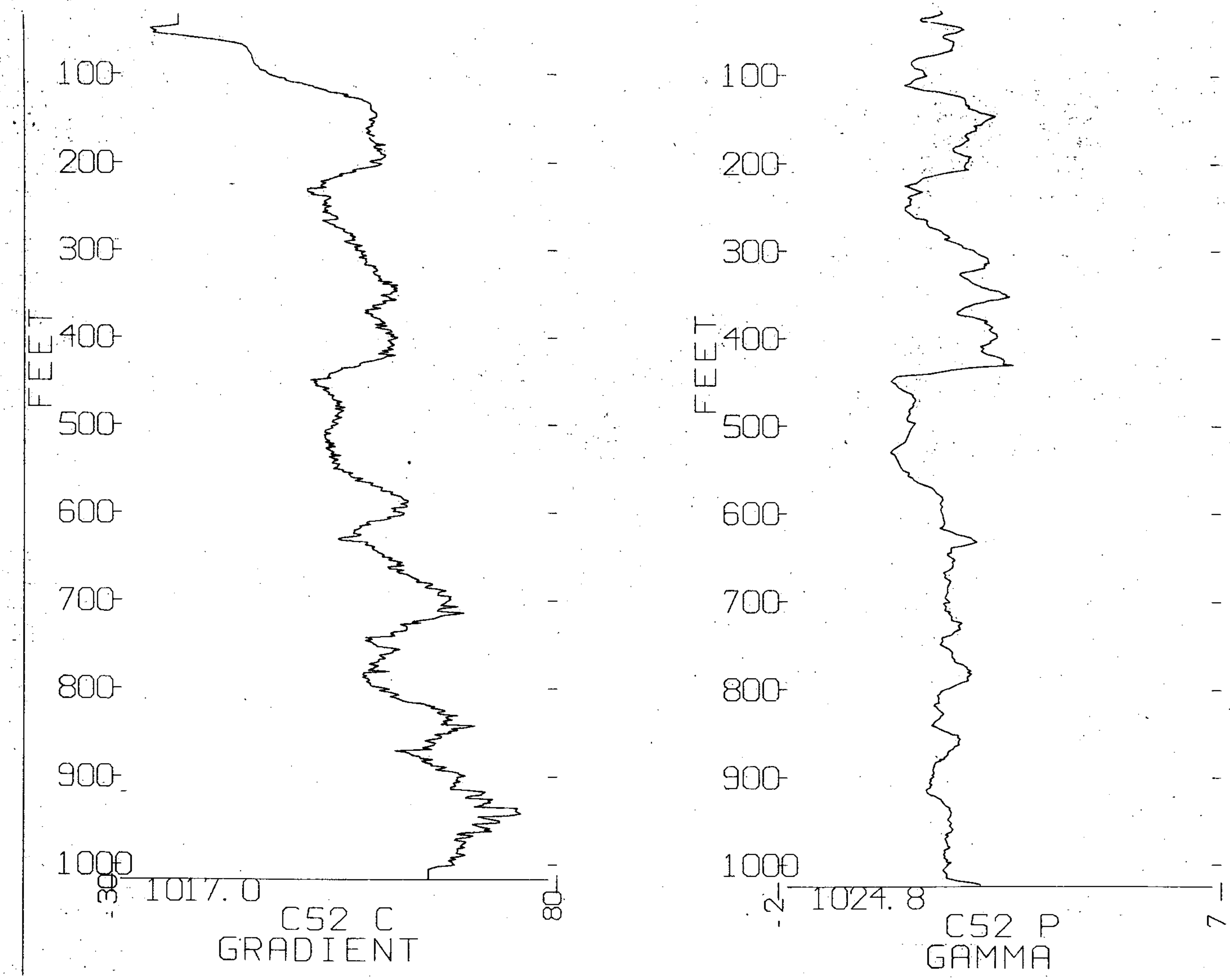

0.0
FEET
100
200
300
400
500
600
700
800
900
-30
975.2
80
C48 B
GRADIENT
NF=17 INC=1
0.0
FEET
100
200
300
400
500
600
700
800
900
1000
-3
1002.0
8
GAMMA
NF=5 INC=1

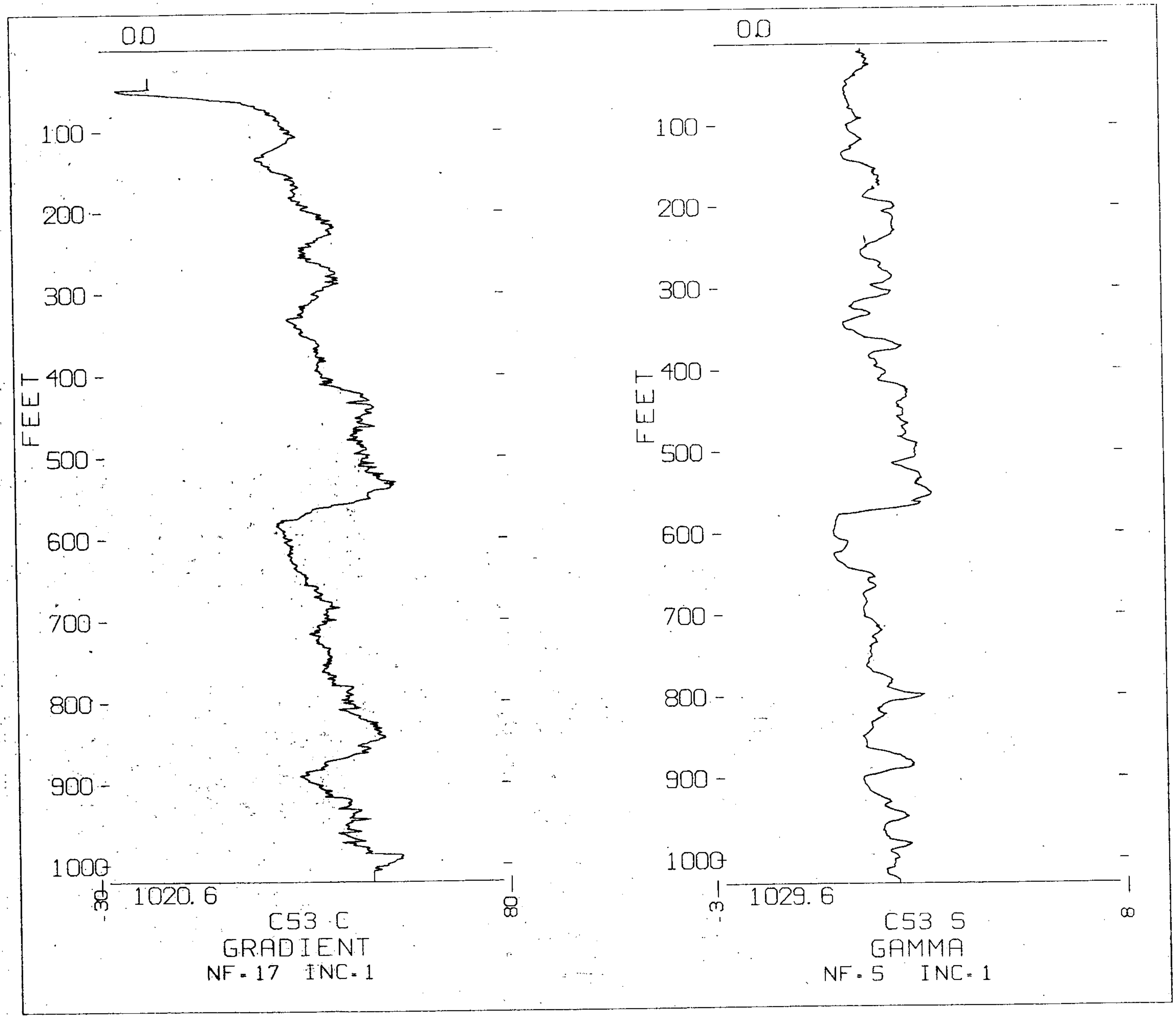

0.0
FEET
100
200
300
400
500
600
700
800
900
1000
-30
1014.9
80
C49 B
GRADIENT
NF = 17 INC = 1
0.0
FEET
-3
1031.2
8
C49 W
GAMMA
NF = 5 INC = 1



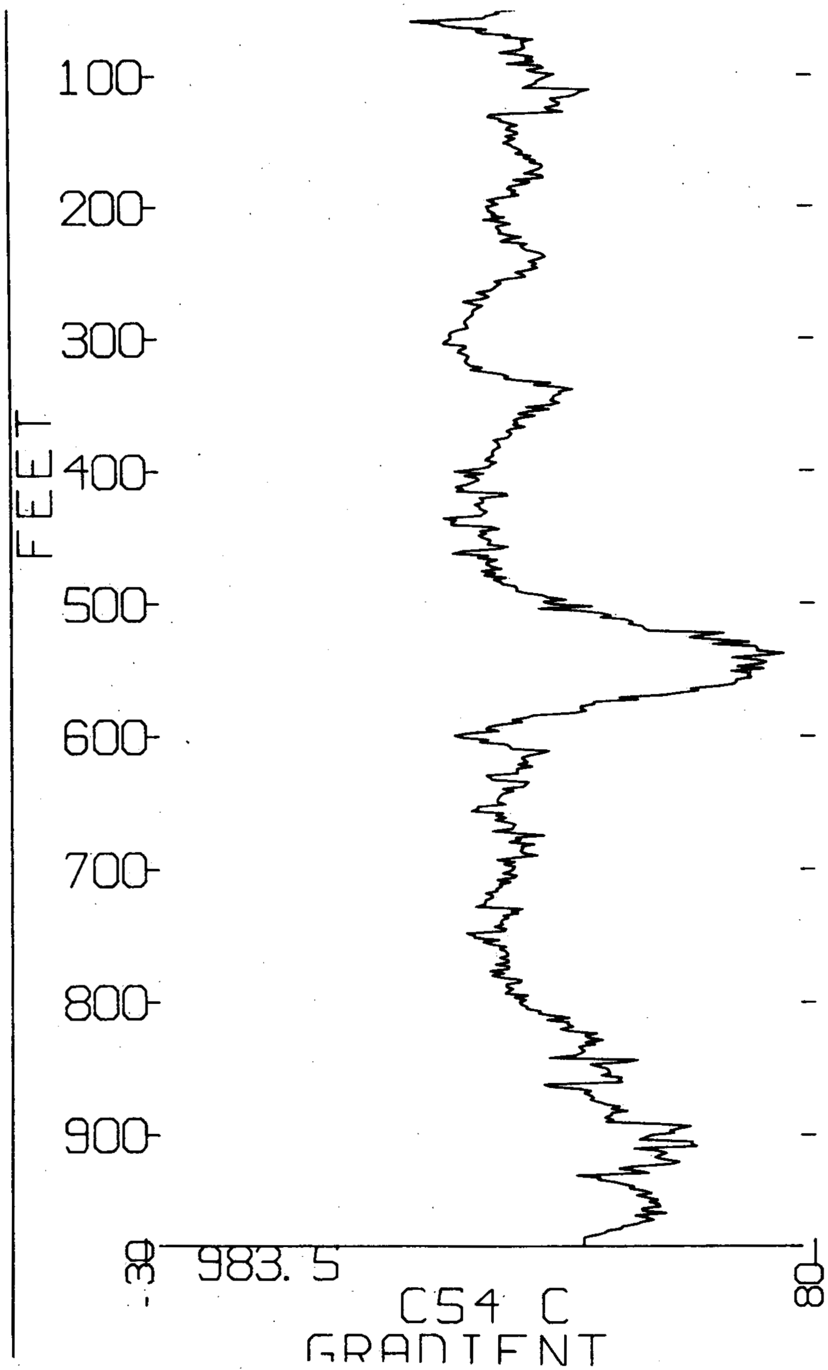
VIRGINIA POLYTECHNIC INSTITUTE & STATE UNIVERSITY

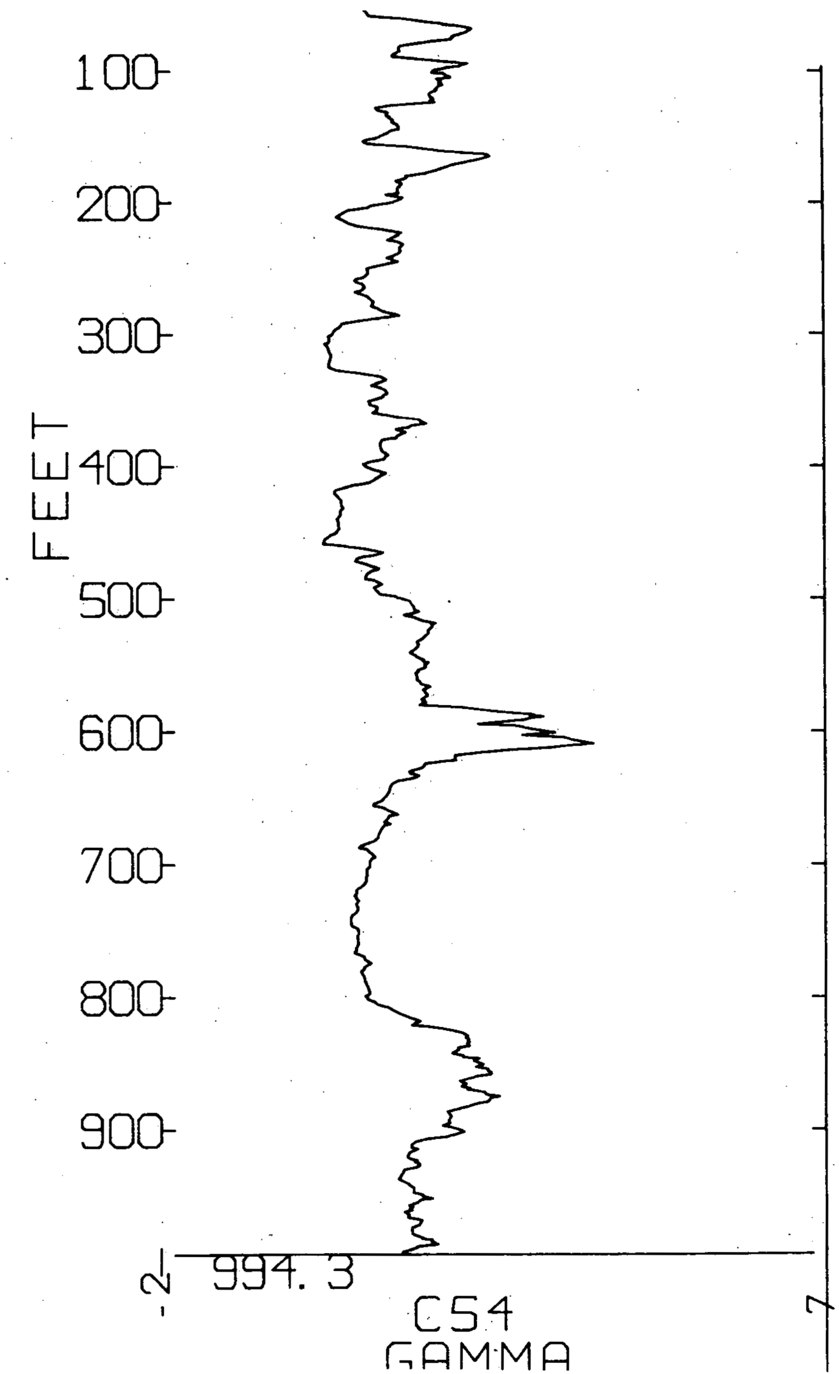

0.0
FEET
100
200
300
400
500
600
700
800
900
1000
-30
1017.3
80
CS1 B
GRADIENT
NF=17 INC=1
0.0
FEET
100
200
300
400
500
600
700
800
900
1000
-3
1018.1
8
CS1
GAMMA
NF=5 INC=1

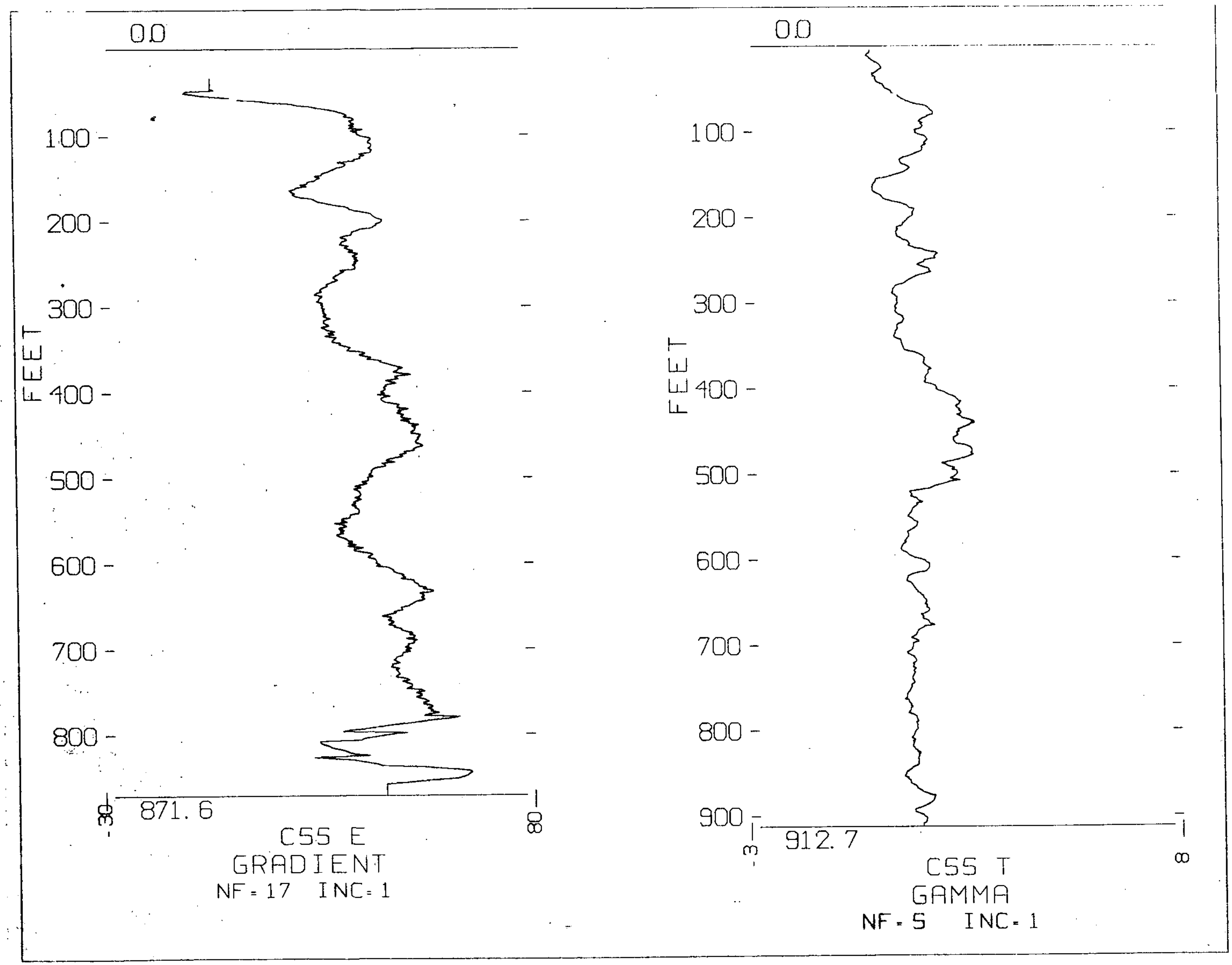

FEET
100
200
300
400
500
600
700
800
900
1000
-30
1017.0
80
C52 C
GRADIENT
FEET
100
200
300
400
500
600
700
800
900
1000
-2
1024.8
7
C52 P
GAMMA

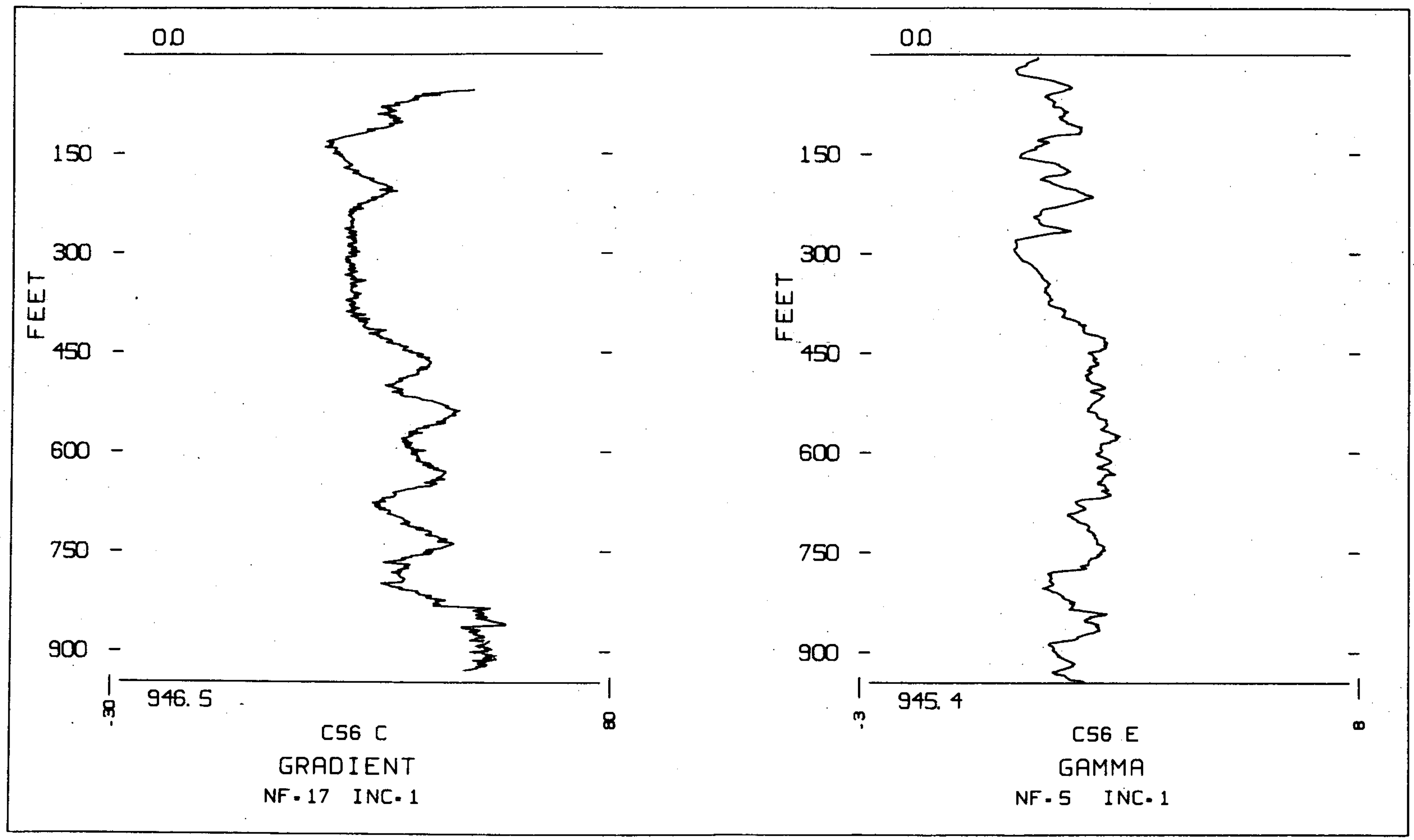


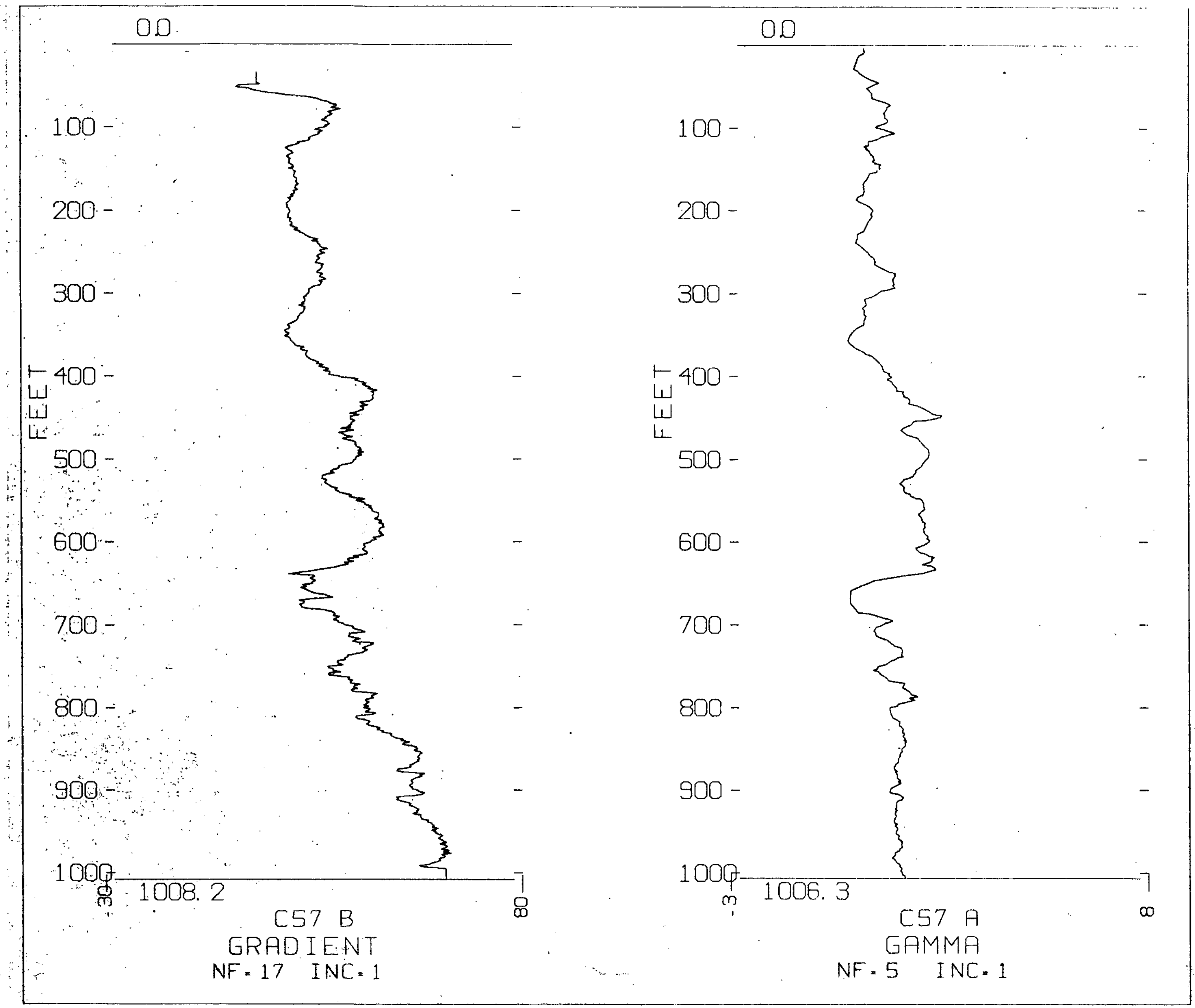
0.0
FEET
100
200
300
400
500
600
700
800
900
1000
-30
1020.6
80
C53 C
GRADIENT
NF=17 INC=1
0.0
FEET
100
200
300
400
500
600
700
800
900
1000
-3
1029.6
8
C53 S
GAMMA
NF=5 INC=1

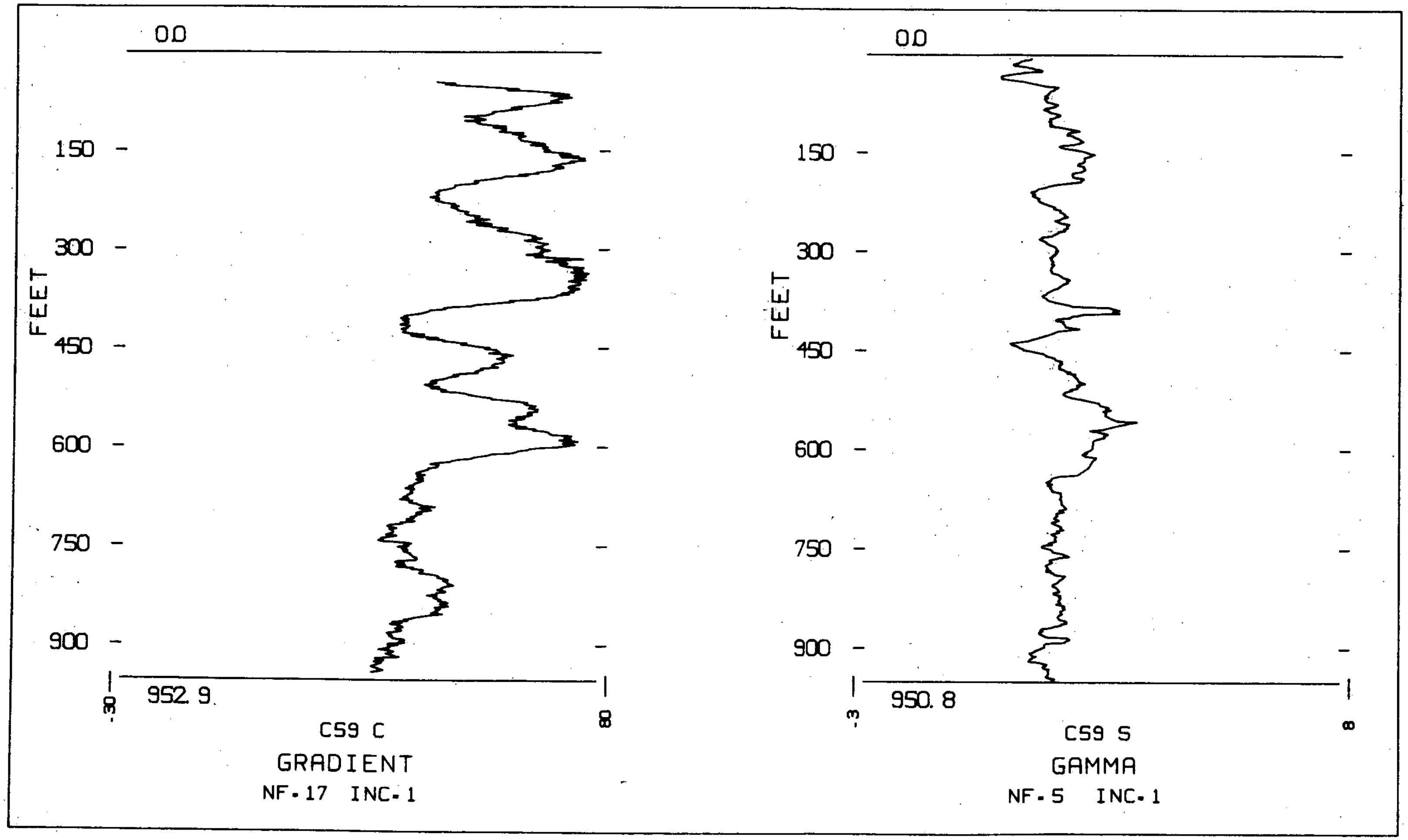

FEET
100
200
300
400
500
600
700
800
900
-30
80
983.5
C54 C
GRADIENT

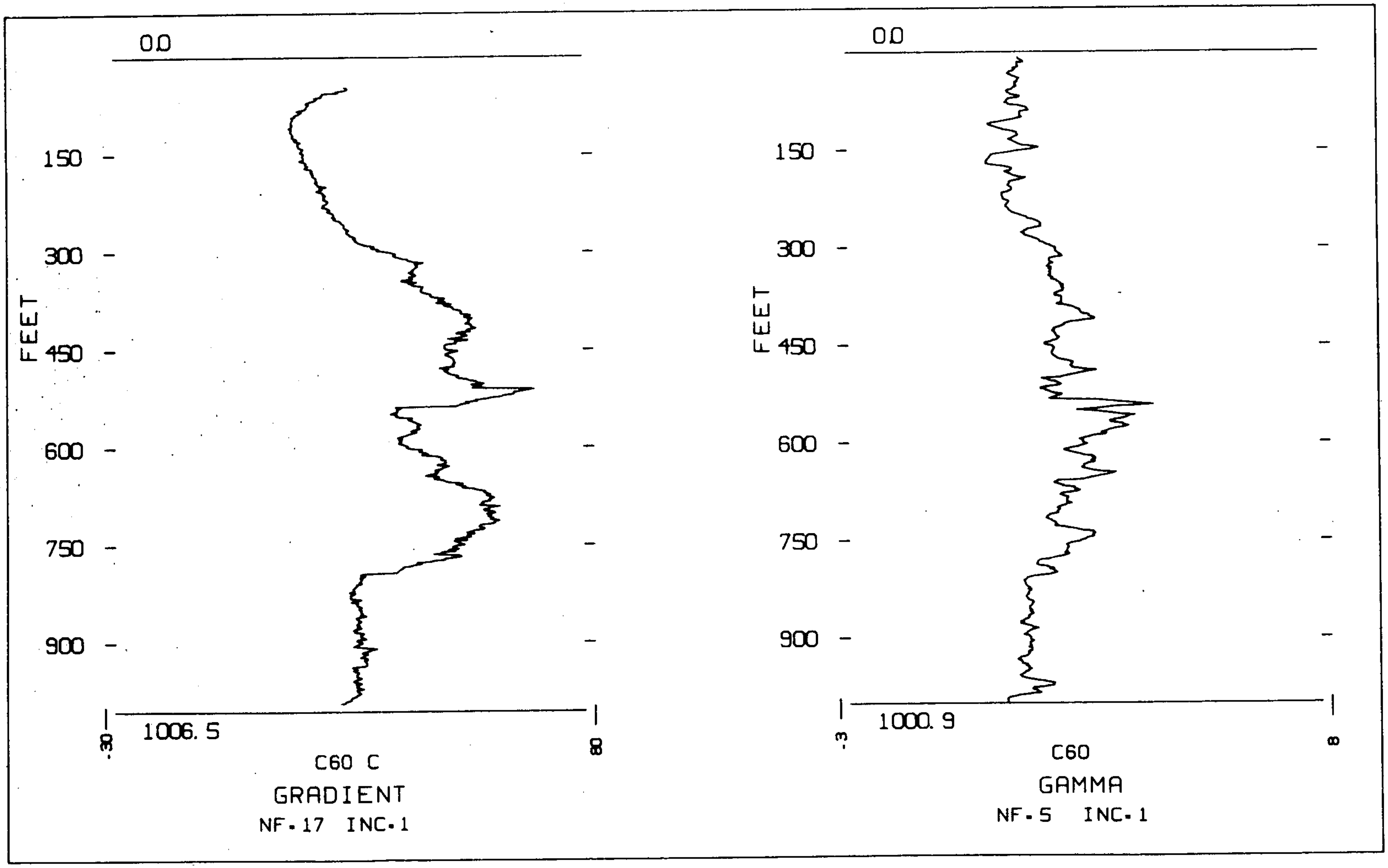

FEET
100
200
300
400
500
600
700
800
900
-2
7
994.3
C54
GAMMA


0.0
100
200
300
400
500
600
700
800
FEET
-30
80
871.6
CSS E
GRADIENT
NF = 17 INC = 1
0.0
100
200
300
400
500
600
700
800
900
FEET
-3
8
912.7
CSS T
GAMMA
NF = 5 INC = 1


0.0
150
300
450
600
750
900
FEET
946.5
-30
80
CS6 C
GRADIENT
NF-17 INC-1
0.0
150
300
450
600
750
900
FEET
945.4
-3
8
CS6 E
GAMMA
NF-5 INC-1


0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-30
80
1008. 2
C57 B
GRADIENT
NF=17 INC=1
0.0
100
200
300
400
500
600
700
800
900
1000
FEET
-3
8
1006. 3
C57 A
GAMMA
NF=5 INC=1


0.0
150
300
450
600
750
900
FEET
952.9
-30
80
CS9 C
GRADIENT
NF-17 INC-1
0.0
150
300
450
600
750
900
FEET
950.8
-3
8
CS9 S
GAMMA
NF-5 INC-1


0.0
FEET
150
300
450
600
750
900
1006.5
-30
80
C60 C
GRADIENT
NF-17 INC-1
0.0
FEET
150
300
450
600
750
900
1000.9
-3
8
C60
GAMMA
NF-5 INC-1

Temperature Logs at Other Locations in the Atlantic Coastal Plain

Samuel S. Dashevsky and Wilson S. McClung

SMITH ISLAND, MD

Smith Island is located in the Chesapeake Bay 12 miles off shore from Crisfield within a regional gravity low aligned with the Bay. Three abandoned water wells were located and logged for temperature. In the community of Ewell, a gradient of 41°C/km was determined in a 245m undisturbed well (SI-3, Fig. A-7). The temperature at 245m (802 ft) is 25°C (77°F). Another well in Ewell (SI-2) was logged to 236 m, but the temperature profile is disturbed by a producing well 1 meter to the side. This log is shown in Figure A-8 along with the log of SI-1 to 76.5m on Rhodes Point.

PARRIS ISLAND, S.C.

A temperature log was obtained in a 725m (2380 ft) flowing artesian well on Parris Island, SC (Figure A-9). The well, flowing at 90 g.p.m. with a discharge temperature of 40.6°C (105°F), is not currently in use. The temperature at 725m is 42.8°C (109°F) which indicates a gradient of 33°C/km for an assuming mean annual surface temperature of 18.7°C (NOAA, 1973).

COLONELS ISLAND, GA

Near Brunswick, GA a hydrologic test well drilled by the U.S. Geological Survey on Colonels Island was logged for temperature to a depth of 829m (2720 ft) (Figure A-10). A heat flow value of 42 ± 7 mW/m^2 was determined. Departure from a linear geothermal gradient in the upper 400 meters is attributed to cooling induced by recharge to zones of groundwater withdrawal. The anomalous temperature profile in the interval 670m - 760m has been verified as real by reproduction in repeated logs. The possibility of obstruction and hangup of the sonde was discounted by the consistant reproduction of the curve when logged from the bottom upward with the cable in tension. It is hypothesized that the zone is highly permeable, probably fractured carbonate rocks, within which complex circulation is maintained to bring the lower boundary at 760m into thermal contact with the upper boundary at 670m. The higher temperature in the upper half of the zone indicates water flow from at least 785m along an inclined fracture plane which may intersect the well bore at 700m. The lower more strictly mono-temperature zone must be a zone of high turbulence and thorough mixing in the vicinity of the well bore. Core was made available by courtesy of the U.S.G.S. for thermal conductivity determinations at VPI&SU. The heat flow value of 42 mW/m^2 represents a background heat flow value in agreement with our measurements at other sites in the Coastal Plain, Piedmont, and Valley and Ridge Provinces. The temperature at the basement surface (1.37 km) is estimated at 45°C (115°F).

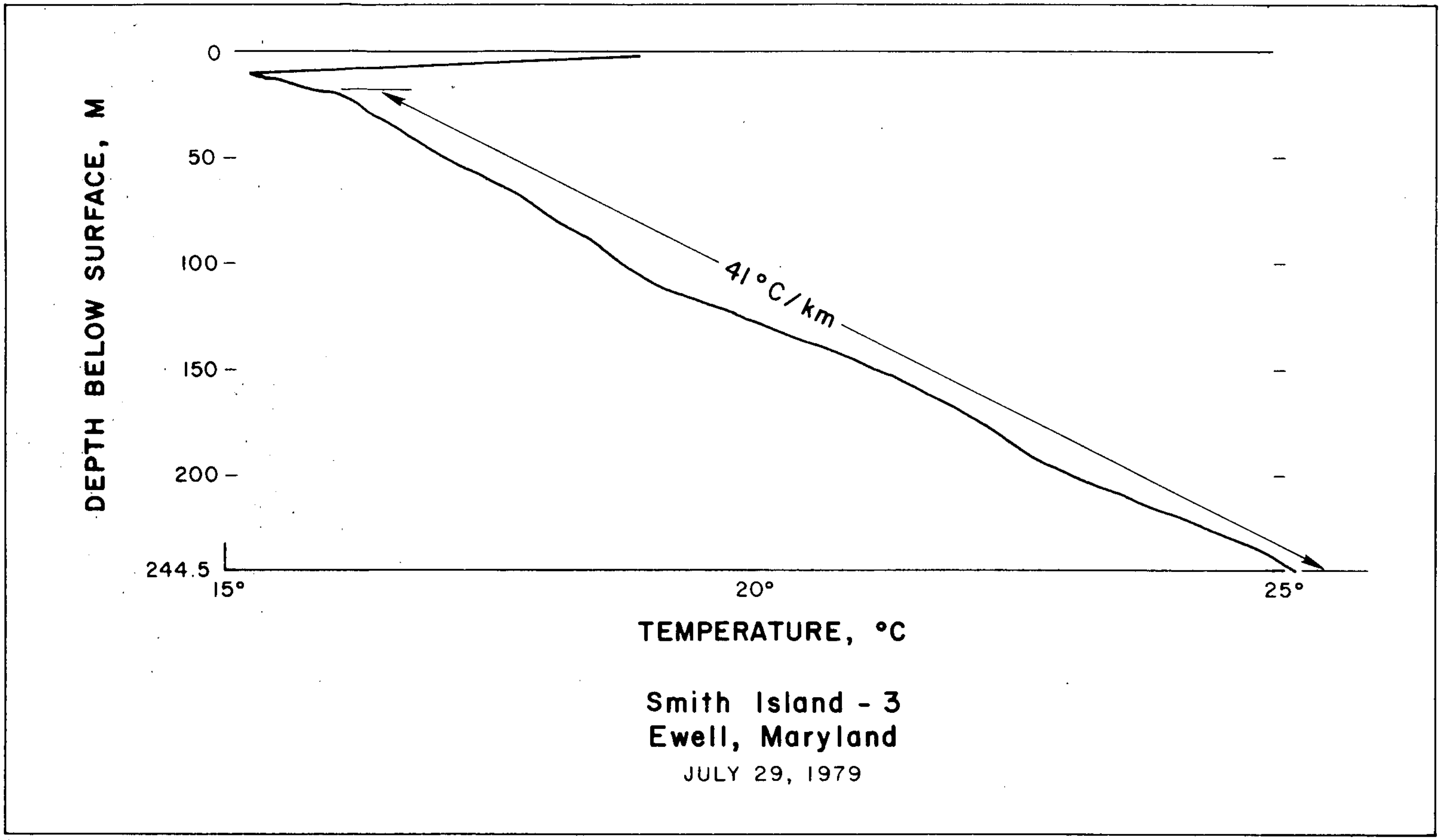


Figure A-7. Temperature log of undisturbed abandoned water well - Ewell, Maryland Smith Island

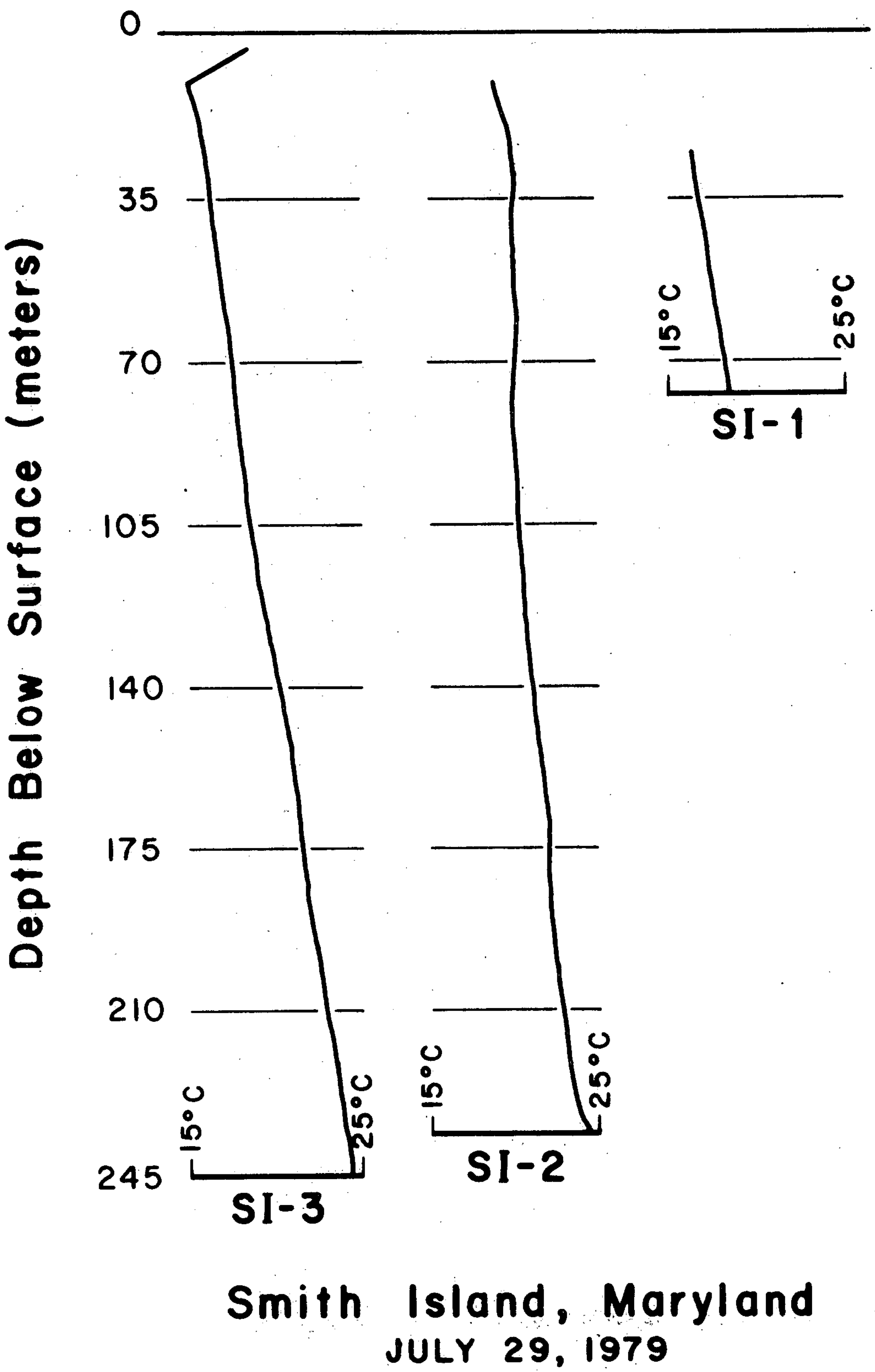


Figure A-8. SI-3, undisturbed water well, 41°C/km
SI-2, disturbed water well
SI-1, undisturbed water well obstructed at 76.5 m, 44°C/km

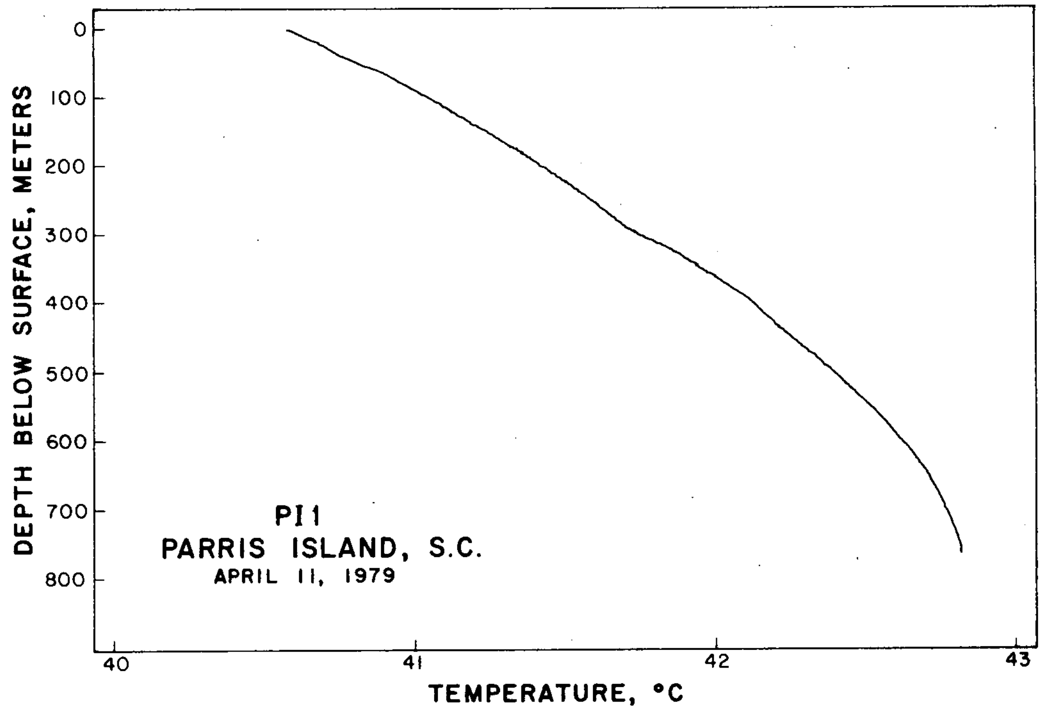


Figure A-9. Temperature log of flowing artesian well PI-1, Parris Island, SC

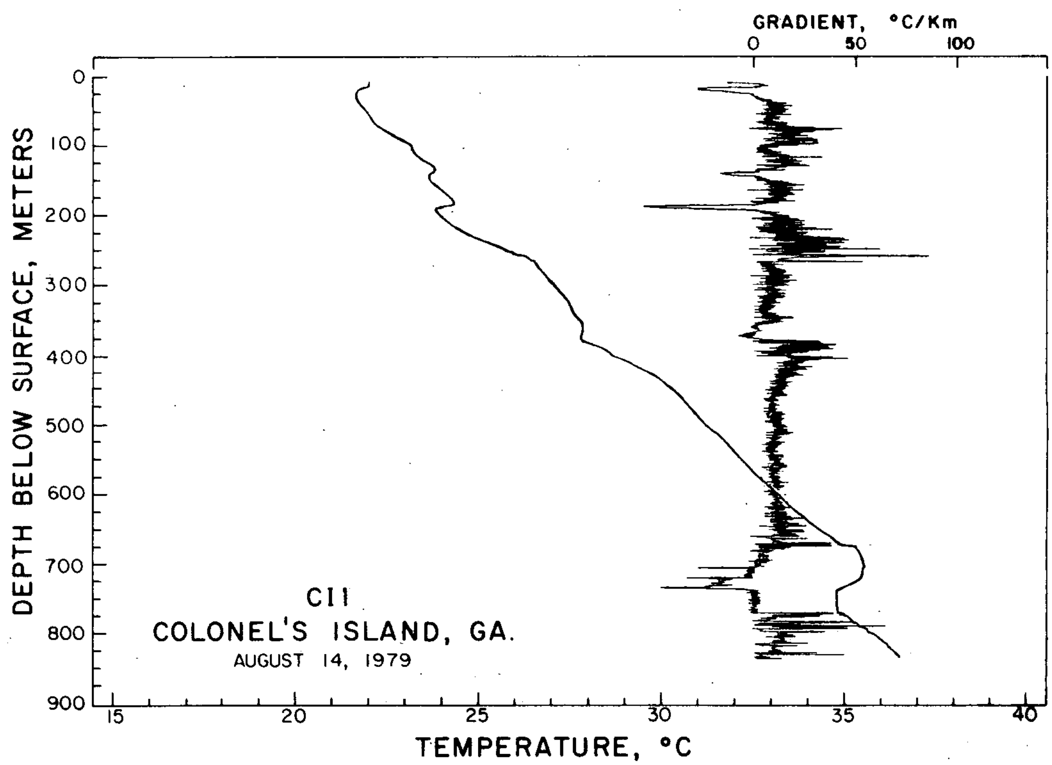


Figure A-10. Temperature log of CI-1 USGS test well, Brunswick, GA

DORT-1, N.C.

The Dort, NC hole was drilled by VPI&SU in Coastal Plain sediments over a circular negative gravity anamoly and was deepened to 415m (1362°) into about 100 m into granite basement (See Becker, this report). The hole is in granite from 315m on down. The temperature log is shown in Figure A-11. The thermal gradient in the coastal plain section of the hole is 31°C/km and is 23°C/km in the deeper granite portion of the hole. The gradient of 23°C/km is one of the highest determined to date in granite in the southeastern U.S.

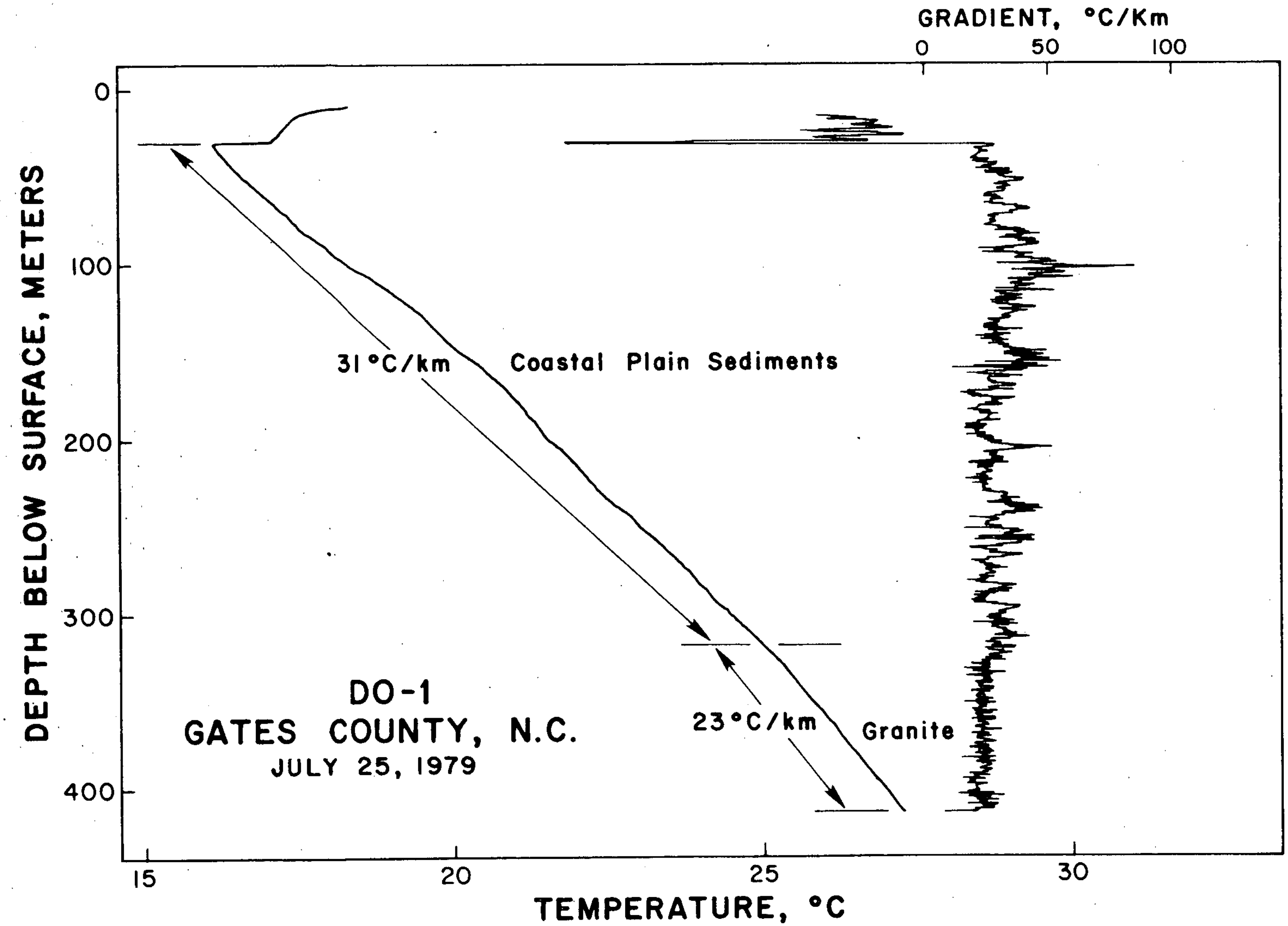


Figure A-11. Temperature log of DO-1, Dort, NC

References

Edwardson, M. Girner, H. M., Parkison, H. R., Williams, C. D., and Mathews, C. S., 1962, Calculation of formation temperature disturbances caused by mud circulation, Journ. of Petroleum Technology.

B. OROGENICS STUDIES LABORATORY (OSL)

GENERAL GEOLOGY OF THE EAST COAST WITH EMPHASIS ON POTENTIAL GEOTHERMAL ENERGY REGIONS: A DETAILED SUMMARY[1]

Lynn Glover, III

Department of Geological Sciences, Orogenic Studies Laboratory
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

Introduction and Background

The relative stability of the East with respect to earthquakes and volcanic activity does not immediately suggest the vast reserve of low to moderate temeprature (40°-125°C?, or 104°-260°F?) geothermal energy that probably exists here. It is understandably difficult to seriously consider geothermal prospects in the East as long as the word "geothermal" brings forth an image of Old Faithful erupting at Yellowstone! Nevertheless, for the low temperatures needed to economically heat large housing (3000 units) and industrial complexes , for example, some of the eastern hydrothermal reservoirs may be both large and favorably located with respect to potential utilization. The importance of developing this resource is easily understood from the observation that currently about 40% of our fuel consumption is devoted to space heating.

Below the effects of the diurnal and annual temperatures variation at the surface, (several hundred feet), the temperature in the earth tends to show a regular rise with increasing depth. In the future, it may become economic in this country to develop geothermal sources in deep aquifers from regions of essentially "normal" geothermal gradient, as is currently being done with a gradient of 33°C/km or 1.8°F/100 ft in the Paris Basin (Rybach, 1979). Secondly, mining heat by circulating water through man-made hydraulic fractures in hot crystalline rocks of the basement below insulating sedimentary basins is an existing technology developed at Los Alamos that may have a future in the East. If so, the temperatures available by this method may even be sufficient to generate electric power. Thirdly, natural fracture zones and fold structures that allow convection of heat by the rise of deeply circulating ground water in regions of essentially normal heat flow, e.g. Hot Springs, Virginia, seem to have immediate but more modest (?) application because of apparent limitations in temperature, volume of water, and location.

Of primary interest at present, however, are elements of eastern geologic elements including: 1) sedimentary basin fillings of very low thermal conductivity (i.e. heat damming) sediments, e.g. water saturated clay-rich deposits, and 2) radiogenic heat sources in the

---

[1]This paper with minor modifications appeared in Special Report No.5, A Symposium of Geothermal Energy and its Direct Uses in the Eastern United States, pp.9-11, Geothermal Resources Council, P.O. Box 98, Davis, CA, 95616.

crystalline continental crust, especially the younger granites of Late Paleozoic (300-260 m.y.) and younger ages. Optimal geologic frameworks occur where: 1) granites of high heat generating capacity (radiogenic heat supplied by spontaneous fission of naturally occurring U, Th, and ^{40}K in the granite), are 2) overlain by large confined or semiconfined aquifers, which 3) are in turn blanketed by thick (water saturated and clay-rich) strata of low thermal conductivity. Such frameworks appear to be most abundant east of the Fall Line, under the Atlantic Coastal Plain. Environmentally clean heat could be extracted by circulating water from an aquifer up one well, through a heat exchanger, and then reinjecting the water down a second well. The optimal geologic framework described above is often referred to as "the buried pluton concept" and is the principal targeting procedure being used by VPI&SU to explore the Atlantic Coastal Plain geologic province. It could be applied as well to many other suitable regions in the U.S. and elsewhere.

From the foregoing it is clear that the aspects of east coast geology of highest priority in a search for geothermal resources include: 1) the thickness, structure, stratigraphy, hydrology, and thermal conductivity of sediments beneath the Atlantic Coastal Plain, and 2) the structure, composition, age and intensity of metamorphism and of granite emplacement, and the heat production of rocks in the basement under the Atlantic Coastal Plain. Because the character of the Atlantic Coastal Plain sediments is discussed by other speakers on this program, the following is concerned with the evolution of 2) above, the heat sources in the basement.

Regional metamorphism and deformation play a key role in the evolution and location of basement radiogenic heat sources. Uranium and thorium in particular are mobilized in fluids and granitic melts during regional metamorphism. Moving under the influence of gravity, thermal gradients, and deformation, much of the uranium and thorium is permanently lost from or homogenized in a metamorphic terrain. A notable exception is the relative concentration of these elements (U, Th, and K) in granitic melts that may crystallize and remain within the zone of metamorphism. Thus "plums" of radiogenic granites are scattered through a "pudding" of metamorphic gneisses and schists that may be somewhat depleted in these heat producing elements. By "concentrated" we mean about 10 parts per million (ppm) of U in the granite vs. 1-2 ppm in the gneisses and schists of the metamorphic terrain. This is hardly ore grade or very radioactive in the usual sense!

In the case of the Appalachian Piedmont and its extension, the basement under the Atlantic Coastal Plain, patterns of metamorphism and igneous activity have wandered through space and time in a complex manner. Thus the U and Th concentrated in granites of one generation of activity may be strongly depleted or homogenized during the metamorphism of another. Only granites that consolidate after the thermal peak of the last metamorphism in an area are likely to have relatively high radiogenic heat production. It is important, therefore, to try to understand these patterns of metamorphism and igneous activity in order to target productive granites beneath the Atlantic Coastal Plain. Targeting of such granites under the Coastal Plain can be assisted by using magnetic, gravity, and seismic surveys, but these are indirect methods that must be controlled by selective core drilling into the crystalline basement. Some cores should come from metamorphic basement rocks (the "pudding") so that we can determine composition, structure, density, seismic velocity, magnetic properties, heat production and the type and age of metamorphism. Other cores must come from young syn- to post-metamorphic granites (the "plums") so that besides their other properties, we can also measure their heat generation directly in order to verify the exploration model and to serve as a double check on certain heat flow related measurements made in the shallower wells of the Atlantic Coastal Plain.

The nature and timing of igneous and metamorphic activity in the crystalline Appalachians (i.e. Blue Ridge, Piedmont, and basement under the Atlantic Coastal Plain) are topics central to plate tectonic hypotheses for the origin of the Appalachians. Because of previous research stimulated by this interest we have a moderate amount of background data to build upon. That is, the data base is sufficient to generate interesting ideas about the nature of possible radiogenic heat sources, but insufficient to verify them. Plate tectonic models provide us with rational hypotheses that explain some of the data and may give us some predictive capability about the nature of certain basement regions. Further discussion of such models, however, is beyond the scope of this paper.

Some Aspects of the Geologic History of the Piedmont as a Guide to the Nature of Heat Sources in the Atlantic Coastal Plain Basement

(The following account greatly oversimplifies a complex geologic terrain. The trends discussed here are <u>not</u> well documented and much work remains to be done.)

Widespread volcanism and plutonism (emplacement of granitic and gabbroic rocks) during the Eocambrian and Cambrian Periods, about 800 to 500 m.y. ago, extended over much of the Piedmont and Blue Ridge. The scanty data suggest that these plutons range from large to small in size, from shallow to deep levels of placement, and were associated with periods of extensive volcanism. All known rocks of this age in the Central and Southern Appalachians have been metamorphosed at least once and appear to be generally characterized by low heat production.

A more distinct pattern appears to have emerged in the igneous and metamorphic history beginning in Ordovician time, about 480 - 425 m.y. ago. In the eastern foothills of the Carolina Blue Ridge and in the <u>western</u> Piedmont of the Carolinas and Virginia, granitic and gabbroic plutons were emplaced during a regional metamorphism that probably ended abruptly as a result of cooling by deformation, uplift, and erosion during the Taconic Orogeny. If the eastern Piedmont was affected by this metamorphism, large regions (the Carolina Slate

Belts) were never raised above low temperatures and pressures (greenschist grade). Additionally, there are probably few or no Taconic age plutons in the eastern Piedmont south of about Fredricksburg, Virginia.

By latest Ordovician and Silurian time, approximately 400 m.y. ago, a few gabbroic and granitic plutons were injected along the central axis of the Piedmont in the Carolinas. Ductile deformation affected some of these plutons, which suggests that regional metamorphism may have continued from the Taconic event or may have migrated eastward with the plutonic activity. The intensity of igneous and metamorphic activity thus far recognized seems diminished by comparison with the Taconic evidence for relative crustal stability at this time recorded in Silurian rocks of the Valley and Ridge.

Late Devonian to Pennsylvanian time saw the central axis of metamorphism and plutonic intrusion migrate into, or at least reach an intensity maximum, in the eastern Piedmont. Dating of this metamorphism suggests a thermal maximum at about 350 - 300 m.y. ago (Acadian Orogeny). The metamorphism diminishes westward into the Blue Ridge where it partially overprints the earlier Taconic metamorphism. It was accompanied, mostly during its waning stage, by widespread plutonism over a span of about 330 to 260 m.y. ago. This produced a very large (ca. 60) group of syn- to post-metamorphic granitic plutons. These Late Paleozoic granites are most abundant along the Fall Line south of Richmond, Virginia, and in Georgia they trend westward into the region south of Atlanta. This westward trend in Georgia appears to be somewhat concordant with Late Paleozoic regional structural features that may link the Appalachians with the Ouachitas.

Because the 350 m.y. Acadian regional metamorphism was the last major metamorphic event to affect the eastern Piedmont, granites of this age or younger have generally retained much of their U and Th. Thus they are the best known sizable group of heat generating plutons south of New England. They commonly produce two or three times as much heat as their older metamorphosed counterparts and the enclosing country rocks.

From the above, the basic pattern in Middle and Late Paleozoic time was eastward migration of the axis of igneous and metamorphic activity. Thus it is natural to ask whether the trend continues in the basement below the Atlantic Coastal Plain. The answer is - possibly - yes. Within the past year several researchers have discovered ductile deformation overprinting young plutons in the easternmost parts of the Piedmont. If this foreshadows discovery of another still younger generation of plutonic and metamorphic activity under the Coastal Plain, we must determine this and also whether these rocks will have a comparable range of heat generation.

A second pattern is emerging from Piedmont studies that may help in exploring the Coastal Plain basement for heat sources. The Late Paleozoic metamorphic-plutonic age province in the eastern Piedmont is subdivided into several NE-trending belts that have been recognized for many years. Some of these belts are: Charlotte, Carolina Slate, Raleigh, Kiokee, Eastern Slate, etc. The basic rationale for recognizing such belts has involved considerations of the relative intensities of matamorphism, plutonism, and deformation. It now appears that low-metamorphic-grade belts are generally syn-formal (downwarped) and are only marginally injected by plutons in the age range of latest metamorphism. Much of the downwarping occurred during the protracted period of metamorphism-plutonism, and the low grade terrains, being more rigid than adjacent high grade (and higher temperature) terrains, resisted injection by granite. Those granites that did manage to inject the margins of these low grade (Carolina Slate) belts tend to be circular in surface outcrop and to have inverted teardrop or spike-like shapes. Thus their gravity and magnetic signatures also tend to be somewhat distinct.

Belts of high metamorphic grade, and therefore of greater ductility at the time of metamorphism, have antiformal (upwarped) shapes and contain large concentrations of granite generated during the time of metamorphism and upwarping. Structural studies strongly suggest wholesale migration of ductile country rock (the "pudding") and granitic magma (the "plums") into the crests of high grade belts and away from the bottoms of downwarping lowgrade belts. If this hypothesis proves true, high grade belts (unless very deeply eroded) should have higher heat generation than low grade belts because of the greater concentration of granitic magma emplaced during the last metamorphic-plutonic event. Additionally, granites coeval with the last metamorphism in these higher grade belts tend to be larger and more nearly concordant than plutons that penetrated more rigid crust. Thus these large bodies of magma, such as the Rolesville and Petersburg, may be 50 - 60 miles long and 20 - 30 miles wide, and locally surrounded by haloes of mixed rocks (migmatites) of granite and country rock. Such bodies tend to produce large elliptical regional gravity lows and may also be outlined by magnetic surveys.

Extrapolation from these Piedmont trends suggest that we might expect to find: 1) a continuation of this pattern of alternating high- and low-grade belts in the basement under the Atlantic Coastal Plain; 2) a concentration of the granites having highest heat production in and marginal to the high grade belts; 3) a possibility of even younger metamorphism and plutonism with heat production ranges different from those measured in the Piedmont. By combining indirect (magnetic, gravity, seismic) and direct (heat flow measurements from shallow and deep Coastal Plain wells, geologic and geophysical studies of selected basement cores) methods we can develop a knowledge of the basement that will eventually allow more routine selection of geothermal sites over buried granites of high heat production. Although a beginning has been made by the U.S.G.S. (high and low grade belts do exist under the Coastal Plain in North Carolina), VPI&SU, Princeton, and several state surveys, much work remains to be done, particularly in obtaining basement core samples to control geophysical-geological extrapolations on a regional basis.

Before leaving this discussion of the Paleozoic development of the Atlantic Coastal Plain basement, the anomalous crust beneath southern South Carolina, and much of Georgia and Florida merits some attention. In this region the familar schistosity of the northern basement and Piedmont is missing. Poorly dated, very low grade volcanics near the Georgia coast are probably Early Paleozoic or Eocambrian in age, and near the Georgia-Florida border, unmetamorphosed, nearly horizontal Early and Middle Paleozoic sedimentary rocks are found in the basement. Much of this is overlain by Early Mesozoic nonmarine sediments and basaltic lavas. Seemingly these differences are best explained by suturing another continental fragment onto the North American Plate during the late Paleozoic. Whatever the cause, the obviously different geologic history of this segment of the present continent suggests the possibility of different heat production-heat flow characteristics.

Finally, Mesozoic and younger lineaments transverse (W to NW trending) to the regional Appalachian trend might in some areas exert a strong influence on heat flow and heat production. Probably there are diffuse but deep fracture zones that extend to the lower crust or mantle. In New England, they are characterized by offshore subsea volcanoes, anomalous seismicity, and Late Paleozoic-Mesozoic emplacement of alkalic granite and gabbro (?) plutons. The Conway Granite, belonging to this trend, has the highest heat flow recorded from a granite of comparable size in the Appalachians. In Virginia, numerous westerly aligned features suggest a similar lineament. Examples are the WNW trending offshore Norfolk scarp, the west trending central Virginia seismic zone, and the Mesozoic to Early Tertiary alkalic shallow intrusives in the Valley and Ridge of Highland County, central western Virginia which also have high U-Th contents. In South Carolina a similar feature passing NW through Charleston has been described by Columbia University and U.S.G.S. researchers.

Study of the Pre-Cretaceous Basement Below the Atlantic Coastal Plain

Richard Gleason

Introduction

As has been discussed in previous reports, the investigation of low-temperature geothermal energy resources in the Atlantic Coastal Plain relies upon an understanding of 1) the lithology and structure of the crystalline rocks ("basement") below the Coastal Plain sediments and 2) the thickness and lithology of the overlying sediments. The former types of data, basement lithology and structure, are necessary to interpret the heat production from basement heat sources, while the latter type of data concerning the overlying sediments are fundamental to the evaluation of the insulating properties of the Coastal Plain sedimentary sequence.

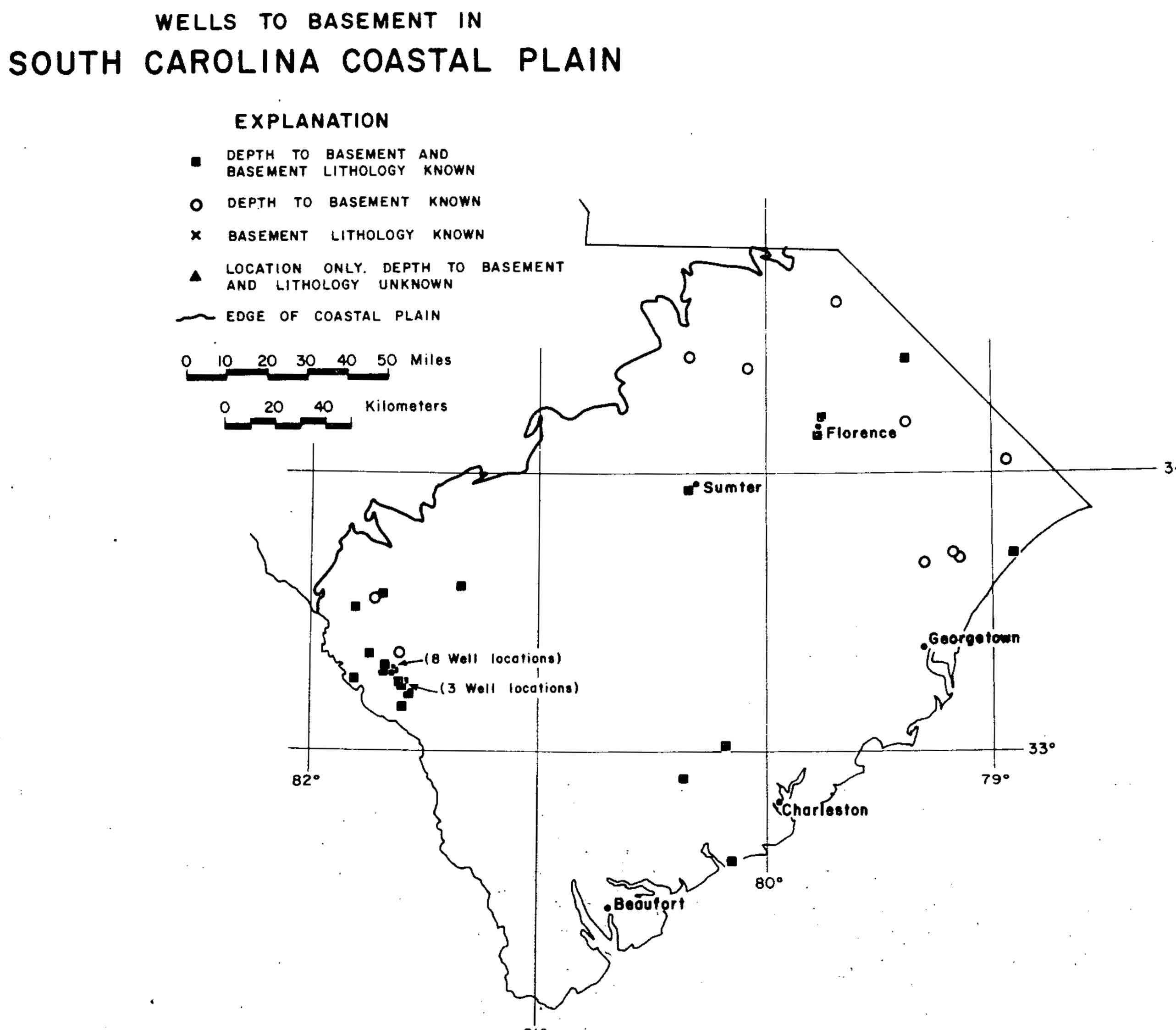
Basement depth and lithologic information may be obtained from geophysical data such as seismic investigations and regional gravity or magnetic studies, or through subsurface drilling data. A considerable amount of drilling data has been published in the geologic literature, including professional journals, oil and gas exploration reports, U.S. Geological Survey publications, and state survey publications. A previous progress report (VPI&SU-5648-5) included a discussion of the ongoing compilation of basement drilling data, which at the time was complete for the states of New Jersey, Maryland, Delaware, Virginia, North Carolina, and Georgia. The following discussion is a summary of the compilaton of drilling data for South Carolina.

South Carolina

A considerable portion of the pre-Coastal Plain surface in South Carolina is comprised of arkosic sedimentary rock or basalts highly suggestive of rocks exposed in the Triassic-Jurassic grabens of the eastern United States (Marine and Siple, 1974; Marine, 1974; Gottfried et al., 1977; Popenoe and Zietz, 1977; Gohn et al., 1978). For the purpose of this compilation, these rocks are considered as pre-Cretaceous basement.

Thirty-six wells which were drilled through the entire Coastal Plain sedimentary sequence have been included in the South Carolina compilation (Figure B-1). These wells are unevenly distributed across the South Carolina Coastal Plain, with a large number clustered near the Savannah River atomic energy facility in the southeastern part of the state. Descriptions of basement lithology have been found for twenty-six of the thirty-six wells. Depths to basement have been compiled for all thirty-six of the wells.

Figure B-1. Map showing location of wells drilled to basement in South Carolina and included in the South Carolina compilation.



REFERENCES

Gohn, G. G., Gottfried, D., Lanphere, M. A., and Higgins, B. B., 1978, Regional implications of Triassic or Jurassic age for basalt and sedimentary red beds in the South Carolina Coastal Plain; Science, vol. 202, p. 887-890.

Marine, I.W., and Siple, G. E., 1974, Buried Triassic basin in the central Savannah River area, South Carolina and Georgia; Geol. Soc. America Bull., v. 85, p. 311-320.

Marine, I. W., 1974, Geohydrology of buried Triassic basin at Savannah River plant, South Carolina; Amer. Assoc. Petrol. Geol. Bull., v. 58, p. 1825-1837.

Popenoe, P., and Zietz, I., 1977, The nature of the geophysical basement beneath the Coastal Plain of South Carolina and northeastern Georgia; U.S. Geol. Survey prof. paper 1028-I, p. 119-137.

Petrography of the Granitic Basement (portion of the) DO-1 Drill Hole in the North Carolina Coastal Plain[1]

S. W. Becker

Introduction

Approximately thirty syn- and post-metamorphic plutons crop out in the southeastern U.S. Piedmont in a belt trending northeast from Georgia to Virginia. Most of the granites in the exposed Piedmont produce closed, nearly circular gravity lows. Gravity studies over the Coastal Plain in eastern North Carolina and Virginia have outlined similar gravity anomalies, suggesting that additional granites underlie the coastal plain sediments. One of the most prominent gravity lows (-20 mgal) straddles the North Carolina-Virginia border near the community of Dort, NC (Figure B-2). As part of an ongoing study of granites in the southeastern Piedmont, a hole was drilled to basement near the center of the Dort anomaly. Basement was encountered at 1060 feet; 287 feet of continuous core was recovered, to a depth of 1347 feet.

Lithology

The recovered core is a grey, coarse-grained amphibole-biotite granite that has been subjected to varying degrees of brittle fracture and alteration (Figure B-3). Minerals visible in hand specimen include subhedral, pale pink K-feldspar, 0.5 - 2.0 cm long; subhedral to anhedral plagioclase up to 1.5 cm long; quartz grains up to 1.0 cm long; and biotite flakes, 0.1 - 0.5 cm across. Color index (C.I.) ranges from 8 to 15. Most plagioclase grains are saussuritized and tinged pale green. In a few segments of the core, the alignment of biotite and K-feldspar defines a moderately to steeply dipping foliation which varies from weak to strong.

Locally the granite is cut by small pegmatite and aplite dikes composed of quartz plus two feldspars. Near the bottom of the core, several mafic clots up to 20 cm across are included in the granite.

Petrography

In thin section, K-feldspar appears as microperthitic microcline clouded red-brown. According to microprobe analyses, bulk compositions average $An_0Ab_8Or_{92}$. Plagioclase is unzoned and has an average composition of $An_{20}Ab_{79}Or_1$; it shows both Carlsbad and albite twinning. The plagioclase is generally saussuritized to epidote ± chlorite ± carbonate ± white mica. In most grains, the epidote is strongly concentrated near the core, suggesting that the original plagioclase

----

[1]This paper will be submitted for publication to "Southeastern Geology".

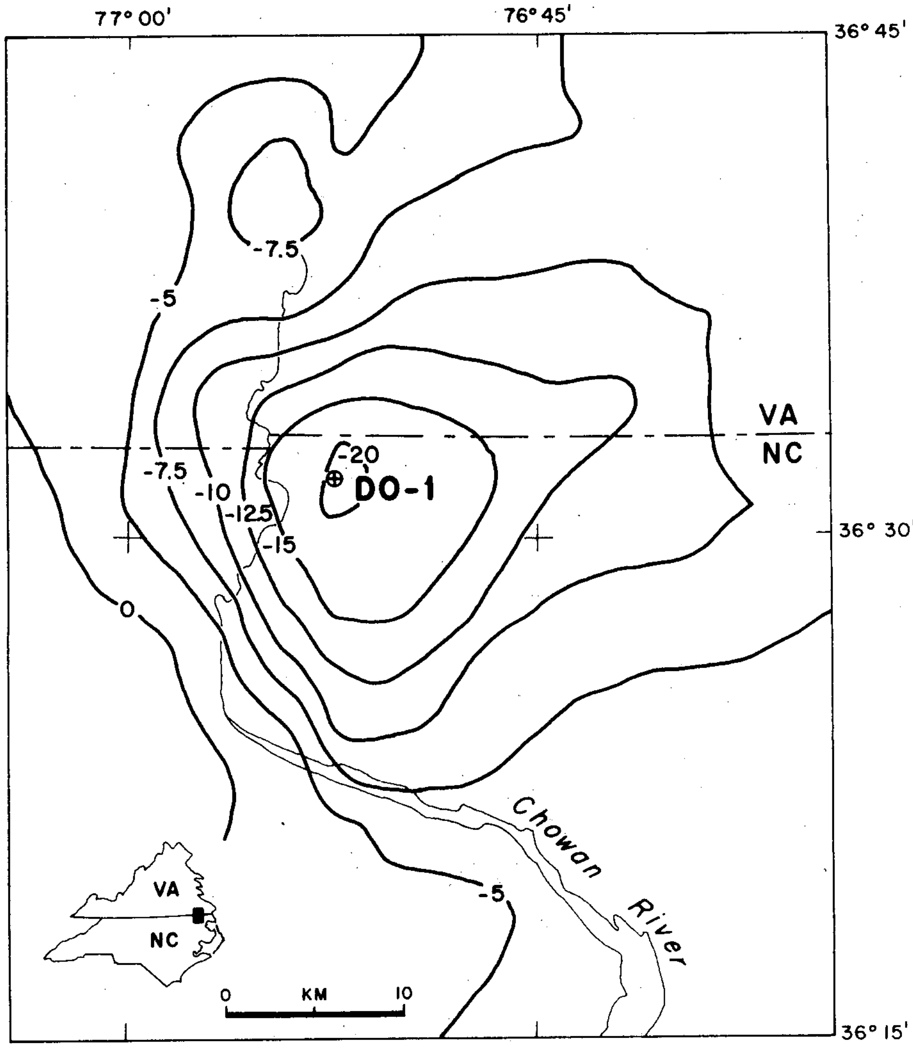


Figure B-2. Location map for DO-1 showing gravity contours determined by the U.S.G.S. (1976).

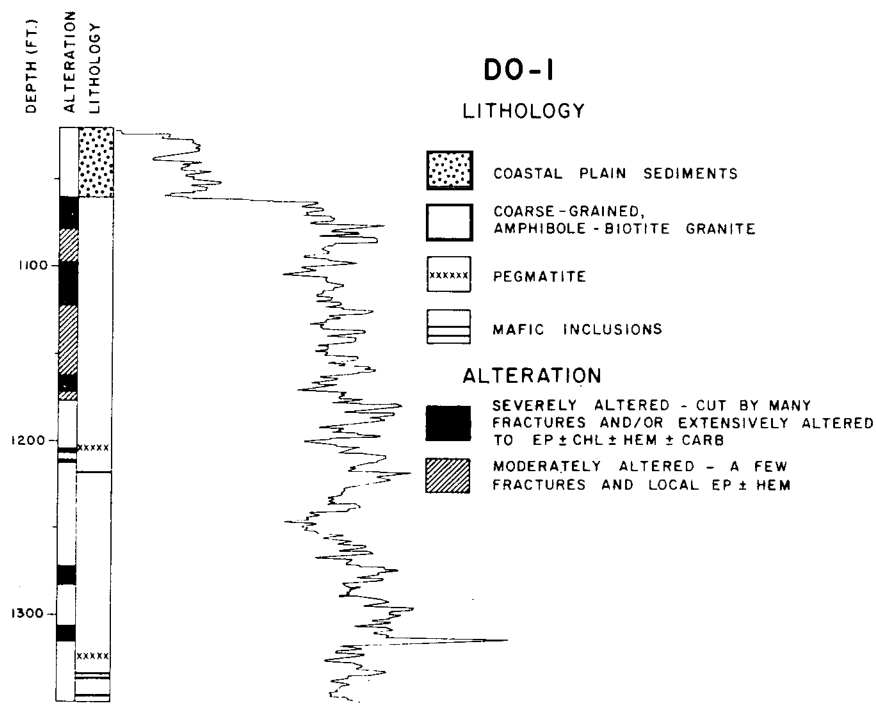


Figure B-3. Lithologic and gamma logs of DO-1.

was normally zoned. Quartz grains have undulose extinction; myrmekite occurs locally.

Biotite is pleochroic tan to dark brown or dark olive green. Compositions plot near the center of biotite compositions determined for postmetamorphic plutons in the exposed Piedmont (Figure B-4; Speer et al., 1979). Chlorite has partially replaced biotite in even relatively unaltered rocks, and epidote occurs along the cleavage planes of scattered biotite grains. Anhedral amphibole comprises §1% of the fresh samples (e.g. DO-1114); it does not occur in many parts of the core because of the extensive alteration. The amphibole is pleochroic: X = tan, Y = yellow-green, Z = blue-green, with 2V - 65°. Following the nomenclature of Leake (1978), it is a potassian ferroan pargasitic hornblende (Table B-2).

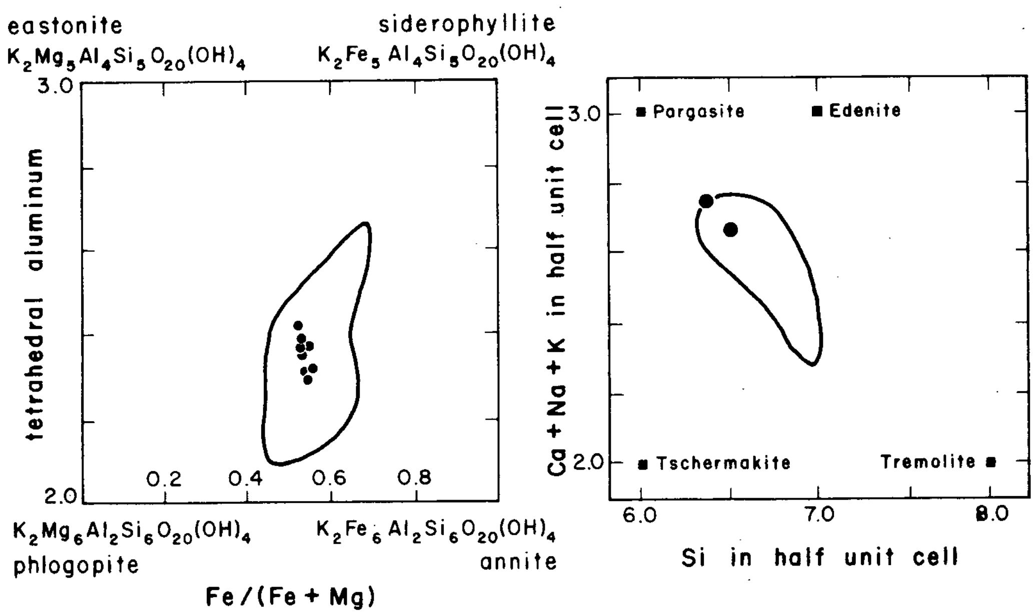


Figure B-4. A - Plot of biotite analyses; B - amphibole analyses. In each diagram, the lines enclose compositons of the respective phases in post-metamorphic granites in the exposed southeastern Piedmont (Speer et al., 1979).

TABLE B-1. Modes of samples from DO-1

	D01-1075	D01-1079	D01-1114
Quartz	28.8	27.9	33.1
K-feldspar	22.5	17.2	18.4
Plagioclase	39.0	39.9	33.6
Biotite + chlorite	8.9	12.6	13.2
Amphibole	-	-	0.3
Epidote	0.4	0.2	tr
Titanite	0.4	2.2	1.1
Opaques	tr	tr	0.2
Accessories	tr	tr	0.1
no. points	1450	1450	1450

TABLE B-2. Microprobe Analyses

	1		2		3	
SiO_2	48.5		36.7		28.7	
TiO_2	0.5		1.7		0.0	
Al_2O_3	11.1		14.9		18.7	
FeO*	22.1		22.2		21.7	
MgO	7.3		10.5		18.2	
MnO	0.4		0.3		0.7	
CaO	11.1		0.0		0.0	
Na_2O	1.7		0.1		0.0	
K_2O	1.6		9.8		0.0	
H_2O**	1.9		3.9		11.7	
Sum	99.5		100.0		99.7	
Si	6.49	8.00	5.64	8.00	2.94	4.00
Al_t	1.51		2.36		1.06	
Al_o	0.52		0.34		1.20	
Ti	0.06	5.00	0.20		0.00	
Fe	2.86		2.85		1.86	
Mg	1.68		2.41	5.84	2.79	
Mn	0.06	2.00	0.04		0.06	
Ca	1.84		0.00		0.00	5.91
Na	0.52	0.85	0.02	1.93	0.00	
K	0.31		1.91		0.00	
O	24.00		24.00		24.00	

1 Amphibole, D01-1114
2 Biotite, D01-1114
3 Chlorite, D01-1122-5
* All Fe as FeO
** H_2O calculated

Analyses plot within the cluster of analyses from southeastern U.S. postmetamorphic granites (Figure B-4) (Speer et al., 1979).

Primary accessory minerals include titanite, apatite, opaques, zircon, and allanite. Some titanite grains enclose a corroded opaque core, suggesting that some of the titanite formed by a reaction that consumed oxides. In all but the freshest samples, titanite is partially altered to carbonate + a dusky opaque mat, probably rutile + quartz. Allanite, which is usually altered, occurs as zoned, prismatic crystals up to 0.3 cm long.

Secondary minerals comprise chlorite, epidote, and calcite. Epidote, the most abundant, is optically negative with 2V = 80-85°, r † V; it is pleochroic colorless to yellow-green. The chlorite (Table B-2) can be classified as a pycnochlorite.

The mineralogy of the mafic clots is the same as that of the granite, with greater amounts of dark minerals, and C.I. about 40. Biotite is present in higher proportions than amphibole. Most mafic clots are finer grained than the granite, with grain size of the major minerals ranging from 0.1 to 1.0 cm.

Fractures

The core is cut by numerous fractures of at least two generations: (1) steeply dipping fractures (0.1 - 1.0 cm wide) filled with calcite ± epidote ± chlorite; and (2) horizontal fractures (0.1 - 0.2 cm wide) filled with calcite alone. Fractures of the second generation cut and clearly postdate those of the first.

In the vicinity of the first generation fractures, the granite is altered and green for a distance of 10 to 20 cm from the fracture. Where the core is cut by numerous fractures, the alteration zones associated with the fractures overlap, so that the core may be continuously altered over a distance of more than a meter. Thin sections show that the pervasive green color of the alteration zones is caused by the presence of abundant epidote and chlorite, which entirely replace biotite and amphibole. Titanite grains, with euhedral outlines still distinct, are completely altered to turbid mats containing clots of opaque minerals. Sericitization and saussuritization are extensively developed in plagioclase, and calcit appears as the most abundant saussuritization product.

The fractures themselves are generally filled with calcite, which in some samples encloses islands of epidote. Some calcite-filled fractures are lined with chlorite. In one sample (DO1-1122), a few chlorite grains contain cores of blue fluorite.

The second generation fractures are filled with calcite, and no alteration of the adjacent granite mineralogy is apparent.

Deformation

The Dort granite has undergone several periods of deformation. After intrusion, during cooling, the granite appears to have been mildly deformed and recrystallized. This episode of high temperature healing is suggested by the aggregates of fine-grained quartz and feldspar grains that fill interstitial areas and border large feldspar crystals.

After the granite cooled, it was subjected to two periods of brittle fracture. During the first episode, steep fractures formed and hydrothermal fluids rich in CO_2-H_2O-F circulated through the fractures, and altered minerals in the adjacent granite to greenschist facies assemblages. During the second episode, the granite was fractured along nearly horizontal planes. CO_2 - rich fluids filled the fractures with carbonate, but had little effect on the granite mineralogy.

At a later time, the granite was uplifted, eroded, and covered by Coastal Plain sediments.

Comparison to Other Piedmont Granites

Petrographically, the Dort granite closely resembles the Petersburg, VA granite which crops out as close as 75 km to the northeast. Samples from the Petersburg granite show textures similar to those of the Dort granite that are indicative of mild deformation at high temperature (Bobyarchick, 1978). In both granites, biotite is the dominant mafic mineral; amphibole occurs in minor amounts in both the Dort granite and some phases of the Petersburg granite.

Conclusions

The basement rock producing the Dort, NC, gravity anomaly is a coarse-grained granite which resembles petrographically the synkinematic Petersburg, VA, granite. The similarity of the two granites suggests that granites like those in the exposed Piedmont occur to the east under the Coastal Plain. In addition, the discovery of a granite under a pronounced gravity low demonstrates that gravity data can be used as an indication of the lithology of basement rocks beneath Coastal Plain sediments.

Acknowledgements

This paper stems from an investigation of low-temperature geothermal resources that is supported by the U.S. Department of Energy Contract No. ET-78-C-05-5648 awarded to J. K. Costain, L. Glover, III, and A. K. Sinha. The paper benefitted from review by J. A. Speer and S. S. Farrar.

References

Bobyarchick, A.R., 1978, Reconnaissance geologic setting of the Petersburg granite and regional geologic framework for the Piedmont in southeastern Virginia: Prog. Rep. VPI&SU-5648-4 prepared for D.O.E. contract no. ET-78-C-05-5648, p. A2 - A37.

Leake, B.E., 1978, Nomenclature of amphiboles: Am. Mineral 63, 1023 - 52.

Speer, J.A., S.W. Becker, and S.S. Farrar, 1979, Field relations and petrology of the postmetamorphic, coarse-grained granites and associated rocks in the southern Appalachian Piedmont (in this report).

U.S.G.S., 1976, Gravity map of the Norfork 2° sheet.

Field Relations and Petrology of the Postmetamorphic, Coarse-grained Granites and Associated Rocks in the Southern Appalachian Piedmont[1]

J. Alexander Speer, Susan W. Becker, Stewart S. Farrar

Orogenic Studies Laboratory
Department of Geological Sciences
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

INTRODUCTION

Many of the postmetamorphic granitoids in the southeastern U.S.A. are generally similar in appearance, and can be characterized by the presence of a coarse-grained facies with K-feldspar megacrysts. They form a subset of plutons whose field relations, mineralogy, and petrology are described here. The distinct nature of these plutons was first noted by Watson (1,2), who described the mineralogy, petrography, and chemistry of twelve plutons. The similar petrographic aspects are a result of the common granitic compositions and nearly parallel crystallization histories of the plutons. Features such as contact aureoles, flow layering, and differing rock facies that are not common to all of the granites probably result from the plutons' different geologic settings.

FIELD RELATIONS

Distribution and Geologic Setting

The twenty-four separate granitoid bodies (Figure B-5) that comprise the postmetamorphic, coarse-grained plutons possess the properties of a supergroup, described by Pitcher (3): they are similar in age, texture, degree of modal variation, and they have similar xenoliths. The number of granitoids in this group will probably increase as more is learned about the other postmetamorphic plutons. The Elberton, Georgia, complex contains rocks like those described here, but, as presently mapped, also contains older rocks. The Cuffytown Creek, SC, pluton is apparently the differentiated cupola of a large pluton (4), the main facies of which may be a coarse-grained granitoid; the Columbia, SC, granitoid contains what are possibly autoliths of a coarse-grained granite.

----

[1]This paper has been submitted for the International Geological Correlation Program, Caledonide Orogen Project Proceedings Volume, VPI & SU Memoir #2.

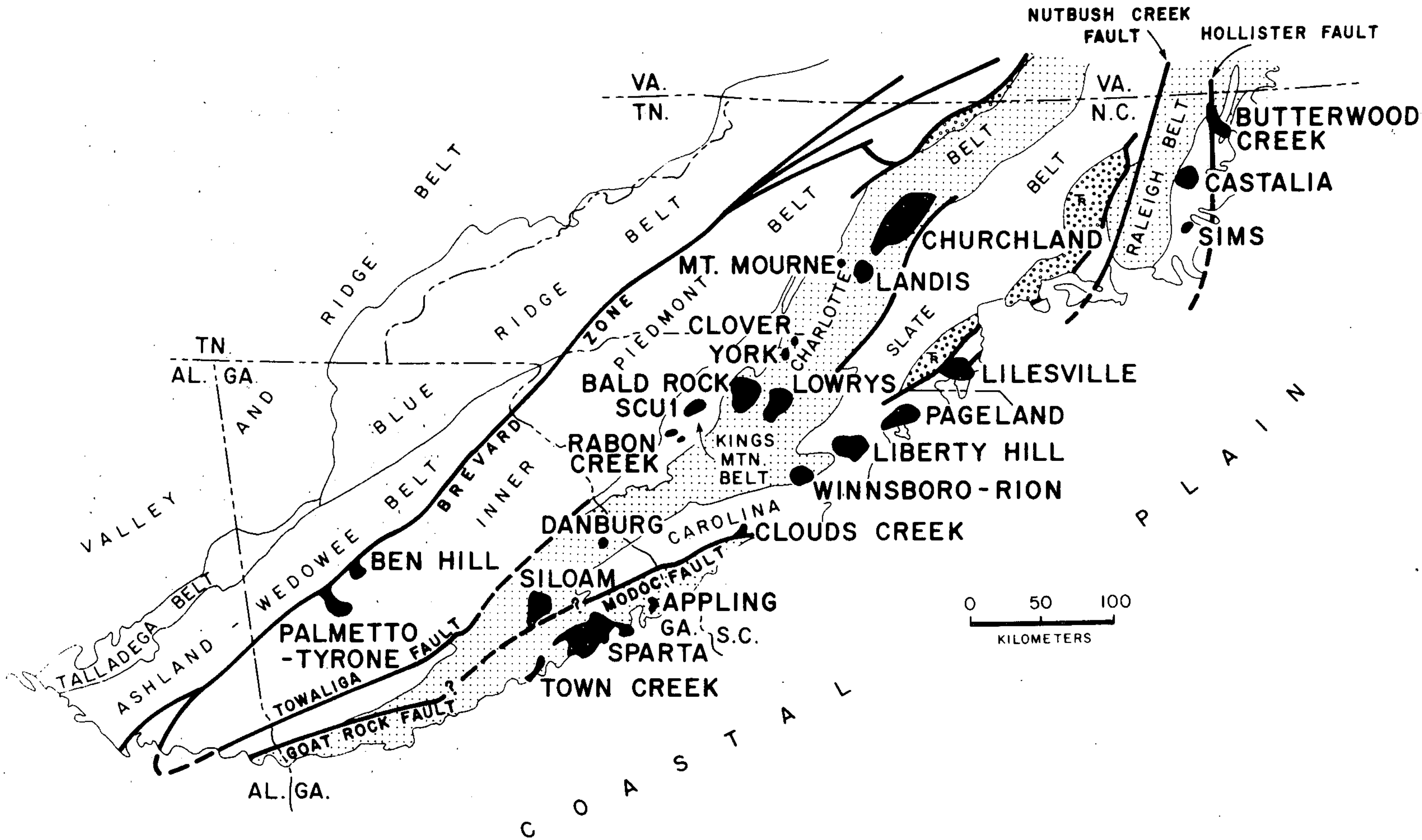


Figure B-5. Geologic setting of the postmetamorphic, coarse-grained granitoid plutons in the southern Appalachian Piedmont.

Fullagar and Butler (5) divided the post metamorphic plutons into eastern and western groups. The only difference they noted, other than geographic distribution, is the higher Sr content of the western group.

The coarse-grained granitoid plutons extend to the eastern edge of the exposed Piedmont, beyond which the crystalline rocks are covered by Coastal Plain sediments. Geophysical data suggest that some rocks below the Coastal Plain sediments are similar to the coarse-grained granitoids exposed in the Piedmont. Drill cores recovered from Coastal Plain basement indicate that a number of these bodies are coarse-grained granite plutons.

The plutons crop out in every major lithologic-structural belt of the Piedmont east of the Brevard zone (Figure B-5). The belts, through their diverse structure, composition, and metamorphic grade, provided varied geologic settings for the granitoids. The Inner Piedmont belt is composed of migmatites, gneisses and schists of amphibolite or higher facies. The Kings Mountain belt is predominantly metasedimentary rocks in the greenschist to amphibolite facies. The Charlotte and Raleigh belts consist largely of metamorphosed felsic to mafic igneous rocks and metasedimentary rocks, all in the amphibolite facies. The Carolina Slate belt consists dominantly of intermediate to felsic pyroclastic deposits and hypabyssal intrusive bodies, as well as epiclastic rocks that were probably derived from them. Rocks of the Carolina Slate belt have been subjected to greenschist facies metamorphism, although sedimentary and igneous textures have commonly been preserved. These country rocks surrounding the granitoids are older than mid-Paleozoic. The youngest regionally penetrative deformation and regional metamorphism that affected the southeastern Piedmont occurred near the end of the Paleozoic and is confined to the easternmost Piedmont (6,35). The isotopic ages of metamorphism become older to the northwest across the exposed Piedmont and are believed to be cooling ages (36). In all cases deformation ceased prior to the emplacement of the coarse-grained granitoids.

Geometry of the plutons

The granitoid plutons are generally elliptical to circular in outcrop (Figure B-6) and range in size from the numerous small stocks of the Ben Hill to the Churchland at over 400 km^2. Previously published pluton maps used to compile Figure B-6 are the Clouds Creek (6), Clover (7), Lilesville (8), Lowrys (9), Pageland (10), Rabon Creek (9), and York (7). Most of the plutons are composite bodies with at least two mappable rock facies, and as many as six in the Siloam. Small volumes of other rock types, such as aplite or pegmatite, are commonly present. Facies are differentiated on the basis of differing mineralogies, textures, grain-sizes, modes, or the presence or absence of euhedral K-feldspar megacrysts. Textural varieties are usually also distinct in both mode and mineralogy. Contacts between the facies may be either intrusive or gradational. An intrusive relation is common between facies differing primarily in texture and mineralogy. Contacts between facies differing only in mineralogy, how-

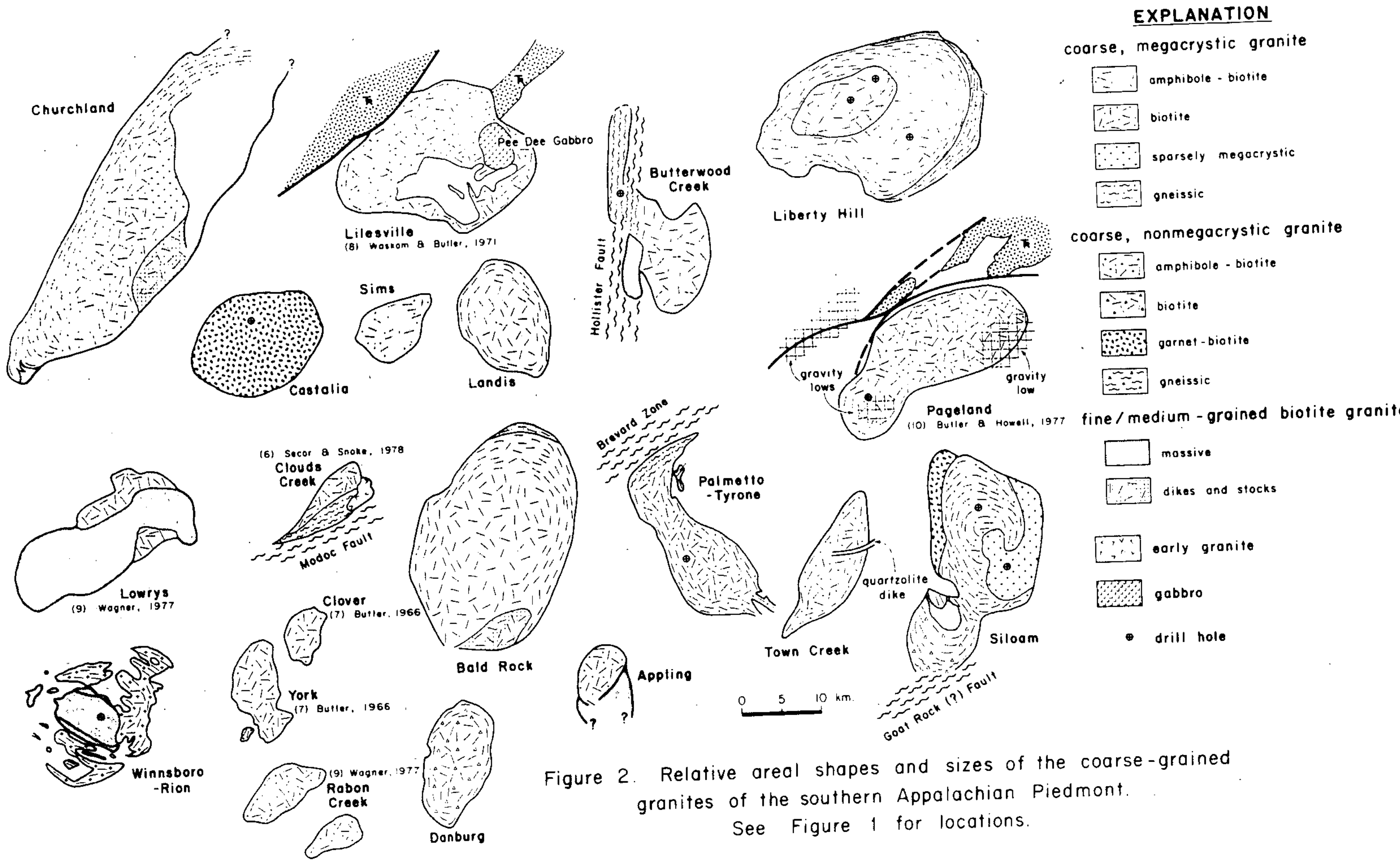


Figure 2. Relative areal shapes and sizes of the coarse-grained granites of the southern Appalachian Piedmont. See Figure 1 for locations.

ever, are usually gradational, and are believed to be caused by physical-chemical gradients extant during or after crystallization.

In many of the plutons, a coarse-grained facies was intruded by a later, fine-grained granitoid. This relation appears in the Appling, Bald Rock, Butterwood Creek, Churchland, Lowrys, Liberty Hill, Siloam, Town Creek, and Winnsboro. Gradational contacts between facies have been noted in the Bald Rock, Danburg, Landis, Liberty Hill, Pageland, Siloam, and Winnsboro. Uniform rock bodies, as presently mapped, are the Castalia, Clover, Lilesville, Palmetto, Panola, Sims and York. The Clouds Creek and Siloam contain an extensive facies that consolidated earlier than the main, coarse-grained facies. In the Winnsboro-Rion and Butterwood Creek, this early facies is a minor component. In the other plutons, these earlier facies are present in rare autoliths.

These facies distinctions are well illustrated in the Liberty Hill, which comprises three texturally and mineralogically distinct facies (Figure B-6). The predominant facies is a central core of very coarse, biotite-amphibole granite and quartz monzonite. The second facies, which grades into the first and occurs along the margin of the pluton, is a very coarse biotite granite. On the north, this border facies contains much larger K-feldspar phenocrysts and prominent flakes of muscovite. Work on mineral chemistry of the xenoliths and granite suggests that this geometry results from a radial variation in intensive parameters (most likely T, fO_2 and fH_2O) within the granite. The youngest facies is a fine- to medium-grained biotite-muscovite (?) granite that intruded the western part of the pluton in the form of large dikes and small stocks. This third facies had a higher fluid pressure as evidenced by the mineralogy.

The granitoids exhibit a variety of internal structures which are interpreted to be igneous flow features. These structures are important in determining late movement of the magma, the shape of the magma chamber, and mechanisms of final emplacement. The best developed and most widespread feature is layering defined by tabular K-feldspar and plagioclase crystals. The feldspars are elongate parallel to $\underline{c}$, and a lineation parallel to the dip of the layering can be locally detected. Modal mineral layering, variably developed, occurs as contrasting amounts of mafic minerals or K-feldspar megacrysts. This type of layering ranges from several centimeters to meters in thickness and occurs as sheets or lenses. Size-graded layering occurs in lenses less than 5 cm thick. Tabular enclaves parallel the other types of layering, and, where grouped, the enclave trains are aligned parallel to the foliation. Schlieren, whether presumed to be smeared xenoliths or early crystallized minerals, are also aligned.

The attitudes of the internal features, and the geometric relations between facies within a pluton, show that the multiple-intrusive complexes are arcuate and nested. The circular forms are not as well developed as in ring dikes or cone sheets, but the plutons do have a center of intrusive activity, and can be described as "centered complexes".

A facies formed from a single pulse of magma can be recognized by its overall homogeneity and lack of internal contacts. Whether the separate magma batches are cogenetic in all cases has yet to be determined.

The 3-dimensional shapes of the plutons can be derived either from the attitudes of internal flow features or from geophysical models. Flow features in plutons which have been studied suggest the following 3-dimensional geometries:

Bald Rock:	a steep-walled, elliptical pipe
Danburg:	an elliptical, asymmetric funnel with steep flow features on the north and shallower features in the south
Landis:	a steep-walled, elliptical pipe
Liberty Hill:	a nearly circular asymmetric funnel with steep dips in the north and shallower dips in the south
Palmetto:	an asymmetric, crescentic pipe dipping ENE
Siloam:	an irregular, composite pipe-like body with near-vertical flow features
Town Creek:	a steep-walled, crescentic pipe

Only 3 plutons have been modeled using geophysical data:

Liberty Hill (11):	steep, inward-dipping contacts, somewhat shallower on the southern edge; depth about 6 km
Lilesville (8):	a circular sheet up to 2.8 km thick, deeper on the northwest, thinning around what is interpreted to be the floor exposed in the center
Pageland (11):	three steep-walled funnels: two coincide with the exposed granite; the third lies to the northwest of Triassic faults and is presumed to be a buried portion of the pluton.

Contact relations

Contact relations are difficult to observe due to the lack of outcrop, but some features can be noted. Contacts between the country rock and granitoids are sharp on an outcrop scale but appear to be lit-par-lit over tens of meters. Aside from rare satellite bodies, swarms of dikes and sills do not emanate into the country rocks, although thin granite dikes dipping inward toward the pluton exist where the granite has been emplaced in relatively massive crystalline rocks. Structures in the country rock are disturbed within about 200 m of the granite contact, but appear to be little affected by the plutons at greater distances. Structures in the country rock of the Lilesville are particularly interesting because the outer aureole has a static metamorphic fabric, whereas the interior contact metamorphic rocks, interpreted to be the floor of the pluton, have a highly contorted gneissic fabric, suggesting that the floor was deformed by the upward movement of the magma.

Variations in the coarse-grained granitoids from center to rim depend on the nature of the magma-wall rock interactions. Most commonly, xenoliths increase in size and abundance toward the rim. Grain size also changes locally at the contacts of some plutons. A finer-grained facies with phenocrysts of plagioclase, quartz, biotite, and K-feldspar occurs along one contact of the Pageland. More commonly, the K-feldspar megacrysts are larger near the contacts than in the interior of the pluton. Changes in major or accessory mineralogy at the contact are also common. For example, amphibole may be absent in amphibole-bearing plutons or abundant muscovite may appear. These differences can be explained by the exchange of fluid between the country rock and magma, but major-element contamination of the granites is apparently not significant. One exception is found at the northeast corner of the Winnsboro, where the normally felsic, coarse-grained granite (CI=5) digested amphibolite and biotite gneiss to become a more mafic (CI=10-20), plagioclase-rich granite. Exchange of trace elements and isotopes between the granitoids and country rocks has not yet been explored.

<u>Granitoids in major fault zones</u>

Four of the plutons lie in or across major late deformation zones of the southern Piedmont (Figures B-5 & B-6). The Clouds Creek is adjacent to the Modoc fault (6). The Butterwood Creek is cut by the Hollister fault. The Palmetto-Tyrone is adjacent to the Brevard zone; the deformation in these rocks is described in more detail by Higgins (12,13), whose accounts of the "Palmetto granite" actually describe the Ben Hill Pluton and other granitoid country rocks. The southern tip of the Siloam has developed deformational features similar to those of other granitoids near fault zones. Although no deformation zones have been mapped in the vicinity of the Siloam, the Goat Rock and Modoc faults have been extrapolated into that area (e.g. 14).

The granitoids associated with deformation zones vary widely in texture, from rocks showing incipient deformation through augen gneiss to mylonite and blastomylonite. An outstanding feature of the deformed granitoids is the crystalloblastic texture seen in thin section. The mineralogy and modes of the deformed rocks are identical to those of the undeformed rocks. This similarity, and the recrystallized textures, suggest that the granitoids were deformed and recrystallized while the rocks were at relatively high temperatures and that no subsequent movement involving the granitoids occurred at lower temperatures. The granitoids, while at elevated temperature, may have "lubricated" the faults. An exception to these observations is the Clouds Creek, which, with its contact aureole, appears to have undergone a pervasive hydrothermal recrystallization subsequent to crystallization. The intensity of deformation in the granitoids may change within a small area and does not always vary systematically with distance from the faults. This suggests that, during a short time interval, approximately coincident with the intrusion of these granites, intense deformation occurred in narrow zones separated by broad zones which suffered little or no deformation.

Mesozoic faulting occurred in the Lilesville, Pageland, and Liberty Hill. The Lilesville is cut by the border faults of the Wadesboro and Ellerbe Triassic basins. The Liberty Hill and Pageland are cut by what may be extensions of these faults (10,11). A buried part of the Pageland, at lower elevation than the rest of the pluton, lies in what may be a down-thrown block north of the Pageland fault (Figure B-6). Effects of Mesozoic and later brittle faulting are rarely seen on the surface, but are frequently encountered in drill holes. Hydrothermal alteration associated with the faulting produced mineral assemblages which include calcite + quartz + hematite + laumontite + K-feldspar + albite. Contemporaneous fissure veins have the same assemblage with minor amounts of pyrite, chalcopyrite, chlorite, and fluorite. A vein in the Palmetto-Tyrone pluton consists of thomsonite and gypsum, formed from a sulfate-rich aqueous fluid rather than the more widespread carbonate-enriched fluid.

Ages

The coarse-grained granitoids, long recognized as "postmetamorphic", were emplaced after the Late Paleozoic metamorphism and penetrative regional deformation, and before the intrusion of the Mesozoic diabase dikes and the uplift and erosion which occurred in the later Mesozoic. Extensive isotopic age work has been done on the granites while little is known of certain other aspects. The Rb-Sr whole rock isotopic ages of these plutons range from 407 to 264 Ma. Most ages, however, fall in the narrower span of 326 to 264 Ma, warranting the more popular designations of "300 my-old" granites (15) or the "325-265 my group"(5). In this study, the 407 Ma old Lowrys and 388 Ma old Bald Rock have been included on petrographic criteria. A review and discussion of the ages of these plutons has been recently published (5).

In plutons comprising several rock facies, determination of the facies' relative ages is of great importance in deducing the petrologic evolution of individual plutons. For most plutons, the relative ages have been established, and most facies are about the same absolute age, although some facies of the Siloam may yield differing isotopic ages (5).

K-Ar isotopic dates on micas have been determined for a number of Georgia granitoids (16). Both mica K-Ar and whole rock Rb-Sr dates are available for two plutons, the Siloam and Sparta. The similarity in ages suggests rapid cooling from the time of crystallization, as given by the Rb-Sr date, through the time of any significant loss of ^{40}Ar at much lower temperatures. Preliminary $^{40}Ar/^{39}Ar$ incremental-release ages of hornblende and biotite from the Liberty Hill are similar to Rb-Sr ages, suggesting that it, too, cooled fairly rapidly.

Contemporaneous gabbroids

Closely associated with the coarse-grained granitoids is a string of postmetamorphic gabbroic plutons (Figure B-7). Hornfelses occur around a number of the gabbroids: Buffalo (17), Gladesville (18), Mt.

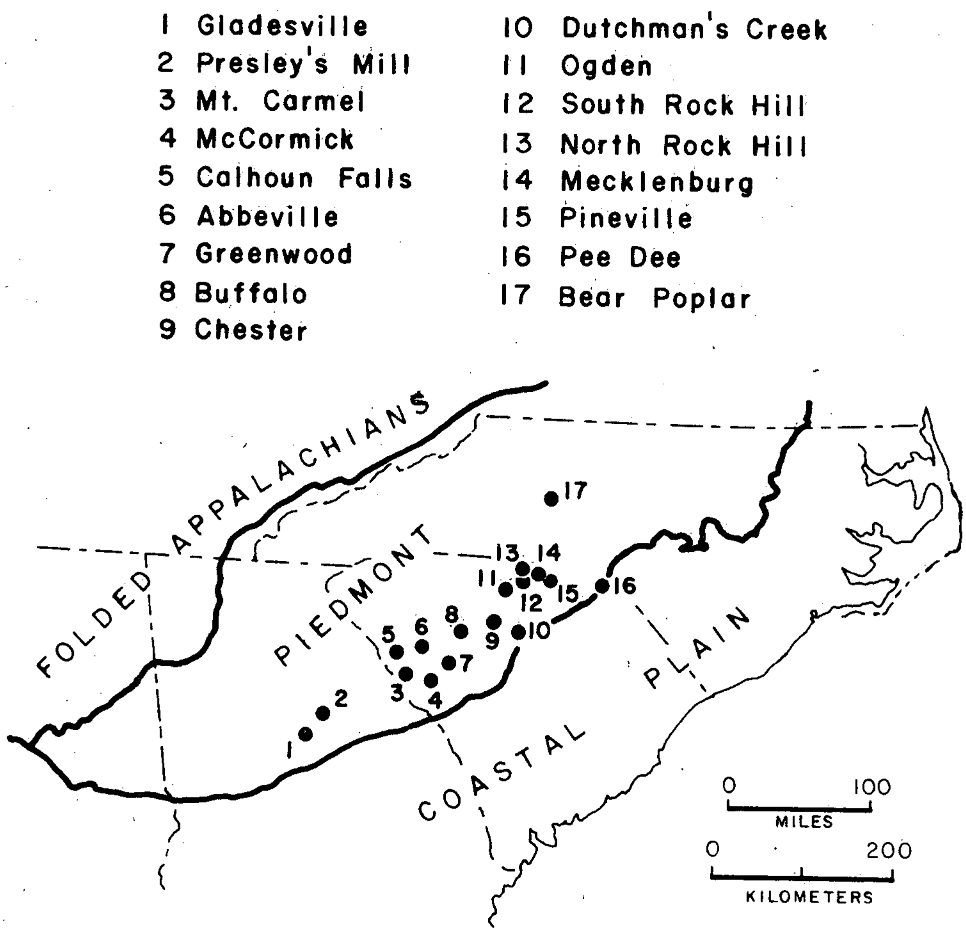


Figure B-7. Locations of the postmetamorphic gabbroic plutons in the southern Appalachian Piedmont.

Carmel (19), Presley's Mill (20), South Rock Hill (7), Abbeville, Calhoun Falls, Dutchman's Creek, Ogden, and Pee Dee. The presence of contact aureoles around these plutons places a maximum age on their intrusion: because regional metamorphic effects have been obliterated in the hornfels surrounding a gabbro, the pluton must be "postmetamorphic", or younger than about 350 Ma.

More definite age relations have been established for three plutons. A norite-diorite body intrudes the Coronaca granite (21); the granite is dated at 278 ±2 Ma. The Gladesville is cut by pegmatite dikes dated at 339 ±16 Ma (22), yielding a minimum age for the gabbro. The Pee Dee gabbro intrudes the Lilesville, which is 326 ±27 Ma(5). Examination of the Pee Dee gabbro-Lilesville granite contact shows that they are mutually intrusive. Small bodies of fine-grained, pillow-like inclusions of gabbro were found in the granite, suggesting that there was mechanical mixing of the two magmas. The pillow-like masses comprise basic magma which was chilled in cooler but still liquid granitic magma.

The general relations of the postmetamorphic gabbroids, and particularly the relations of the Pee Dee and Lilesville plutons, show that the gabbroids and coarse-grained granitoids were approximately contemporaneous. Whether a cogenetic or only coincidental interpretation is attached to the occurrence of a bimodal suite, it is clear that the late Paleozoic magmatic event in the southern Appalachians produced plutons of two extreme compositions, with few if any intermediate rocks.

PETROLOGY

Petrography

Modally, most of the rocks are monzogranites and quartz monzonites (Figure B-8). The scatter of points into the syenogranite and quartz syenite fields results from the variation in the Winnsboro. The points near and in the granodiorite field show modes of the earlier-consolidated facies of the granites, and plagioclase-rich plutons, such as the Palmetto.

The most abundant and characteristic rock type of the plutons is a coarse-grained, hypidiomorphic-inequigranular, biotite- or biotite + amphibole-bearing granite. The feldspars are tabular, and euhedral to subhedral. Several varieties of coarse-grained granitoid can be differentiated on the basis of mineralogy and texture. The mineralogical varieties are: biotite + amphibole, biotite, and biotite + muscovite, all of which can be further divided by the presence or absence of certain accessory minerals. More subtle variations are defined in terms of differences in granularity, subdivided according to the size of quartz or K-feldspar. The K-feldspars can vary from a size comparable to that of the other minerals up to several times that size. As they increase in size, they become more euhedral. The size of the K-feldspars within a facies is generally uniform, but local changes produce granites that are porphyritic over a limited area or that contain only a few megacrysts.

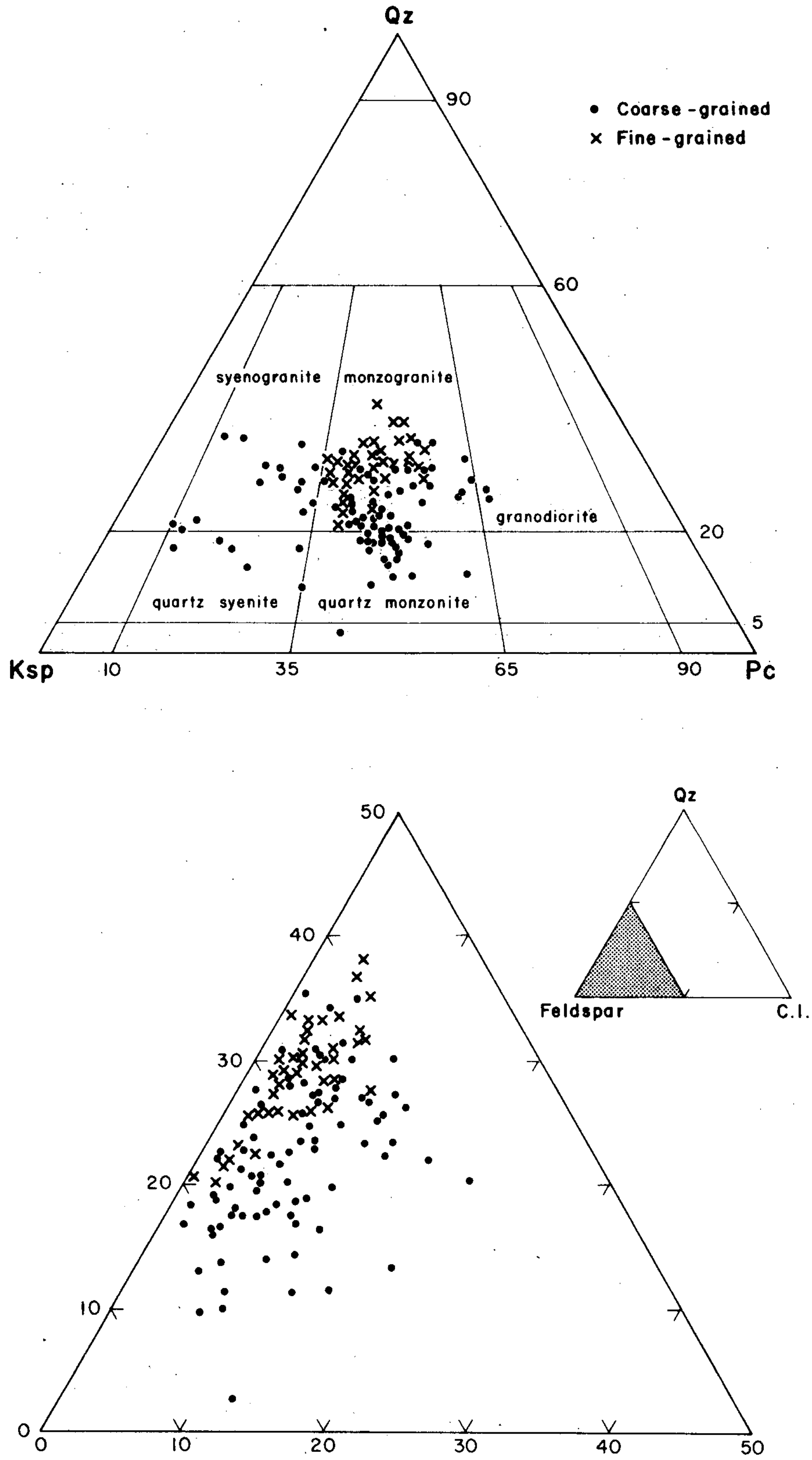


Figure B-8. Modal distribution of a) quartz, K-feldspar, and plagioclase, and b) quartz, total feldspar, and color index in the rocks of the postmetamorphic, coarse-grained granite plutons of the southern Appalachian Piedmont. IUGS subcommission on the Systematics of Igneous Rocks classification (37).

A wiborgitic texture is variably developed, but widespread in the coarse-grained granites. In contrast to the ovoidal K-feldspars mantled by plagioclase in the wiborgite of the rapakivi granites of Scandinavia, the K-feldspars of the coarse-grained granites of the southeast U.S.A. are tabular and subhedral. The plagioclase mantles are oligoclase.

The finer-grained facies are more uniform. They are medium- to fine-grained, allotriomorphic-equigranular, biotite-feldspar-quartz rocks, commonly with muscovite + chlorite + epidote. They are more quartz-rich and felsic than the associated coarse-grained granites (Figure B-8). Subsolidus reactions are more prominent in these finer-grained rocks, suggesting that they were richer in a fluid phase, which reacted with the rock. The finer-grained granites are generally younger than the associated coarse-grained facies and may contain xenocrysts of the latter, which have locally reacted with the melt.

The earlier consolidated facies of the coarse-grained granites, which are not included in Figure B-8, are granodiorites or tonalite and they are quite varied in appearance. In general, characteristic features include a high color index (CI 15), finer-grain size, and phenocrysts of plagioclase and quartz, in addition to K-feldspar. The early mineral phases, pyroxene and amphibole, occur in higher concentrations in this facies than in the rest of the pluton. The plagioclase is more calcic than that in the enclosing granite, and in some cases, including the early facies of the Butterwood Creek, plagioclase has K-feldspar rims - an antiwiborgitic texture. Locally, the K-feldspar megacrysts appear to have grown metasomatically. These rocks have reacted with the enclosing granite and have been affected by the more hydrous nature of the later melts.

A few aplite and pegmatite dikes, presumably associated with the granitoids, cut all the plutons. Small amounts of muscovite, biotite, magnetite, and garnet are the mafic minerals. Large quartzolite dikes cut the granites and adjacent country rocks; the largest, 4 km long and 0.3 km wide, intrudes the Town Creek.

Mineralogy

Biotite occurs as a mafic phase in all the granitoids. Petrographically, biotites from various plutons and rock types differ only in pleochroic scheme: some are pleochroic in shades of green, and some in red-brown. Microprobe analyses (Figure B-9) show that the biotites contain a large annite component, plotting at the magnesian and aluminous corner of the annite quadrant. The TiO_2 content varies between 1.8 and 3.5 wt %. Biotites in any <u>one</u> pluton or rock facies are suprisingly consistent in total iron content expressed as Fe/(Fe+Mg). Fe/(Fe+Mg) values obtained for several plutons:

Appling, coarse	0.58
Bald Rock	0.52
Castalia	0.60
Landis, amphibole granite	0.50

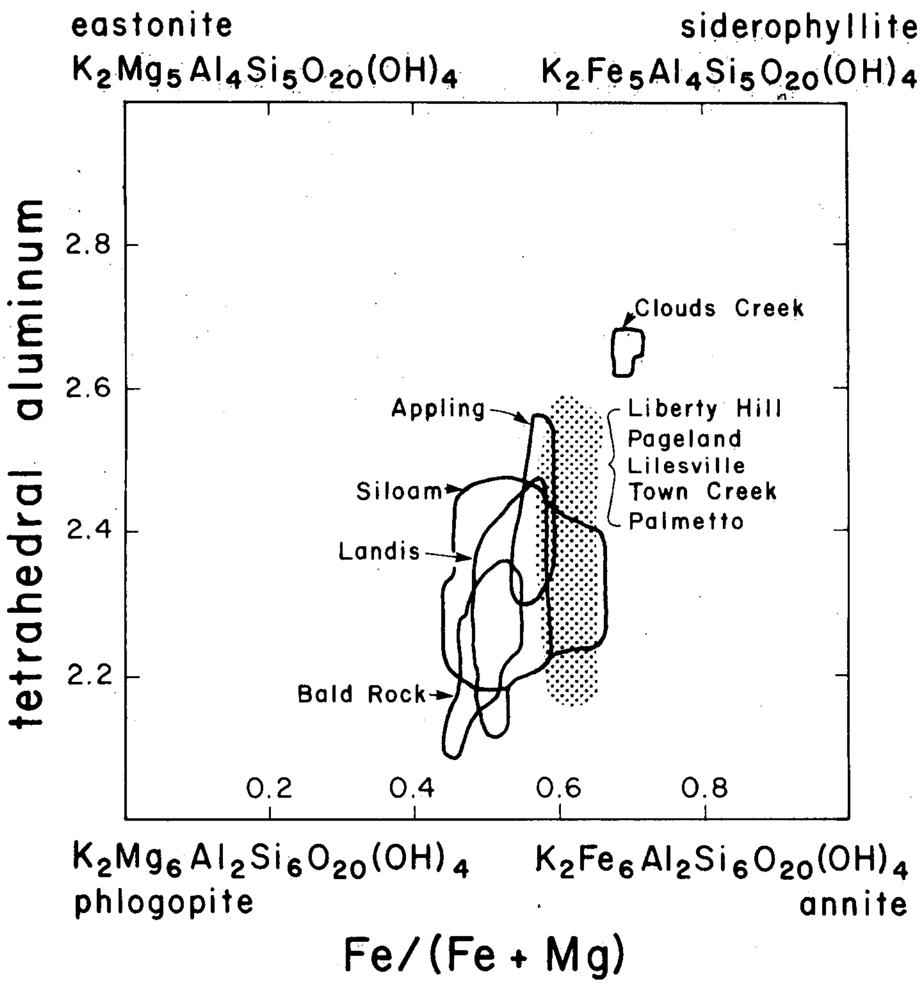


Figure B-9. Biotite compositional fields of the postmetamorphic, coarse-grained granitoid plutons projected onto the phlogopite-annite-eastonite-siderophylite field.

Landis, biotite granite	0.55
Liberty Hill, coarse	0.60
Liberty Hill, fine	0.65
Lilesville	0.60
Lowrys, coarse	0.45
Pageland	0.61
Palmetto	0.58
Town Creek	0.62

The differences in Fe/(Fe+Mg) between plutons or between rock facies of the same pluton are believed to reflect differing intensive parameters during crystallization. In contrast to the behavior of Fe/(Fe+Mg), the tetrahedral aluminum contents of biotites in any one pluton or rock facies are variable, causing the vertical trends of Figure B-9. The reasons for the variations in aluminum are not clear. In the Liberty Hill pluton, the tetrahedral aluminum content of the biotites decreases radially, being more aluminous toward the center. This may result from changes in fO_2 and fH_2O from core to rim of the pluton as evidenced by the mineralogy of the granite and xenoliths. The Fe/(Fe+Mg), unlike the tetrahedral aluminum content of the biotite, may be insensitive to these changes and dependent on a variable which differed among the plutons and rock facies.

Biotites from the Siloam pluton have the widest range in aluminum and Fe/(Fe+Mg) contents as expected for a pluton composed of many facies. The very aluminous biotites of the Clouds Creek coexist with cordierite and reflect the aluminous nature of the rock.

Amphibole occurs in one or more facies of the Butterwood Creek, Bald Rock, Clouds Creek, Landis, Liberty Hill, Lowrys, Pageland, Siloam, and Winnsboro plutons. The amphibole grains, up to 0.5 cm long, are prismatic, and euhedral to subhedral. They are pleochroic: X = yellow-brown; Y = yellow-green; Z = blue-green, and they are commonly twinned on (100). Analyses show they are edenites, ferroedenites, edenitic hornblendes, and ferroedenitic hornblendes, according to the new nomenclature for amphiboles (23). The compositions plot close to the limit of Ca+Na+K that igneous amphiboles can incorporate at a particular Si content (24) (Figure B-10). Amphiboles in any one pluton have a fairly narrow range in Fe/(Fe+Mg) ratios, with the following averages:

Bald Rock	0.56	Liberty Hill	0.61
Landis	0.57	Pageland	0.64
Lowrys	0.47	Siloam	0.52

The partition coefficient (Fe/(Fe+Mg) in biotite / Fe/(Fe+Mg) in amphibole) for the coarse-grained granites is nearly 1.0 (Figure B-11). The points of Figure B-11 which deviate most from the line are from the Bald Rock and Landis.

Amphiboles in some plutons are color-zoned, and chemically inhomogeneous. Zoning is particularly evident in amphiboles with "bleached" cores or irregular or skeletal clinopyroxene cores. In the

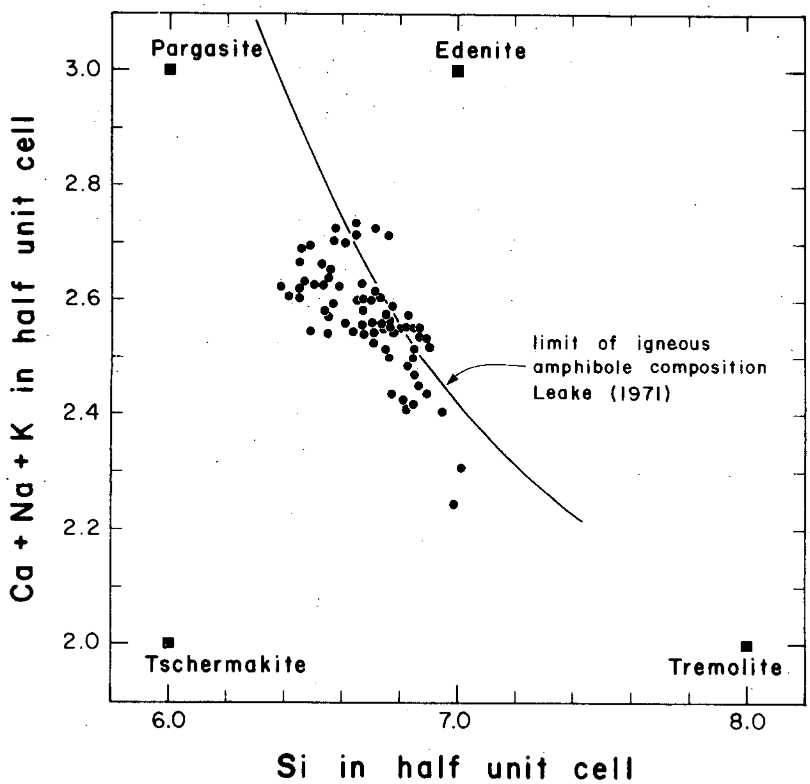


Figure B-10. Plot of Si against Ca+Na+K in the half unit cell for amphiboles from the postmetamorphic, coarse-grained granitoids.

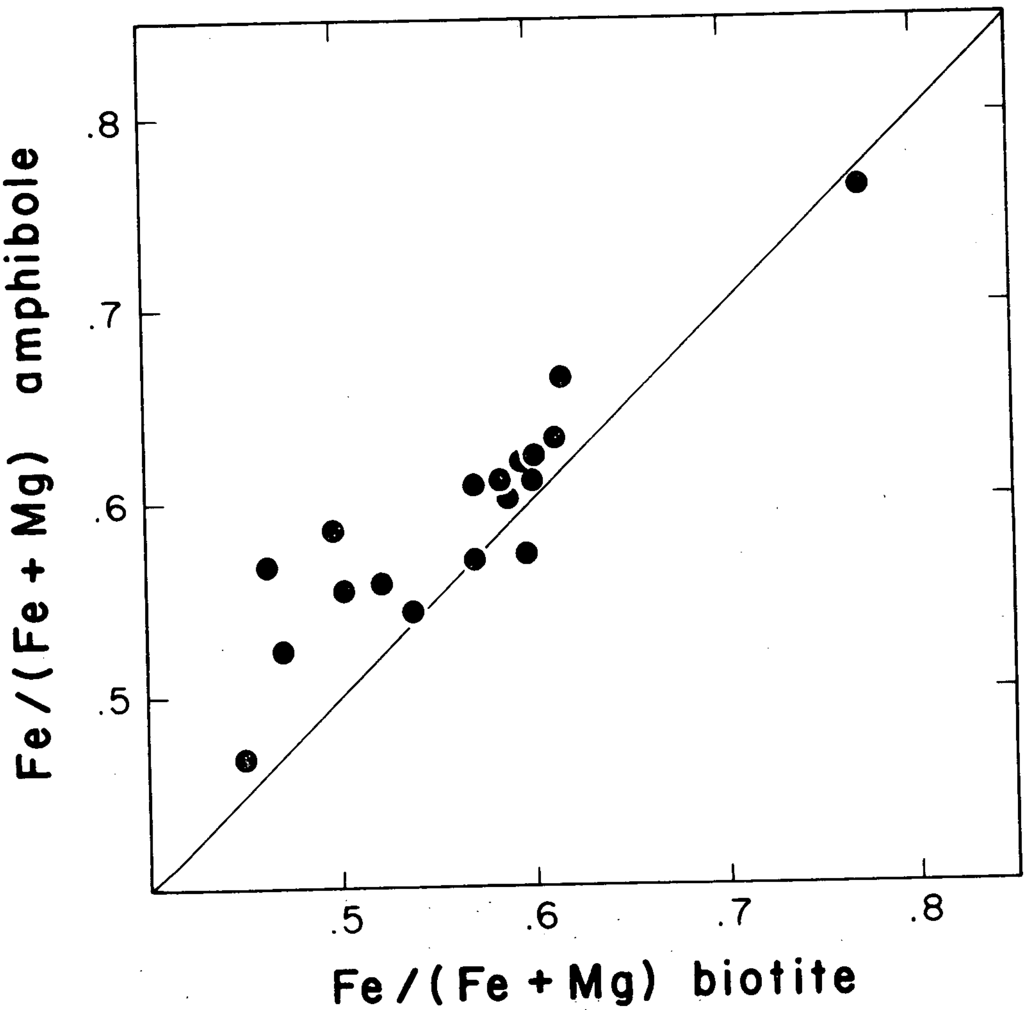


Figure B-11. Distribution of Fe and Mg between coexisting amphiboles and biotites of the postmetamorphic, coarse-grained granitoids.

Liberty Hill, the pyroxene is a pale green salite, near Wo_{47} En_{33} Fs_{18} Mn_2 in composition. The "bleached" cores are patches of pale green or colorless amphibole with small inclusions of quartz. The pale green amphibole is a magnesio-hornblende with Fe/(Fe+Mg)=0.48. This is the type of amphibole that also is adjacent to the clinopyroxene cores. The bleached cores probably represent pyroxene that has been converted to amphibole (cf. 25); they have also been found in the Clouds Creek (6) and Lowrys.

The textures of the biotite and amphibole-bearing granites suggest, in some cases, that biotite crystallized first, and in others, that amphibole crystallized first. Wones and Dodge (26) suggest, on the basis of experimental work, that in K-rich magmas, the ferromagnesian phase to appear next after pyroxene is dependent on H_2O activity. The sequences biotite-amphibole or amphibole-biotite reflect the differing H_2O activities of the granites.

The granites contain two distinct groups of alkali feldspars: K-feldspar megacrysts and groundmass K-feldspar. The pink megacrysts, which are not present in all rock facies and plutons, are euhedral to subhedral, flattened perpendicular to (010) and elongated parallel to c. The largest megacryst observed was 15 cm long. The megacrysts of the Appling are particularly platy, with thickness:width:length ratios at least 1:4:6. Most megacrysts are poikilitic with oriented inclusions of plagioclase, quartz, and biotite. The elongate and tabular minerals are oriented parallel to the megacryst faces. Where the inclusions are particularly abundant, they define a textural zoning in the feldspars. The K-feldspar megacrysts are perthites, microperthites and cryptoperthites. In contrast, groundmass K-feldspar grains are smaller, anhedral micro- and cryptoperthites. The albite phase of both the megacryst and groundmass K-feldspar forms film, braid, patch and veinlet perthite. The amount of perthite in the megacrysts can vary and define a zoning which is believed to reflect original magmatic zoning of the K-feldspars.

Single crystal, X-ray studies of Liberty Hill perthites showed that a monoclinic potassic phase (orthoclase) is the dominant X-ray average, but weak, diffuse bands parallel to a* and b* caused by very fine scale Albite and Pericline twins indicate the presence of twinned, triclinic microcline. This is consistent with the commonly observed microcline grid twinning. An Albite-twinned, low albite is also present.

According to microprobe analyses, the exsolved phases of the alkali feldspar are nearly end-member compositions, at least as sodic or potassic as Ab_{97} and Or_{97}. Bulk compositions of the alkali feldspars are estimated to be Or_{85-89} with less than An_1. This estimate is more potassic than the results of Whitney and Stormer (27) and Watson (2), who reported bulk analyses of megacrysts from some of the Georgia granitoids as Or_{60-67} with An_{1-4}.

The plagioclase crystals are smaller than the megacrystic K-feldspars. They are white or locally green as a result of saussuritization. Most plagioclases are subhedral, but many are anhedral because of subsolidus reactions. Compositional determinations show that the plagioclase is oligoclase having well-developed normal oscillatory zoning, with nearly unzoned cores of An_{30-27} and rims of An_{15-10}. All grains that were analyzed contain less than Or_1. Some antiperthite is present. A discontinuous rim of albite mantles most plagioclase grains, and is usually associated with myrmekite where adjacent to alkali feldspar. The plagioclases of the more mafic granitoids and schlieren are more calcic, An_{40}, and commonly contain inclusions of clinopyroxene, amphibole, and biotite. Depending on the availability of post-magmatic fluid, the calcic cores of the plagioclases are saussuritized, producing a more sodic plagioclase, epidote, muscovite, calcite, and quartz.

Chlorite, muscovite, and epidote have widespread occurrence in the granites. They are believed to be products of early post-magmatic reequilibration. In certain instances, particularly with respect to muscovite, arguments can be made for a late-magmatic origin.

Chlorites form largely by the alteration of biotite, and, in some instances, amphibole. In fluid-rich facies, all of the biotite is commonly altered. Analyses of the chlorites show that they closely follow the Fe/(Fe+Mg) range of the biotites. The chlorites are ripidolites and brunsvigites, according to the classification of Hey (28).

Muscovite and epidote have two parageneses, as saussuritization products of plagioclase, and as constituents of the matrix, where they are commonly intergrown with the other mafic minerals. In some cases, the matrix epidote has grown as rims on allanite. In most rocks there is compositional equilibrium between the alteration minerals though not between the alteration minerals and the parent minerals. In some rocks, saussurite minerals in the host feldspar grew in isolation from the matrix assemblage, resulting in two populations of epidote and muscovite, each with characteristic compositions. The matrix epidotes are Fe-rich, with pistacite contents greater than 25%. They are generally more Mn-rich than the Fe-poor epidotes of the isolated saussuritized plagioclase (Figure B-12). The matrix muscovites of the coarse-grained granites are phengites, with a fairly large celadonite component, (Fe+Mg)/(Fe+Mg+Ti+Al)=0.15 (Figure B-13) They have a small paragonite component, between 2 and 4.5%. The muscovites of the isolated saussuritized plagioclase contain much less celadonite and quite a large paragonite component, up to 17 mole %.

Numerous accessory minerals have been found in the granitoids; in the following list, those marked with an asterisk are thought to be secondary.

allanite	hematite*	sphalerite
apatite	ilmenite	thorite
carbonate*	magnetite	titanite
chalcopyrite	molybdenite	tourmaline
coffinite	monazite	uraninite
cordierite	pyrite	uranothorianite
fluorite	pyrophanite	xenotime

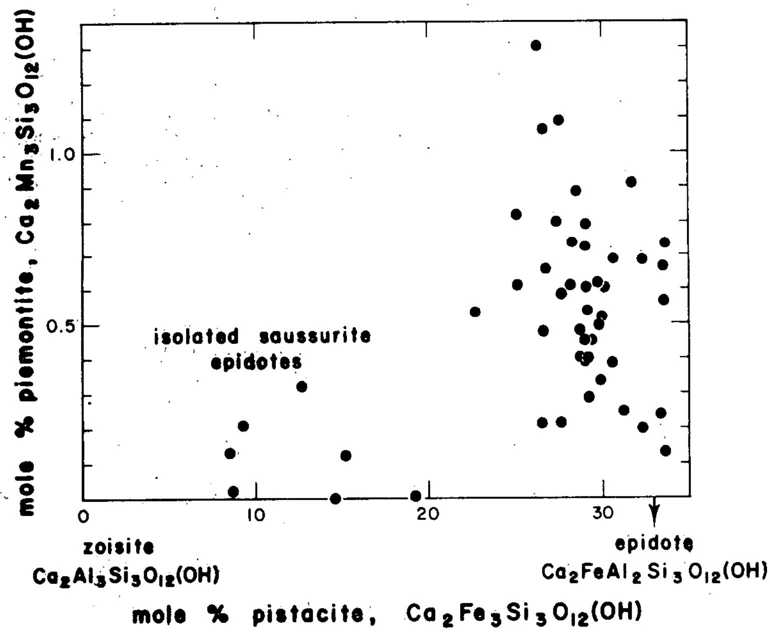


Figure B-12. Compositions of epidote in the granitoids.

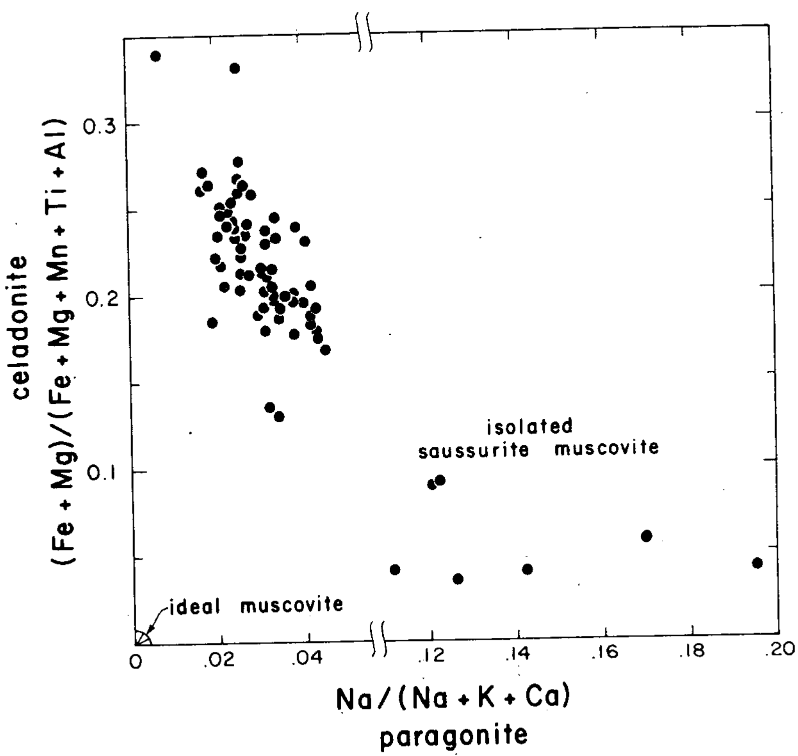


Figure B-13. Compositions of white micas in the granitoids.

galena	pyrrhotite	zircon
garnet	rutile*	

Zoned allanites, up to 3mm long, and titanite, up to 2mm in size, are the characteristic and most abundant nonopaque accessories of the granitoids, although one or both are absent from some facies. Allanites associated with epidote are commonly rimmed by the epidote. Textural evidence suggests that titanite formed in at least two generations: as large, euhedral primary titanite and as small, anhedral secondary titanite interlayered with biotite and rimming the oxides. Both types of titanites have similar compositions in a given rock. Aluminum and iron substitute for titanium up to 13 and 8 mole % respectively. Titanite, along with rutile, occurs with chlorite as an alteration product of biotite.

Zircon, apatite, magnetite and ilmenite are ubiquitous. Zircon and apatite generally occur as inclusions in major minerals, especially biotite. Commonly what appears to be zircon has, on closer examination, been identified as the isostructural minerals thorite, coffinite, and xenotime. Magnetite generally contains lamellae of ilmenite, as a result of exsolution of a primary titanomagnetite. Ilmenite only locally contains networks and blebs of hematite, probably as a result of exsolution of the ilmenite-hematite solid solution. The ilmenites are manganiferous, containing up to 6 wt % MnO.

The sulfides pyrite and chalcopyrite are fairly widespread, although chalcopyrite is not abundant. Sphalerite has been found in the granites near metasedimentary xenoliths and in pegmatite and aplite segregations. Pyrrhotite crystallizes particularly early, and occurs only as inclusions in zircon, apatite, magnetite, allanite, calcic plagioclase, and amphibole. Evidently the sulfur fugacity increased during crystallization until only pyrite was stable. Molybdenite occurs both as disseminated flakes and as aggregates in quartz veins. The occurrence of molybdenite in these granitoids has been discussed in detail (29). Two additional occurrences have been noted since that work, the Siloam (30) and the Butterwood Creek.

The remaining accessory minerals, except for those of secondary origin, are fairly restricted in occurrence. The blue-to-brown pleochroic tourmaline of the Clouds Creek has an intermediate composition, approximately $schorl_{55}$ $dravite_{45}$. The garnets are spessartine-almandine solid solutions, with the average compositions: Castalia, $Sp_{52}Al_{30}Gr_{18}$ and Siloam, $Sp_{58}Al_{36}Gr_{5}$. The compositional variation of the garnets is small in the Siloam and is about 5 percent in the Castalia. The cordierite in the Clouds Creek has an intermediate composition, $Fe_{49}Mg_{48}Mn_{3}$, and contains a large amount of sodium, up to 1.25 wt % Na_2O, which is typical of cordierites in igneous rocks. The uranium and thorium oxides have been positively identified in only two plutons, the Liberty Hill and Town Creek. Evidence of their presence in the form of very large radiation damage halos in biotite has been spotted in a number of other granites, although the minerals themselves do not lie in the plane of the thin section. Some of the radiohalos appear to be polonium halos (^{214}Po), although they could be overexposed ^{238}U halos (31).

Accessory minerals are more than curiosities. They provide evidence of differences in chemical and physical conditions that may not be recorded by the major mineralogy. Because the accessory minerals contain the primary sites for many trace elements, the accessory mineralogy records the behavior of the trace elements during crystallization and subsequent events such as hydrothermal alteration and weathering. Rare earth phosphates, for example, may occur instead of allanite near large xenoliths or wall rocks which have contaminated the granite with P. U and Th are minor constituents of both the easily weathered allanites and the much more resistant phosphates, monazite and xenotime, and the behavior of these elements will be determined by the mineralogy.

Enclaves

Enclaves in the coarse-grained plutons are not abundant, but encompass a wide variety of types.

Xenoliths are the only enclaves that are angular. The constituent rock types are varied, reflecting the diverse lithologies in which the granites were emplaced. Epixenoliths are the largest, most common, and most easily recognized type of xenolith. Formed from nearby country rock, they are most abundant near contacts. Hypoxenoliths, derived from the country rock at depth, can be identified by their similarity to rocks that are found in the Piedmont, but not in the vicinity of the pluton.

Xenocrysts, not a common feature, are limited to multiple-intrusion plutons. They have been identified where a later, finer-grained granitoid intruded a coarser-grained granitoid and picked up large, single crystals from the earlier facies. A reaction texture is commonly present between the xenocrysts and finer-grained matrix. A late facies of the Liberty Hill, the "xenocrystal granite", contains up to 25% xenocrysts.

Three types of autoliths have been recognized. Most easily identified are felsic mineral segregations with a CI§1. Included in this group are autoliths composed entirely of K-feldspar megacrysts, which suggest an igneous origin for the megacrysts. A second type, comprising schlieren and enclaves of mafic mineral segregations, can be interpreted as autoliths, although some may be skialiths. The third type of autolith, which is perhaps the most useful for interpreting the evolution of a granite, includes those believed to consist of a rock facies that was consolidated earlier and at greater depth than the pluton at the present surface. This type of autolith, found in every granite examined, characteristically is more mafic than the enclosing granite and shows reaction textures with the enclosing rock and post-consolidation growth of hydrous mafic minerals and K-feldspar. Autoliths of earlier facies give rise to spectacular double enclaves. The doubly enclosed enclaves are probably either hypoxenoliths or even earlier autoliths.

Skialiths are fairly rare in the coarse-grained granites. The few examined appear to be granitic xenoliths that recrystallized in the younger melt. Because they were already close to granite in composition, these enclaves were able upon reaction to approach the enclosing rocks in composition, mineralogy, and texture in the time available.

CONTACT METAMORPHISM AND

CONDITIONS OF EMPLACEMENT

The nature of the contact metamorphic aureoles of the granitic plutons varies widely. The plutons studied were probably similar in magmatic temperature and shape. The diversity in contact metamorphism is therefore most likely caused by emplacement at different depths in rocks of varying composition and metamorphic grade.

Thermal aureoles produced by the granites have been recognized around the Clouds Creek, Danburg, Liberty Hill, Lilesville, Pageland, Sims, Town Creek and Winnsboro plutons. Contact metamorphism developed only in xenoliths has been detected in the Palmetto-Tyrone and perhaps the Bald Rock, SCU 1 and the Siloam. Contact aureoles are best developed around plutons emplaced in the low-grade Carolina Slate belt. For those intruded into mudstones, contact effects can be seen up to 4 km from the margin of the pluton. The aureoles can be grouped as:

1. trifacial, composed of granulite, amphibolite and greenschist facies, e.g. The Liberty Hill and Lilesville.

2. bifacial, composed of amphibolite and greenschist facies. The Pageland, Town Creek and Winnsboro plutons are examples. These plutons could be trifacial if granulite facies assemblages were to be found.

3. monofacial, composed solely of greenschist facies assemblages. The Clouds Creek and Danburg appear to belong to this type.

Contact effects are difficult to find around plutons emplaced in country rocks in which the metamorphic grade is amphibolite facies or higher. In this case, rocks showing contact metamorphism are limited to xenoliths and immediately adjacent country rocks. Observed contact metamorphism in these xenoliths and aureoles is limited to the granulite and amphibolite facies, conditions at or above those of the enclosing rocks. The Palmetto and Siloam are examples of plutons emplaced in high grade country rocks.

The contact metamorphism appears to have been largely isochemical for the major elements, although exchange of fluid phase components was common. The behavior of the trace elements and stable isotopes is not well documented, but they do appear to have been affected by fluid phase migration. In the Rion facies of the Winnsboro and the Danburg, fluid was apparently expelled into the country rock. Most plutons, on the other hand, appear to have absorbed water from the country rock, as shown by the mineralogy of the granite, aureole, and xenoliths.

The mineral assemblages of the hornfelses are diverse, reflecting a wide range in composition of the original country rocks. Commonly occurring and interesting mineral assemblages include:

1. xenoliths and innermost aureoles

a) pelitic rocks (in addition to pc+ksp+qz)

opx+gar+cd+bt
opx+cd+bt
opx+bt
gar+cd+bt
gar+si+bt+musc
gar+bt±musc
staur+gar+si+bt
cd+bt±musc
si+musc
and+bt+musc
and+cd+bt+musc
si+cd+bt

b) basic rocks (in addition to pc + qz)

cpx+opx±brn hbl+bt
opx+brn or grn hbl+bt
cpx+brn or grn hbl+bt
cumm+brn or grn hbl+bt
gar+cpx+hbl
gar+cumm+bt
cpx+cumm+hbl
grn hbl+bt±epid

c) calcareous rocks

grossularite+cpx+trem+zoisite+cc
trem+cpx+zoisite

2. inner aureoles

a) pelitic rocks (in addition to pc + qz)

cd+bt+ksp
cd+bt+musc
and+cd+bt+musc
and+staur+bt+musc

b) basic rocks (in addition to pc + qz)

amph+bt+epid+chl

3. outer aureoles

a) pelitic rocks (in addition to pc + qz)

chl+cd+bt+musc
chl+musc±epid
bt+musc±chl

b) basic rocks (in addition to pc + qz)

amph+epid+bt+musc
epid+chl+bt+musc

The mineral assemblages in the outer part of the aureole grade into the earlier assemblages of regional metamorphism. The trifacial contact aureoles contain all three of the above groups of mineral assemblages; the bifacial aureoles contain groups 2 and 3; and the monofacial aureoles contain only group 3 mineral assemblages.

The contact aureoles of individual plutons can be quite complex, as is the Liberty Hill aureole, which is trifacial. The pelitic country rocks have an earlier, regional greenschist facies assemblage of vermiculite+chlorite+epidote+albite+quartz. The mineral isograds encountered toward the granite contact are: vermiculite-out; epidote+albite-out, which coincides with the cordierite+biotite+andesine-in; chlorite-out; K-feldspar-in; and magnetite - or muscovite-out. Garnet, orthopyroxene and andalusite appear in the xenoliths.

The estimated pressure of emplacement of the Liberty Hill, obtained from compositions of coexisting garnet-cordierite pairs, is 4.5 kb, which corresponds to a depth of between 15 and 18 km. This pressure estimate is further supported by the aluminum silicate transition of andalusite-sillimanite, the coexistence of sillimanite with muscovite, K-feldspar and quartz, and the possibility of igneous muscovite in the border facies of the granite. Using the muscovite stability data (32) and the aluminum silicate stability data (33), pressure brackets of 5.5 and 4.5 kb are obtained. The Lilesville contact aureole is nearly identical to that of the Liberty Hill, but compositions of the garnet-cordierite pairs suggest a slightly higher pressure, perhaps 5 kb. Preliminary work on the contact metamorphism of the Pageland, Sims, Town Creek and Winnsboro plutons indicates that they were emplaced at pressures of 4.5 to 5.5 kb. A minimum pressure estimate of 4 kb can be placed on the western plutons, Palmetto-Tyrone, SCU 1, and Siloam, although the pressure appears greater.

Temperature estimates for the xenoliths in the Liberty Hill fall in the range 670 - 740°C. Maximum estimates of temperature in the aureole are 680°C at the contact and less than 610°C in the outermost aureole. P_{H_2O} was approximately half P_{total} in the granite. These conditions, at a pressure of 4.5 kb, are just above or at the granite solidus (34). This is a reasonable result, for the Liberty Hill is at the level relative to surrounding rocks where it completed crystallization.

Conclusions

Twenty-six post-metamorphic granitoid plutons in the southeastern U.S. possess the properties of a supergroup (3): they are similar in age, texture, degree of modal variation, and mineral compositions, and they have similar xenoliths. Compositions of minerals from contact aureoles suggest that hot, dry magmas were emplaced at 4 - 5.5 kb and crystallized to coarse-grained granitoids. Later, finer-grained facies formed from magmas that were cooler and wetter.

These granitoids are part of a Late Paleozoic magmatic event which produced contemporaneous granitic and gabbroic plutons. It is uncertain whether the two magma types are consanguineous, or whether their simultaneous production was coincidental.

Disparate local settings and variations in intensive parameters produced numerous variations in the granitoids and lessened the similarities between them. The granitoids vary from homogeneous, sill-like sheets to multiply intrusive, funnel-shaped complexes. Some granites were emplaced in major mylonite zones, and others have been cut by Mesozoic brittle faulting. Variations also occur in the mineralogy and crystallization sequence of the mafic and accessory phases, as well as in the extent of post consolidation recrystallization. Recognition of the effects of local setting will allow identification of general features that can be used to determine the granitoids ultimate, common origin during the Late Paleozoic magmatic event.

Acknowledgements

This paper is part of an investigation of low-temperature, geothermal resources supported by U.S. Department of Energy Contract No. ET-78-C-05-5648 awarded to J. K. Costain, Lynn Glover, III, and A. Krishna Sinha with supplemental support from Los Alamos Scientific Laboratory. We also acknowledge the field and laboratory assistance of W. Clifford Bourland and Arthur Baldasari.

References

1. Watson, T.L., Geol. Survey Georgia Bull., 9-A, 367p, 1902.
2. Watson, T. L., U.S. Geol. Survey Bull., 426, 282p, 1910.
3. Pitcher, W. S., Jour Geol. Society, 135, 157-182, 1978.
4. Becker, S. W., Geol. Soc. America Abs. with Programs, 10, 162, 1978.
5. Fullagar, P. D. and J. R. Butler, Am. J. Sci., 279, 161-185, 1979.
6. Secor, D. T. and A. W. Snoke, Carolina Geol. Soc. Field Trip Guidebook, 65-123, 1978.
7. Butler, J. R., South Carolina State Devel. Board Div. Geology, Bull. 33, 65p., 1966.
8. Waskom, J. D. and J. R. Butler, Geol. Soc. America Bull. 82, 2827-2844, 1971.
9. Wagner, H. D., South Carolina State Devel. Board; Geol. Survey, Min. Resources Series 5, 65 p, 1977.
10. Butler, J. R. and D. E. Howell, Geol. Notes, 20, 133-149, 1977.
11. Bell, H., III and P. Popenoe, U.S. Geol. Survey Jour. Research, 4, 667-682, 1976.
12. Higgins, M. W., Georgia Geol. Survey Bull. 77, 49p, 1966.

13. Higgins, M. W., U.S. Geol. Survey Misc. Geol. Inv. Map I-511, 1968.
14. Hatcher, R. D., D. E. Howell, and P. Talwani, Geology, 5, 636-640, 1978.
15. Fullagar, P. D., Geol. Soc. America Bull. 82, 2845-2862, 1971.
16. Smith, J. W., J. M. Wampler, and M. A. Green, Georgia Geol. Surv. Bull. 80, 121-139, 1968.
17. Medlin, J. H., C. P. Thornton, and D. P. Gold, Southeastern Geology 14, 73-106, 1972.
18. Matthews, V., III, M.S. Thesis, Univ. Georgia, 68 p, 1967.
19. Medlin, J. H., Ph.D. Thesis, Penn. State Univ., 328 p, 1968.
20. Libby, S. C., M.S. Thesis, Univ. Georgia, 99p, 1971.
21. McSween, H. Y., Jr., Geol. Notes, 14, 57-84, 1970.
22. Jones, L. M., R. H. Carpenter, and J. A. Whitney, Geol. Soc. America Abs. with Programs, 6, 369, 1974.
23. Leake, B. E., Am. Mineral., 63, 1023-1052, 1978.
24. Leake, B. E., Min. Mag., 38, 389-407, 1971.
25. Taubeneck, W. H., Geol. Soc. America Spec. Paper 76, 295-296, 1964.
26. Wones, D. R. and F. C. W. Dodge, Thermodynamics in Geology, 229-247, 1977.
27. Whitney, J. A. and J. C. Stormer, Contrib. Mineral. Petrol., 63, 51-64, 1977.
28. Hey, M. H., Min. Mag., 30, 277-292, 1954.
29. Speer, J. A., Econ. Geology, 73, 558-561, 1978.
30. Guinn, S. A., Abs., Bull. GA Acad. Sci., 31, 81, 1973.
31. Gentry, R. V., Annual Rev. Nuclear Sci., 23, 347-362, 1973.
32. Chatterjee, N. D. and W. Johannes, Contrib. Mineral Petrol., 48, 89-114, 1974.
33. Richardson, S. W., M. C. Gilbert, and D. M. Bell, Am. J. Sci., 267, 259-272, 1969.
34. Kerrick, D. M., Am. J. Sci., 272, 946-958, 1972.
35. Kish, S. A. and P. D. Fullagar, Carolina Geol. Soc. Field Trip Guidebook, 61-64, 1978.
36. Butler, J. R., Am. J. Sci., 272, 319-333, 1972.
37. Streckeisen, A., Earth-Sci. Rev., 12, 1-33, 1976.