REPORT TO THE EARTHQUAKE AND WAR DAMAGE COMMISSION

Piezocone Investigation of Liquefaction Sites,

Loma Prieta, California Earthquake of 17 October 1989

R.A. Vreugdenhil and J.B. Berrill

December 1992

Department of Civil Engineering
University of Canterbury
New Zealand

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INTRODUCTION

The purpose of this report is to describe the fieldwork undertaken in the United States during June 1990, and to present the data collected from the field testing. The main aim of the visit by Roger Vreugdenhil was to document sites of liquefaction and non-liquefaction, on level ground, associated with the Loma Prieta earthquake of 17 October 1989. At the same sites, the US Geological Survey (USGS) is carrying out coventional boring, standard penetration testing and sampling. The results will enable current methods of predicting liquefaction potential to be checked and improved. They should also lead to improved correlation between cone readings and soil properties. In particular, the combined piezocone and drilling data from locations that liquefied and those that did not should allow us to better understand the role of fines in inhibiting liquefaction, and to relate fines content to piezocone response. Such a study forms the doctoral thesis topic of the first author.

The visit to California by Roger Vreugdenhil was arranged as a cooperative research venture by the Department of Civil Engineering at the University of Canterbury, and the Western Region Headquarters of the United States Geological Survey, with the financial support of the NZ Earthquake and War Damage Commission and the USGS.

PREPARATION FOR THE FIELD TESTING IN CALIFORNIA

Preparation for the California visit was for the most part concentrated on becoming familiar with the Cone Penetration Test hardware and test procedures.

During February 1990 a number of CPT and CPTU soundings were conducted at the north end of the South Island of New Zealand, near Blenheim. The purpose of this fieldwork was primarily to record data from the Wairau Pa site associated with historical liquefaction, but it also served as a practice run for the Californian work. In addition, these tests verified that the equipment was functioning properly, and that alterations made to the data logging programme earlier that month were correct.

The data logging programme underwent further modifications during April 1990. In addition the sensitivity of the pore water pressure reading was doubled, and the entire set-up was converted to run off a 110 volt power supply. Minor changes were made to some of the components of the set-up in order to make the transition between drill rigs as easy as possible. The cone was calibrated before departing for California.

In conjunction with the technical preparation, the first author continued a literature survey of liquefaction and a review of computer programming, and techniques for programme editing and de-bugging. Much organisational work was necessary to ensure that the visit would be successful in its purpose.

DESCRIPTION OF SITES AND EXPERIMENTAL PROCEDURE

Ten sites of liquefaction were tested using the piezocone, with a total of 35 probes undertaken. Of these, 32 were with the cone in a state of total saturation. Two of the sites were located on sand spits, seven were alongside the banks of either the Pajaro or Salinas rivers, and one was located in the Marina District of San Francisco city. The sites are shown in Figure 1.

At each site the positioning of the probes was arranged so that data was collected from both regions of failure and non-failure. The purpose for this was to provide a distinction between these regions, which would assist in identifying the layers which failed by liquefaction.

The piezocone was subjected to a standard de-airing procedure at each site where an accurate pore water pressure record and dissipation tests were required. The cavity behind the pressure transducer was injected with water while the cone was submerged in a clear cylindrical tank (approximately volume two litres). Following this, the cone, a porous filter stone and the cone-tip were subjected to a vacuum of 67kPa under water for 30 minutes. After this time, the vacuum was removed and the cavity behind the transducer was re-injected under water (this time with de-aired water). The piezocone was then assembled under water and a latex sheath slipped over the tip and part of the shaft, covering the porous stone. During the de-airing procedure, a hole would be augered to the water table. Once the drill rig pushing device was in position over this hole, and the remaining set-up complete, the cone would be removed from the vacuum tank and connected to the rods. This was always the final connection to be made, so that the cone maintained a guaranteed saturated state for as long as possible. Once this connection was secure, the power to the cone would be switched on and the electronics given a few minutes to warm up before recording zero readings. After zeroing, the cone would be lowered down the hole and allowed to rest on the ground at the base. From this point on the test would continue as a standard CPT.

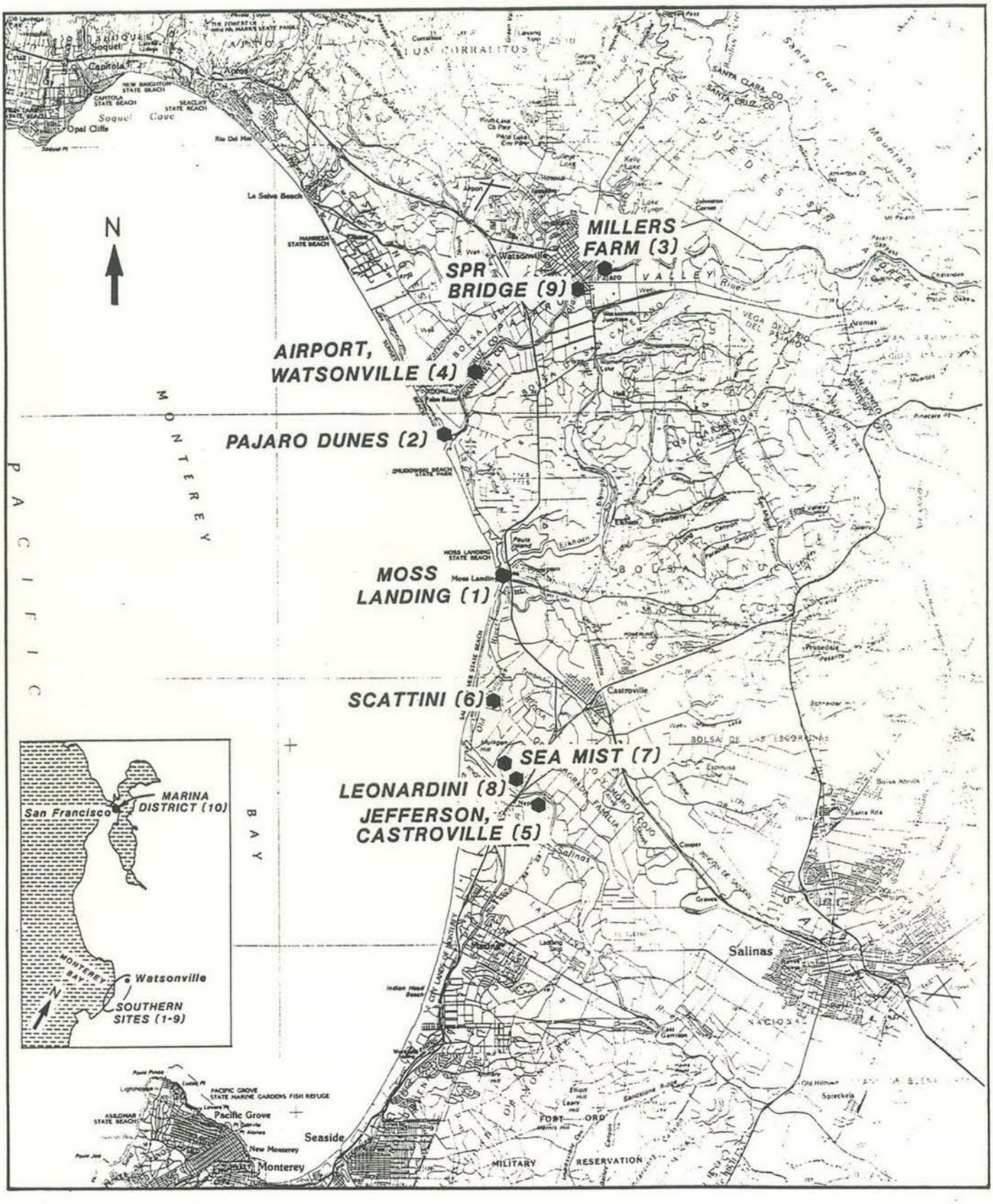


Figure 1 - Piezocone test sites

The average probing distance between dissipation tests was set at half a metre. At several sites the first pass length was purposely decreased to 250mm in order to gain dissipation data as close to the water table as possible. At no time did the pass length intentionally drop to less than 200mm. An average of 15 dissipation tests were conducted during each probe.

The piezocone data was recorded using the University of Canterbury CPTU data logging system. A computer file was generated as output for each probe, comprised of the penetration and dissipation data. In addition to the cone resistance, friction ratio and pore water pressure data recorded, points of interest (such as evidence of liquefaction) were noted, and site maps were constructed. The geographical locations and major features of the ten sites are described below.

(1) Moss Landing

Moss Landing is located on the west coast of California approximately midway between the mouths of the Pajaro and Salinas Rivers. Part of the small township occupies a 1km long sand spit, zones of which liquefied during the Loma Prieta event (the spit is in fact an extension of an island, since the Old Salinas River separates this land from the mainland). Testing was carried out at the locations shown in Figure 2 in the vicinity of a cluster of four Chevron oil and gasoline tanks near the end of the spit, which underwent a foundation failure as subsurface layers liquefied. According to an eye-witness, moderate ground cracking began in a west to east direction just outside the northwest corner of the tank enclosure, approximately 3-4 seconds after the shaking commenced. The opening of these ground cracks was accompanied by an ejection of a mixture of sand and water which rose to a height of 2 metres, level with the bow of a boat and trailer parked adjacent to the enclosure.

The cone was de-aired for two of the three tests conducted here. A CPT and a CPTU were performed side by side in a region of no apparent liquefaction, approximately 30 metres to the south of the tank enclosure. A second CPTU was conducted in the

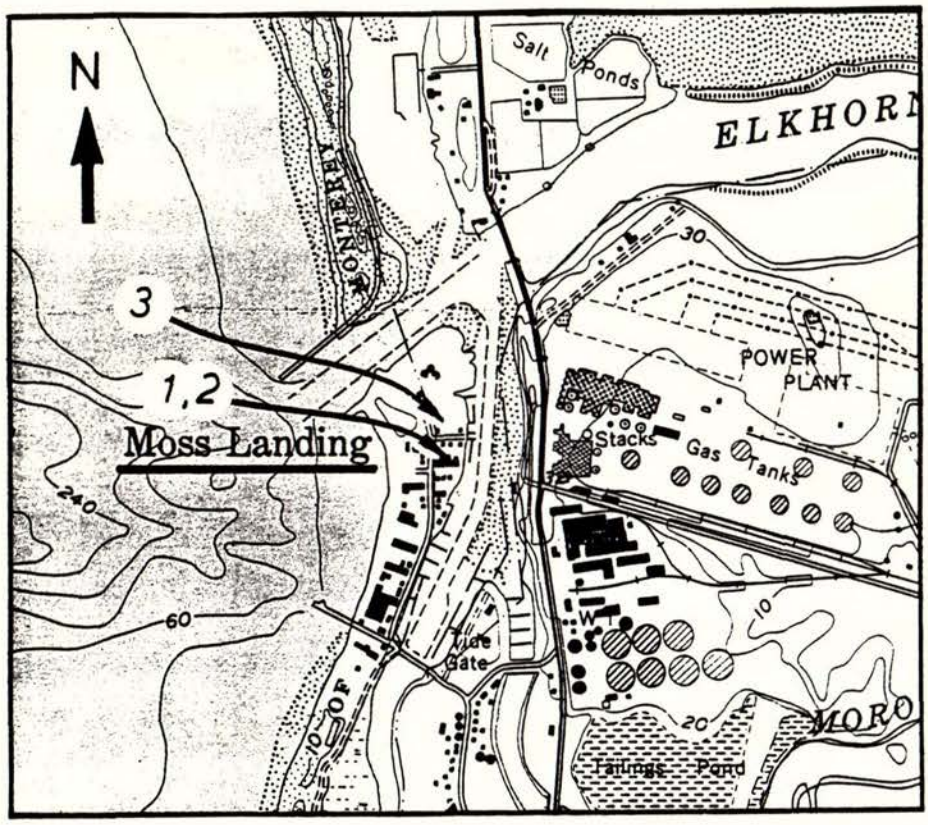


Figure 2

vicinity of the reported ground cracking. The author also assisted with Standard Penetration Tests conducted here by the U.S.G.S. during the last week of May 1990.

(2) Pajaro Dunes

Pajaro Dunes is a relatively small and modern holiday retreat situated inside the dunes of Sunset State Beach, just north of the Pajaro River mouth. The complex is bordered to the east by the Watsonville Slough, and is therefore effectively built on a sand spit. The development is comprised of several holiday homes and large four storey condominiums. Access to Watsonville township is via Beach Road.

Liquefaction during the Loma Prieta event caused the disruption of pavements and services to buildings at the south end of the complex. There was also some settlement

of a few of the larger buildings in this region, and a small lateral spread which resulted in the partial failure of a retaining wall constructed along the north bank of the Pajaro River. Two tests were conducted here, the first inside the east tip of the island within the south carpark, and the second further north along the slough side of the access road that is in parallel alignment with the Watsonville Slough. Test locations are shown in Figure 3. The cone was de-aired for both tests. Unfortunately the second test ended at a comparitively shallow depth due to the very high resistance to penetration of the dense sandy soil.

(3) Miller's Farm

Miller's Berry Farm is situated to the east of Watsonville, on the north side of San Juan Road. The farm occupies an area of 19.5 hectares (48.1 acres), and has as its north boundary the south levee of the Pajaro River. As with most of the berry and produce farms in the Pajaro Valley, the fields had been ploughed and levelled shortly before the day of the earthquake. The 'quake caused significant deformation and disruption of the ground surface, creating bands of subsidence trending in a north-east to south-west direction. Large areas of sand boils indicated that there had been liquefaction of one or more of the sub-surface soil layers. A total of eight de-aired tests were conducted at this site, as shown in Figure 4. These were arranged in three north to south lines, in order to cover as much of the deformed ground area as possible, and to provide some contrast between areas of failure and non-failure. Lines of three tests were conducted at the east and west ends of the farm, and the remaining two tests were conducted in the centre. There appeared to be some confinement of the ground water. The water table consistently rose by approximately half a metre after drilling through a comparitively dry layer of clay. This suggests that pore water pressures in the soil were elevated naturally before the earthquake, which have accelerated the liquefaction process.

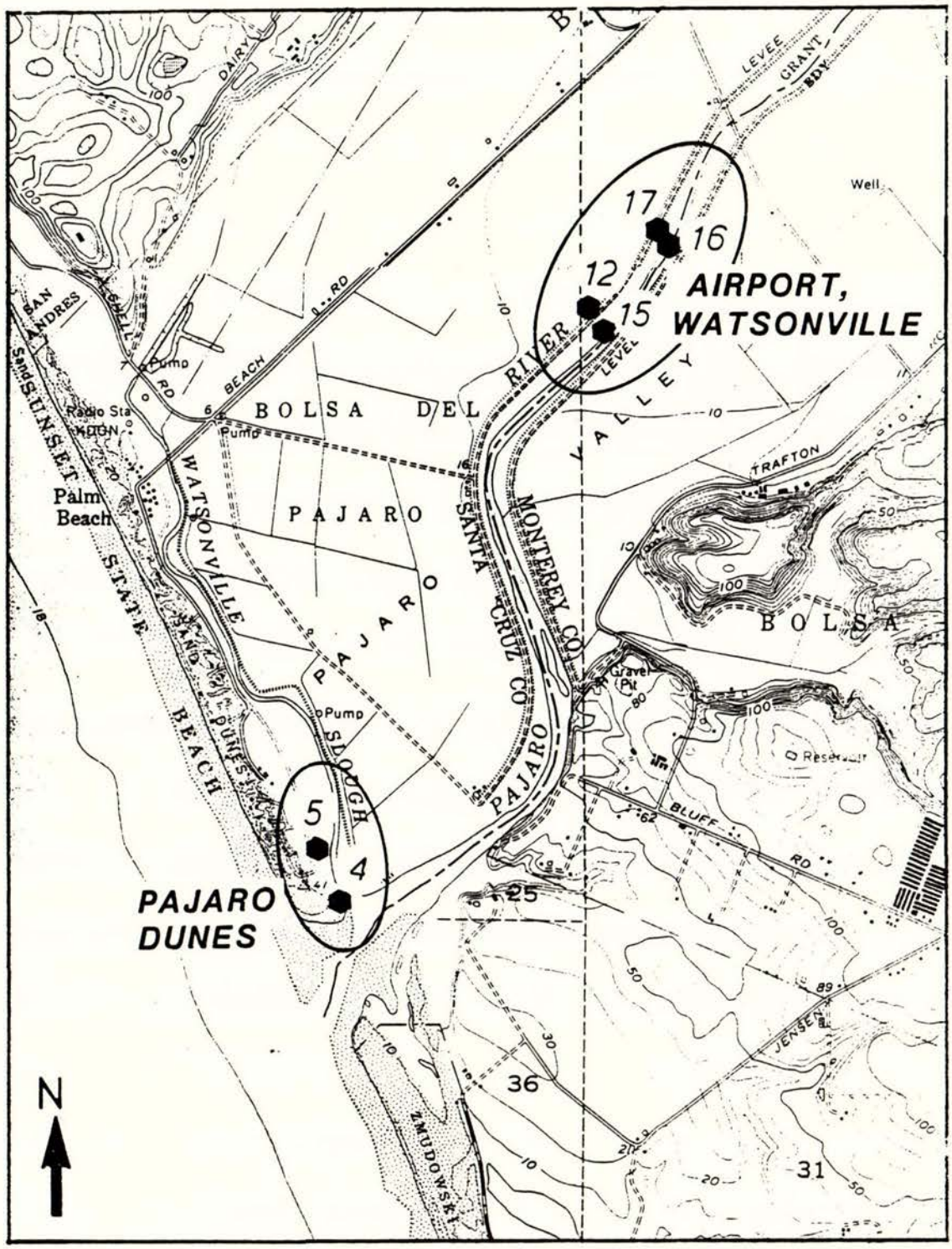

AIRPORT, WATSONVILLE
PAJARO DUNES
17
16
12
15
5
4
25
36
31
BOLSA DEL PAJARO
PAJARO VALLEY
SANTA CRUZ CO.
MONTEREY CO.
WATSONVILLE SLOUGH
PAJARO RIVER
LEVEE
GRANT
BDY.
DAIRY
SHELL RD
BEACH
SAN ANDRES
SUNSET STATE BEACH
SAND DUNES
Palm Beach
Radio Sta KHUN
Pump
Well
TRAFTON
BOLSA
Gravel Pit
Reservoir
BLUFF RD
JENSEN
ZMUDOWSKI
N

Figure 3

(4) Airport Watsonville

Model aeroplane enthusiasts residing in the Pajaro Valley make use of a runway which has been constructed inside the north levee of the Pajaro River, situated approximately midway between Watsonville and Pajaro Dunes. This "airport" can be accessed from Watsonville by heading west along Beach Road, turning left onto Thurwachter Road then right onto the levee itself. The runway is in parallel alignment with the river and levee.

Lateral spreading of the Pajaro River banks disrupted the surface of the runway, causing cracking and changes in elevation throughout its cross-section. Four tests, located in Figure 3, were conducted here, one outside and three inside the levee. The test outside the levee, and one between the runway and the river, were conducted at the south west end of the runway. The other two tests were conducted at the north east end of the runway, one between the levee and the runway and one between the runway and the river. The cone was de-aired for all four of these tests. During the last week of May, the author worked with the U.S.G.S team conducting Standard Penetration Tests at this site also.

(5) Jefferson Castroville

The Jefferson produce farm is bordered on its north side by the south levee of the Salinas River. It is situated to the east of Highway 1, approximately 4 km south of the small township of Castroville. The Loma Prieta earthquake caused significant subsidence of approximately one third of the 50 hectare farm, reducing the elevation of some regions by as much as half a metre. This disrupted the drainage of the fields, making it necessary for them to be re-levelled. The subsidence had not ceased at the time of the piezocone probing, and it is causing on-going problems for the land owner.

The cone was de-aired for all of the four tests conducted here. Two probes were performed inside the levee on a track which led to the river. The other two were

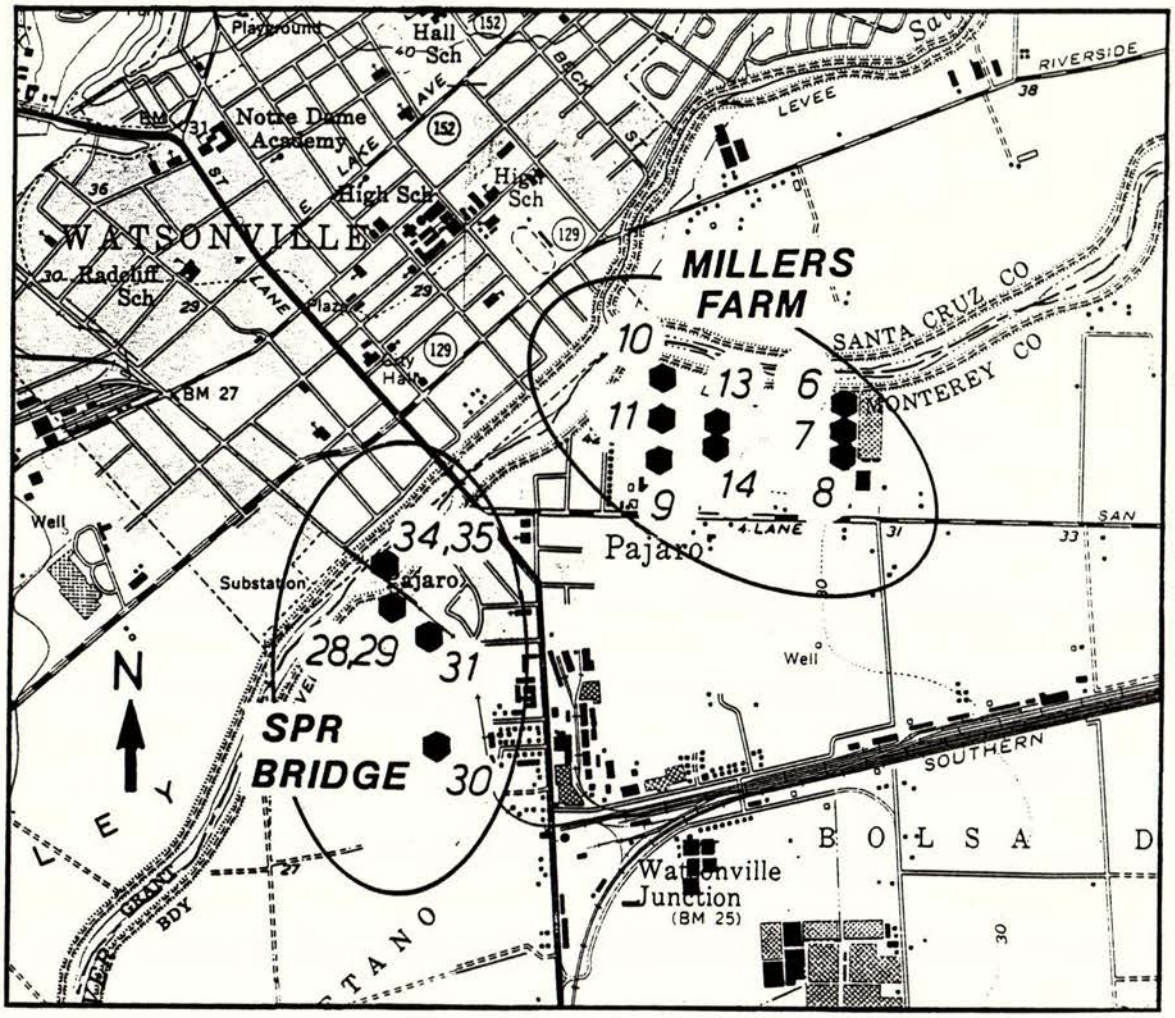


Figure 4

conducted on the tracks dividing the fields, one close to the levee and one further away on higher ground, outside the failure zone. Locations are shown in Figure 5.

(6) Scattini

The Scattini site is nestled into a loop of the Old Salinas River, a few hundred metres east of the coast. The site is accessed by heading north-west out of Castroville along Highway 1, turning left onto Molera Road, right over the Old Salinas River bridge then left onto Monterey Dunes Way.

The Loma Prieta earthquake initiated a large lateral spread at this site, the slide block moving to the north. Two de-aired tests were conducted here along the centreline of the spread. The first was within 20 metres of the slough towards which the spreading occurred, and the second was approximately 200 metres away from the slough, outside the apparent failure zone. Test sites are shown in Figure 5.

(7) Sea Mist

At this site a large lateral spread towards the Salinas River occurred. In this instance the slide block moved to the south-west. The cumulative movement totalled approximately 2 metres.

The Sea Mist property is less than 2 km south of Scattini, and its southern border is the north bank of the Salinas River. Two de-aired tests were conducted here, one inside and one outside the lateral spread limit. Figure 5 shows the locations.

(8) Leonardini

This site is similar to the Sea Mist site but is 500 metres further upstream along the Salinas River. As with Sea Mist, the southern boundary of the Leonardini property is the north bank of the Salinas River. The farm is bordered to the east by Highway 1.

Two de-aired holes were conducted here, again one inside and one outside the lateral spread limit, as shown in Figure 5.

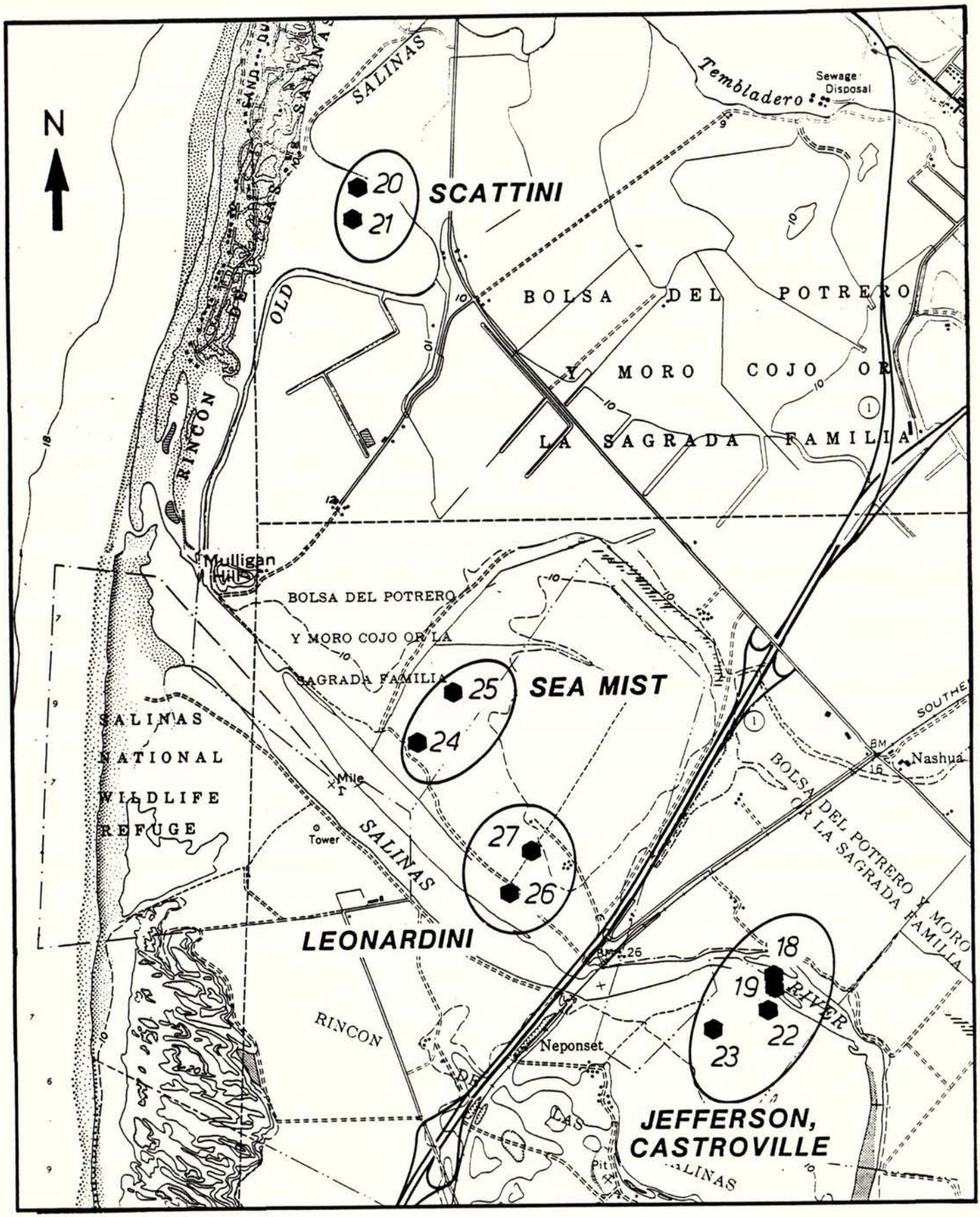

N
SCATTINI
20
21
SALINAS
Tembladero
Sewage Disposal
OLD SALINAS
BOLSA DEL POTREROY MORO COJO OR LA SAGRADA FAMILIA
RINCON
Mulligan Hill
BOLSA DEL POTREROY MORO COJO OR LA SAGRADA FAMILIA
25
24
SEA MIST
SALINAS NATIONAL WILDLIFE REFUGE
Mile
Tower
SALINAS
27
26
LEONARDINI
Nashua
BOLSA DEL POTRERO Y MORO COJO OR LA SAGRADA FAMILIA
18
19
22
23
RIVER
RINCON
Neponset
JEFFERSON, CASTROVILLE
Pit

Figure 5

(9) Southern Pacific Railroad Bridge

The Southern Pacific Railroad bridge crosses the Pajaro River approximately 400 metres downstream of the Watsonville Main Street bridge. The bridge was subjected to both compression due to lateral spreading and shaking during the Loma Prieta event. One concrete pier on the south bank failed, but it was replaced with braced steel columns before the piezocone work was performed. Extensive ground cracking was evident inside and outside the south levee.

A total of 6 tests were conducted at this site, as shown in Figure 4. The cone was only de-aired for four of these tests. A CPT and a CPTU were conducted side by side inside the south levee, to the north side of bridge. These tests were inside the ground cracking associated with the primary lateral spread. Another CPT and CPTU were conducted outside the south levee, to the south side of the bridge. Two additional tests were conducted, one 30 metres further down the railway line (in line with an apparent secondary lateral spread), and one approximately 1 km due south of the bridge along a track centreline (this probe was away from the failure zone, in a different geological deposit). The tests conducted outside of the levee were on land owned by Mr Sakata.

(10) Marina District

The Marina district is situated at the very northern tip of the San Francisco peninsula. The district is residential and consists of large apartment blocks and three to four storey timber framed buildings.

Two probes were conducted here, one in the centre of the Marina Green in line with the centre of Filmore Street, and the other in the courtyard of the Winfield Scott school. The cone was de-aired for both of these. The first hole went to a depth of almost 20 metres and could have gone further if more rods had been available. The

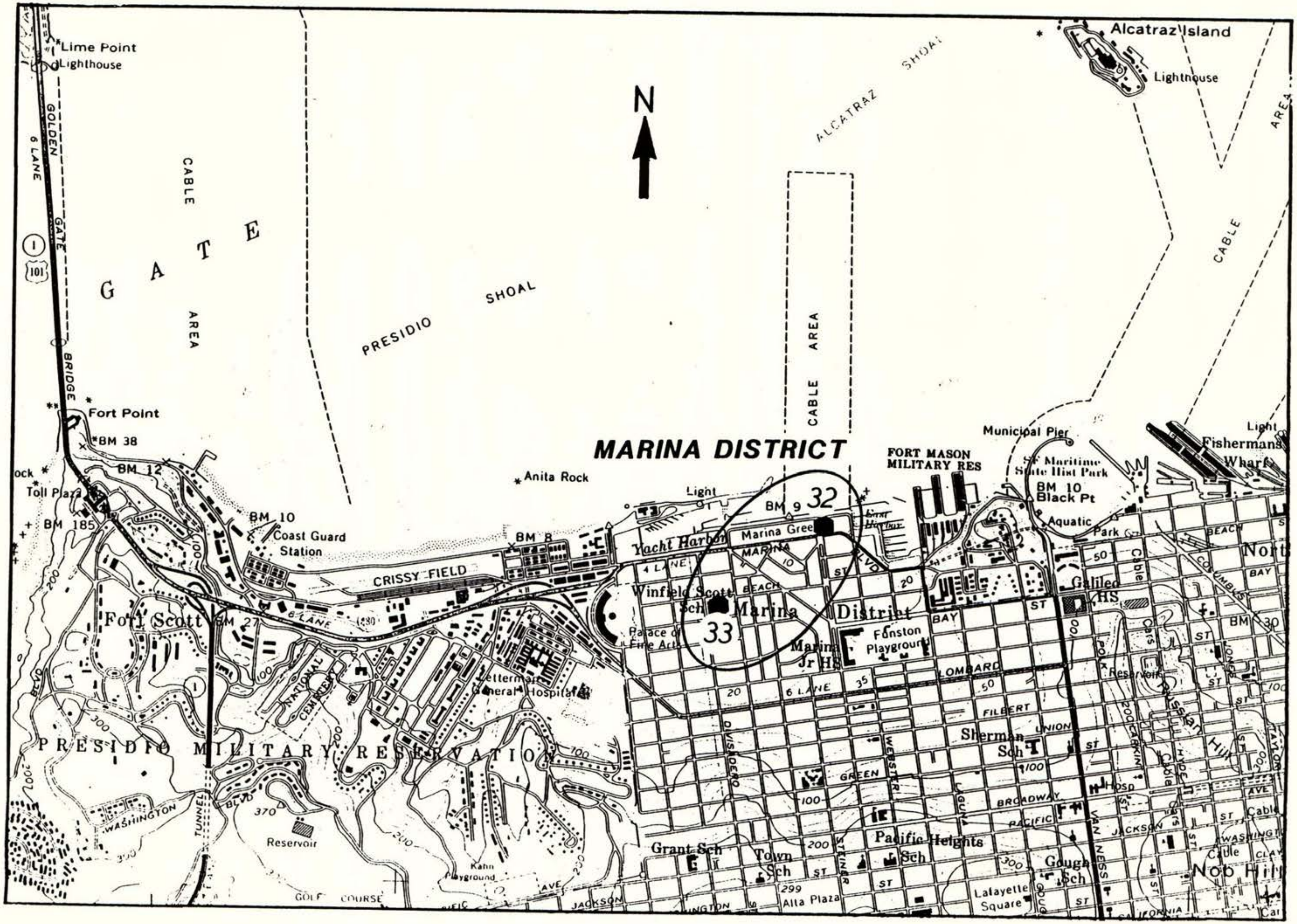

N
MARINA DISTRICT
32
33
Alcatraz Island
Lighthouse
ALCATRAZ SHOAL
CABLE AREA
Lime Point
Lighthouse
GOLDEN GATE BRIDGE
6 LANE
G A T E
PRESIDIO SHOAL
Fort Point
BM 38
BM 12
Toll Plaza
BM 185
BM 10
Coast Guard
Station
CRISSY FIELD
BM 8
Anita Rock
Light
BM 9
Marina Green
Yacht Harbor
MARINA
BLVD
Winfield Scott
Sch
Marina
District
Palace of
Fine Arts
Fonston
Playground
Marina
Jr HS
LOMBARD
FORT MASON
MILITARY RES
Municipal Pier
BM 10
Black Pt
Aquatic
Park
Galileo
HS
Fishermans
Wharf
Light
BEACH
BAY
COLUMBUS
Fort Scott
BM 27
NATIONAL
CEMETERY
Letterman
General Hospital
PRESIDIO MILITARY RESERVATION
WASHINGTON
TUNNEL
BLVD
Reservoir
Kahn
Playground
GOLF COURSE
JACKSON
FILBERT
UNION
GREEN
BROADWAY
PACIFIC
DIVISADERO
WEBSTER
STEINER
LAGUNA
VAN NESS
Sherman
Sch
Hosp
Grant Sch
Town
Sch
Pacific Heights
Sch
Alta Plaza
Gough
Sch
Lafayette
Square
Russian Hill
Nob Hill
Reservoir
Cable
CALIFORNIA

Figure 6

second hole only went to a depth of 4.7 metres due to complications with the drill rig lifting. The test locations are shown in Figure 6.

GENERAL COMMENTS

A standard testing procedure was followed for each probe conducted in California in order to minimize errors. There are, however, several possible sources of errors within the experimental set-up.

The zero readings for the piezocone were stable, with only minor fluctuations creating errors of approximately one percent. Plots of the variation in the zero readings for the "Qc", "Qf", "U" and "C+F" channels have been included in the appendices. Only one zero reading has been abandoned as erroneous and replaced by an average zero. This reading was for the "U" channel during test number 21 (the second test at the Scattini site).

The depth recording device mounted on the drill rig consistently measured short during probing in dense sands, due to complications with the drill rig lifting. This depth error was checked on numerous occassions, and it consistently fell between 0.5% and 1%. As yet this has not been allowed for in the main file. Typically a probe of 1000mm would register as 993mm on the device. This error is cumulative of course.

The cone was calibrated in May before the first test and a new set of calibration factors calculated. A second calibration was performed late in June at the end of testing. The variation between the two sets of calibration factors came to less than 0.3%, indicating that there were no major changes in the cone during the testing.

ACKNOWLEDGEMENTS

The authors wish to thank the Earthquake and War Damage Commission for their financial support of the project and to Messers T.L. Holzer, M.J. Bennett and J.C. Tinsley III of the USGS for their cooperation in the project and for the warm welcome they showed us both during the testing and immediately after the Loma Prieta earthquake itself.

APPENDIX I

Comparison of labels, watertable levels and estimated peak acceleration

Location	USGS Site No.	University of Canterbury Site No.	Depth of Watertable (m)	Peak ** ground acceleration (g)
Moss Landing	14B	1	1.55	0.23
	14B	2	1.51	
	14	3	2.24	
Pajaro Dunes	44	4	3.08	0.3
	43	5	3.20	
Millers Farm	3	6	4.57	0.34
	2	7	3.66	
	1	8	3.05	
	10	9	3.75	
	8	10	4.39	
	9	11	3.96	
	5	13	4.30	
	12	14	3.66	
Airport Watsonville	22	12	1.22	0.35
	21	15	1.92	
	18	16	2.12	
	16	17	1.44	
Jefferson Castroville	32	18	1.87	0.17
	33	19	1.17	
	34	22	1.50	
	35	23	3.17	
Scattini	28	20	0.74	0.20
	23	21	1.54	
Sea Mist	31	24	1.19	0.18
	29	25	2.41	
Leonardini	39	26	1.46	0.175
	37	27	2.05	
SPR Bridge	Sakata 45	28	4.54	0.34
	Sakata 48	29	(≈ 4.5m)*	
	Sakata 46	30	2.62	
	Sakata 47	31	4.51	
	Sakata 48	34	(≈ 5.0 m)*	
	Sakata 48	35	4.95	
Marina District	Marina 7	32	2.31	0.09
	Marina 8	33	2.37	

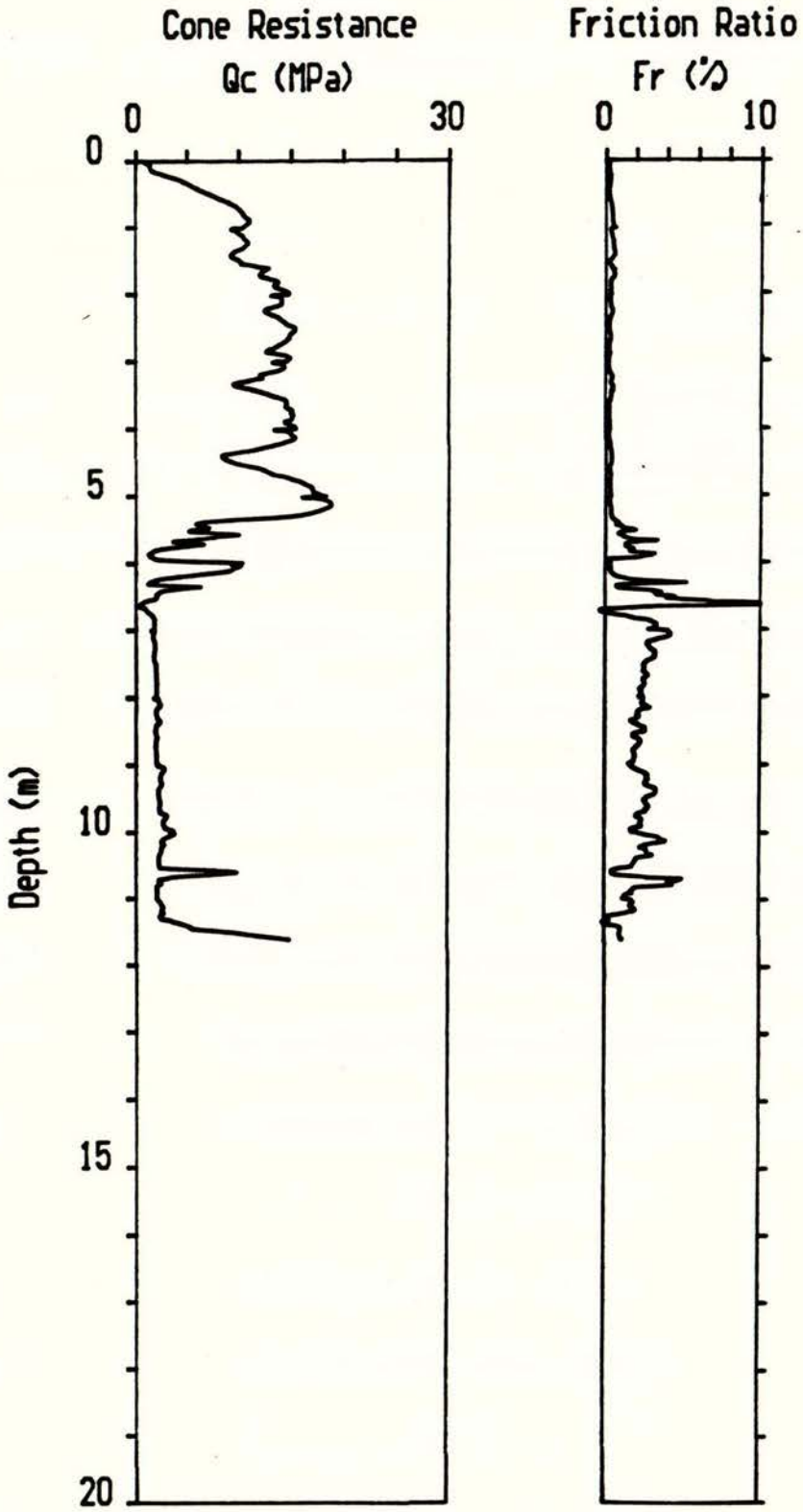
* not measured; value inferred from CPT log

** estimated by JC Tinsley, pers comm.

APPENDIX II

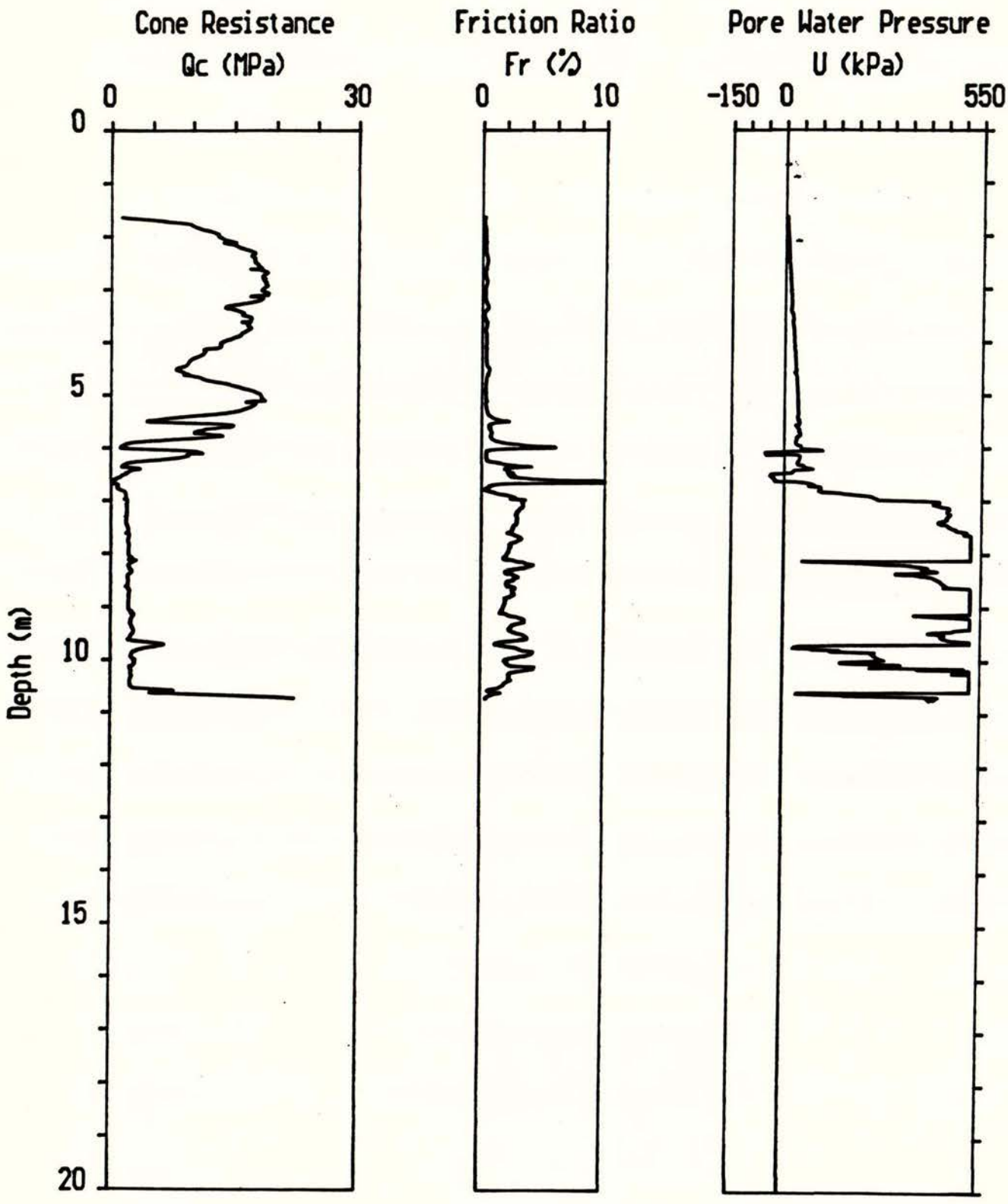
MOSS LANDING

Test 1 4 June 1990



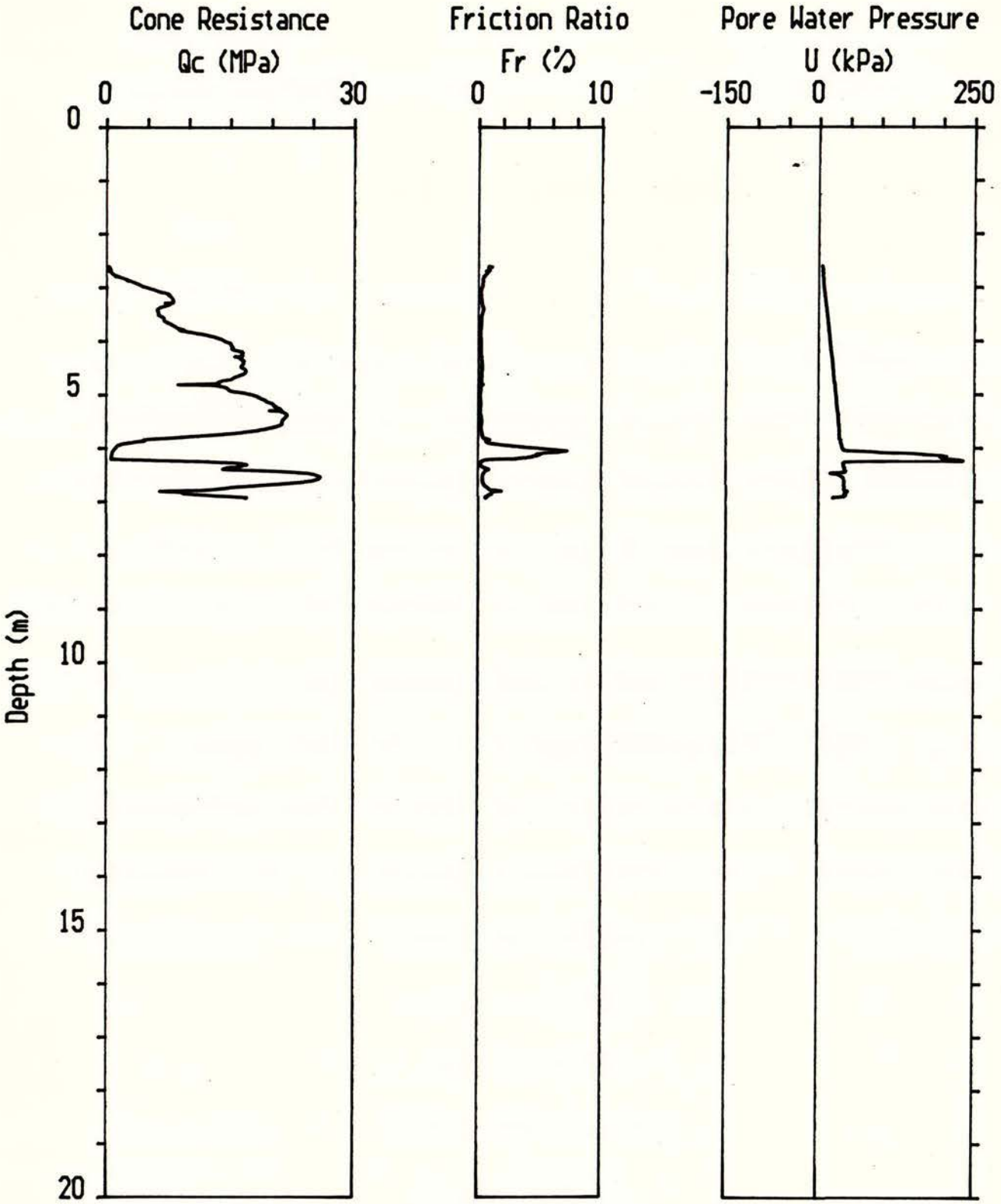
MOSS LANDING

Test 2 4 June 1990



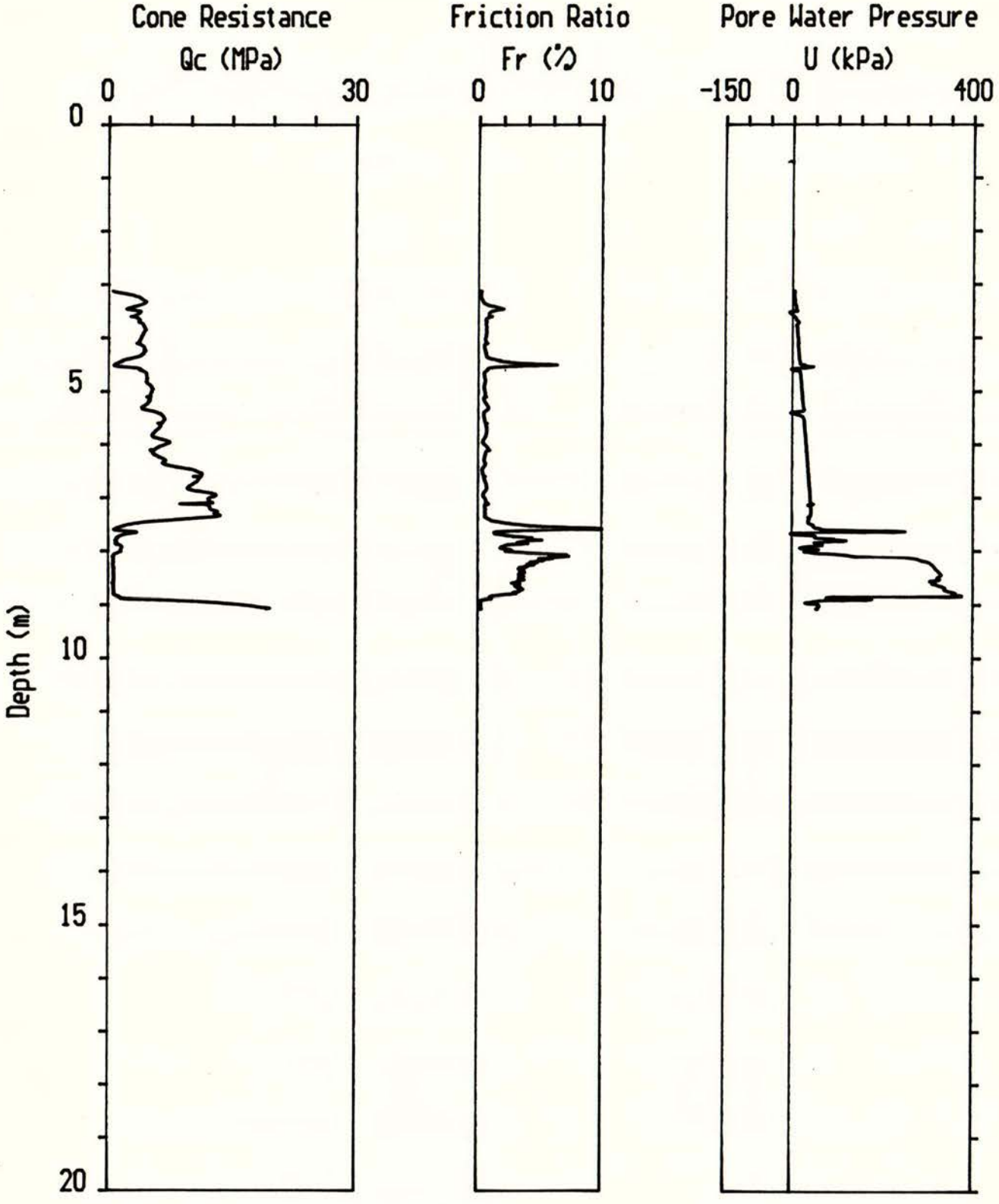
MOSS LANDING

Test 3 5 June 1990



PAJARO DUNES

Test 4 5 June 1990



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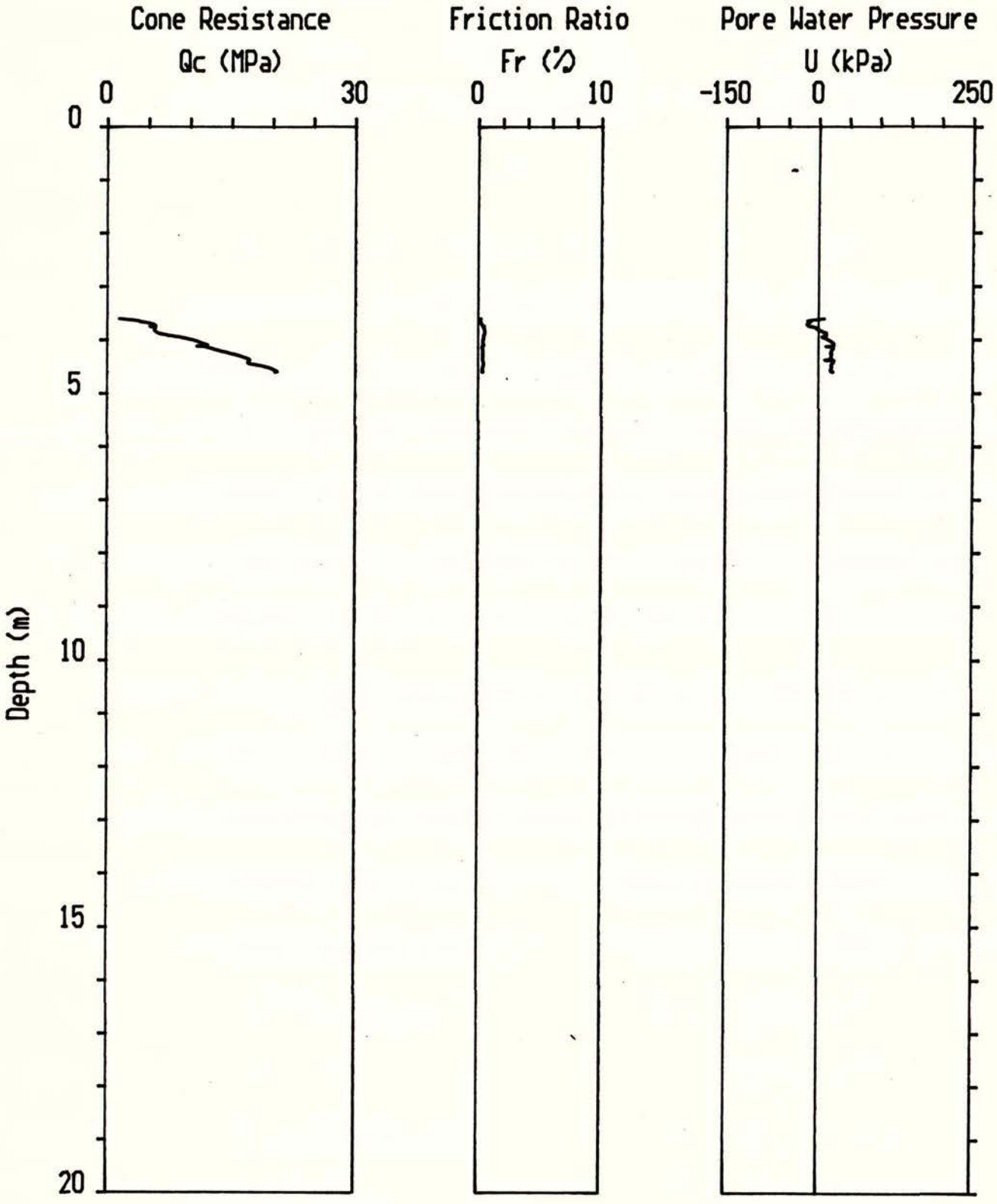
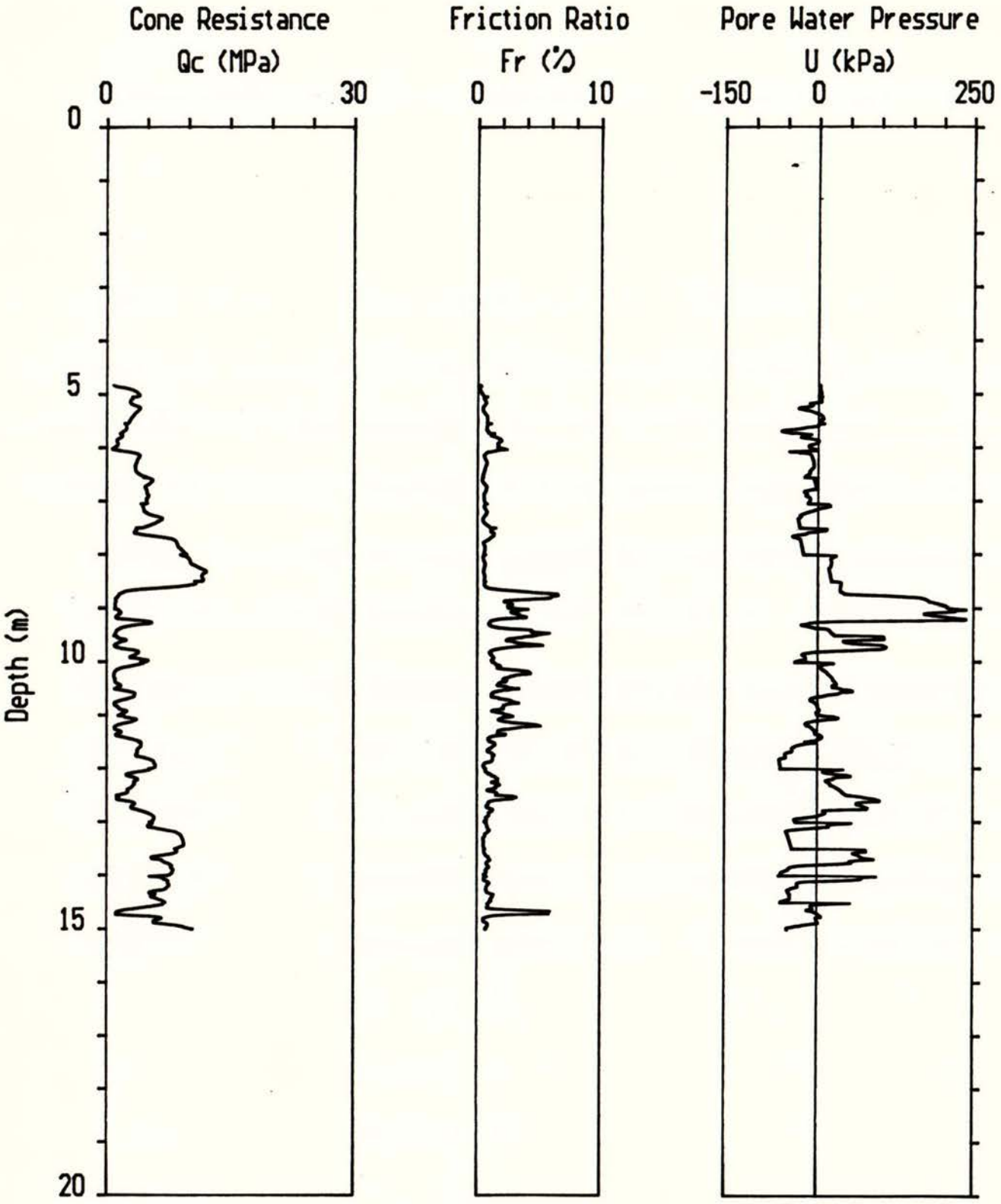


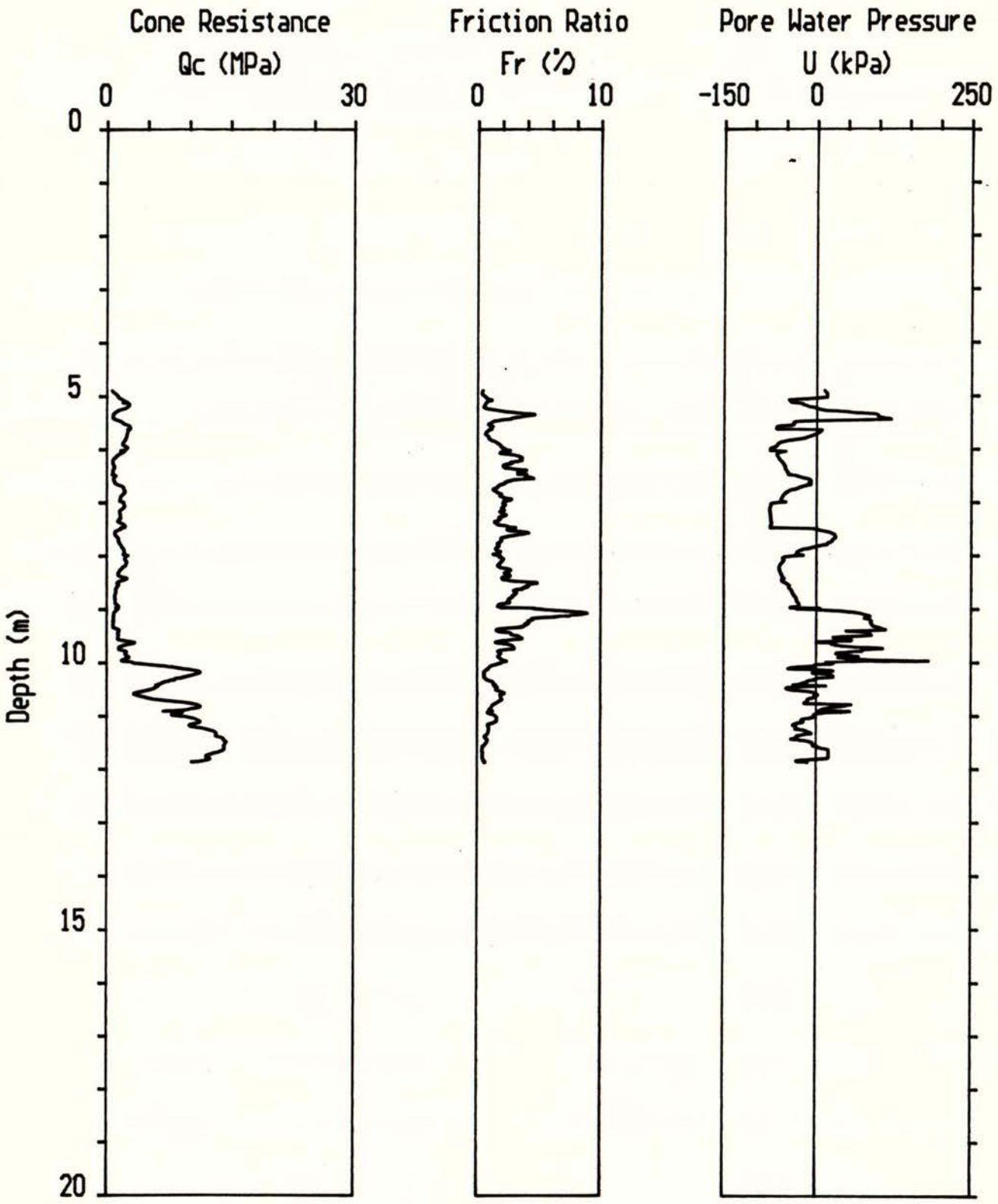
MILLERS FARM

Test 6 6 June 1990



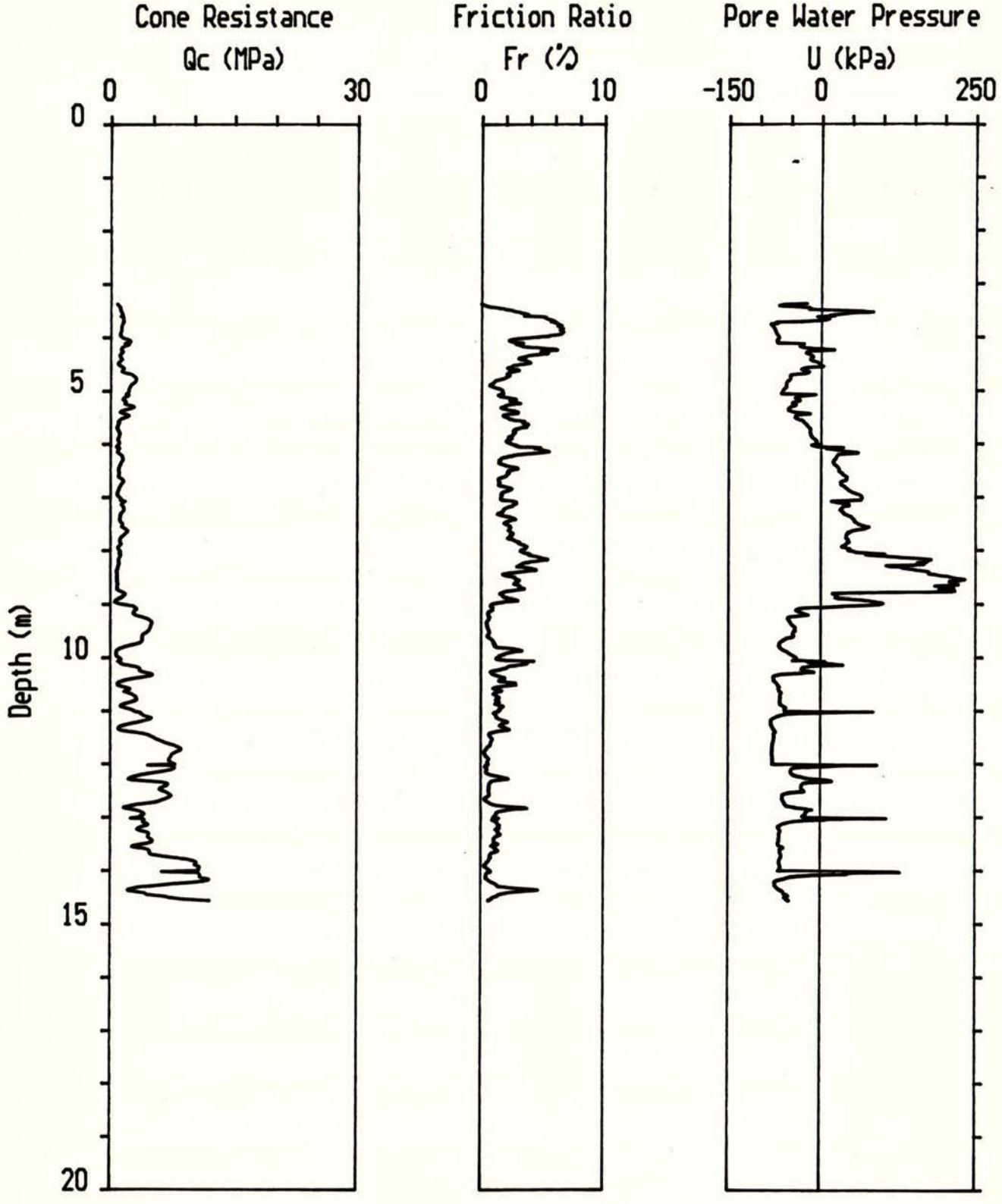
MILLERS FARM

Test 7 6 June 1990



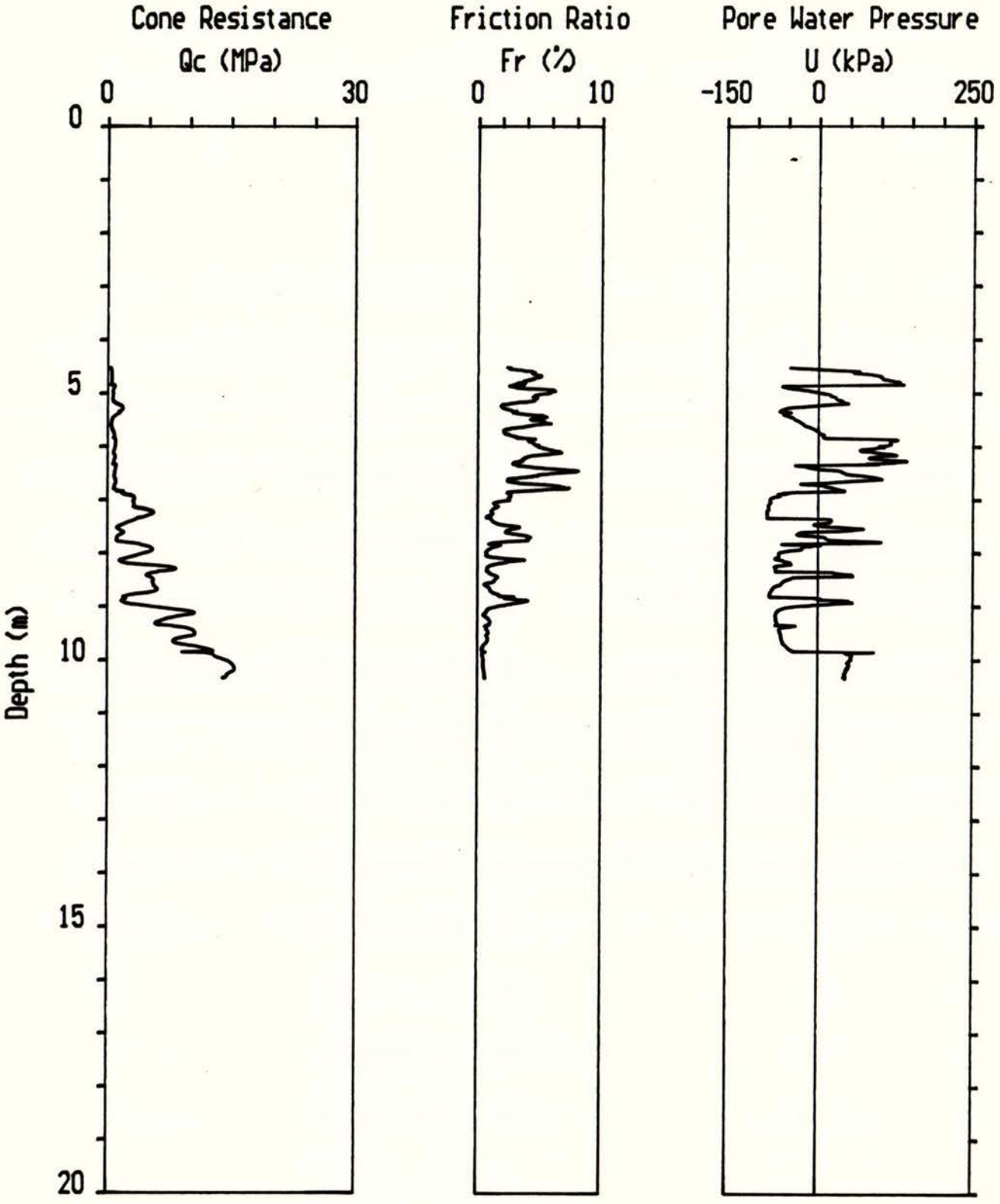
MILLERS FARM

Test 8 6 June 1990



MILLERS FARM

Test 9 7 June 1990



MILLERS FARM

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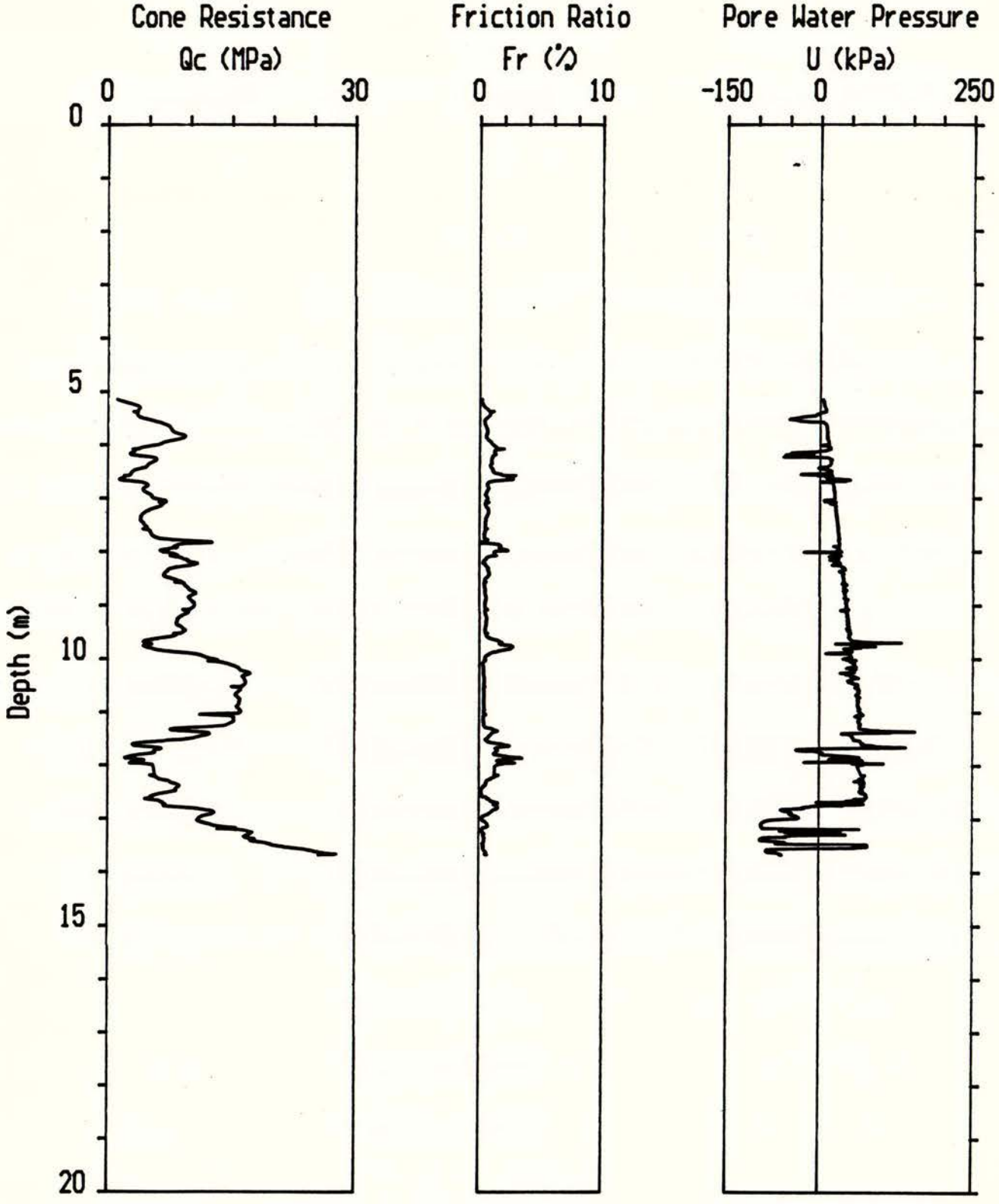

MILLERS FARM

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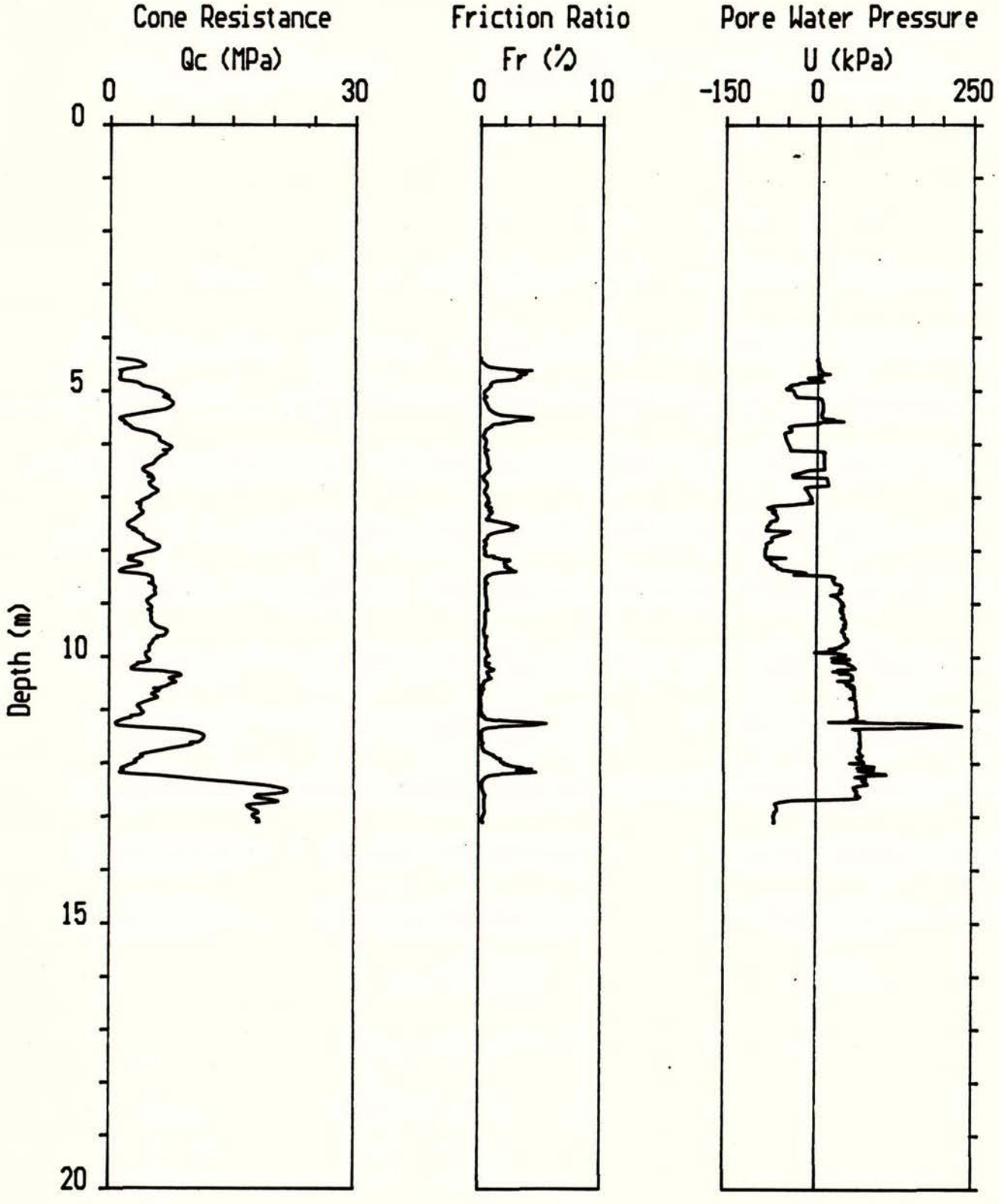
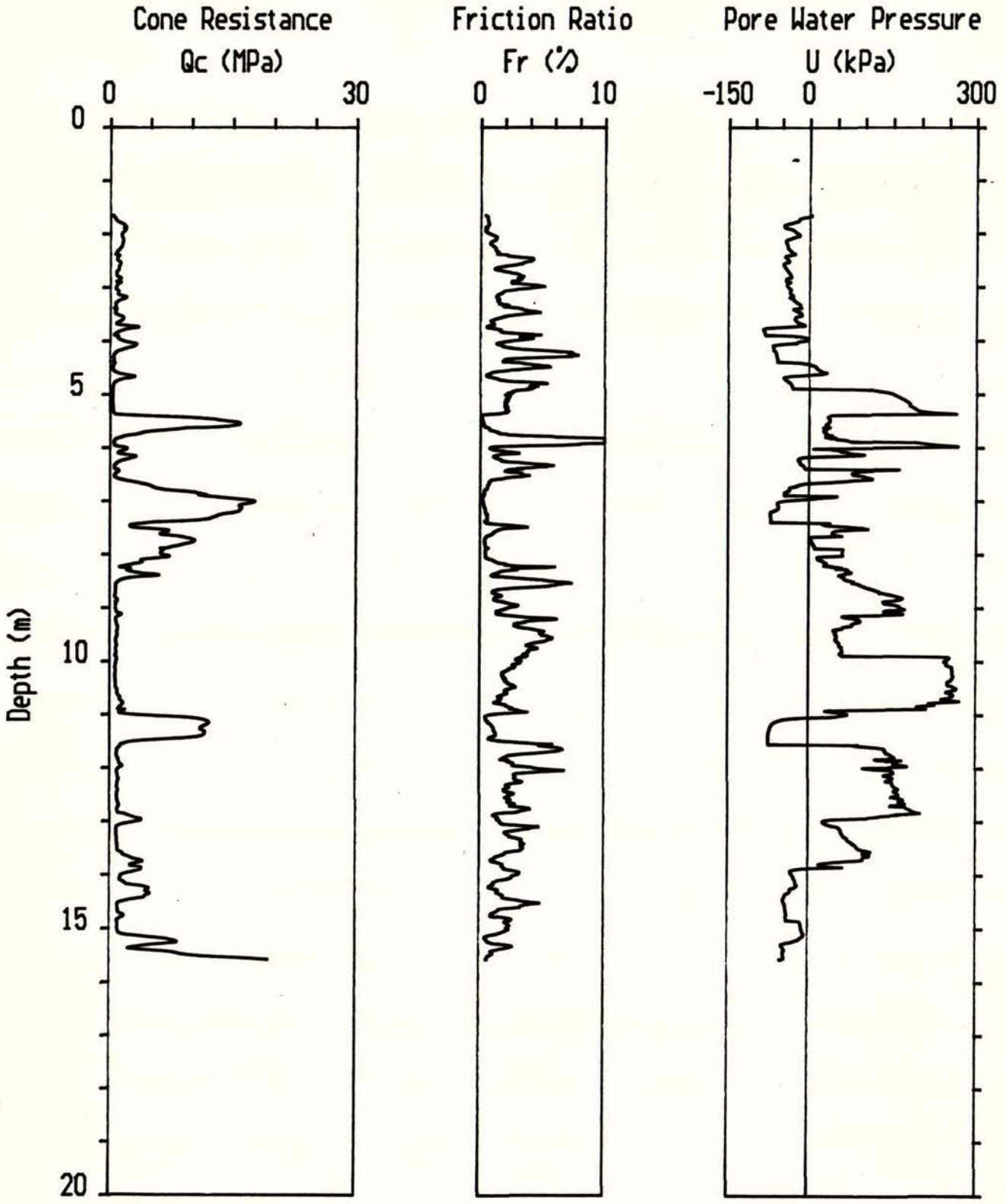


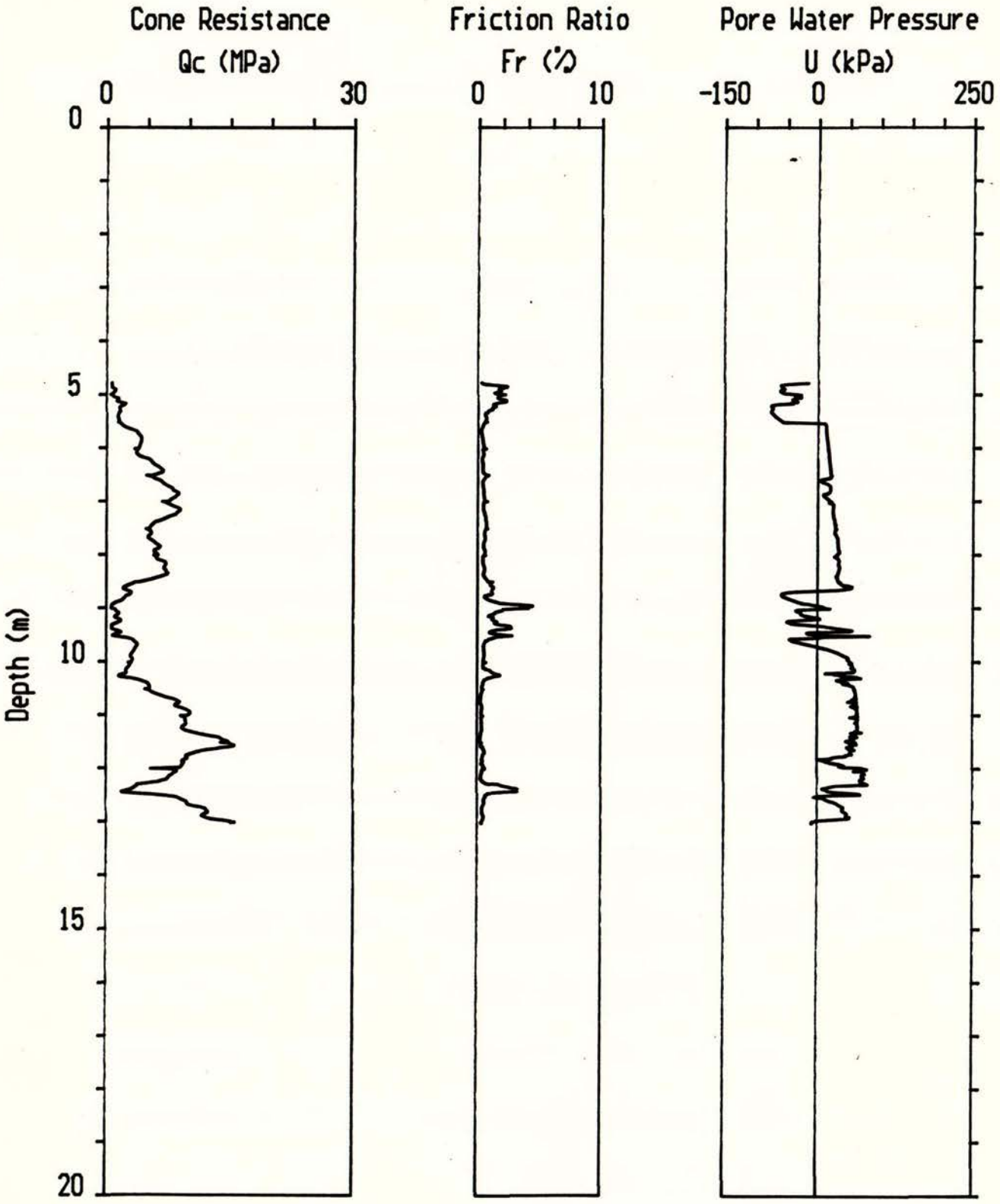
AIRPORT WATSONVILLE

Test 12 11 June 1990



MILLERS FARM

Test 13 12 June 1990



MILLERS FARM

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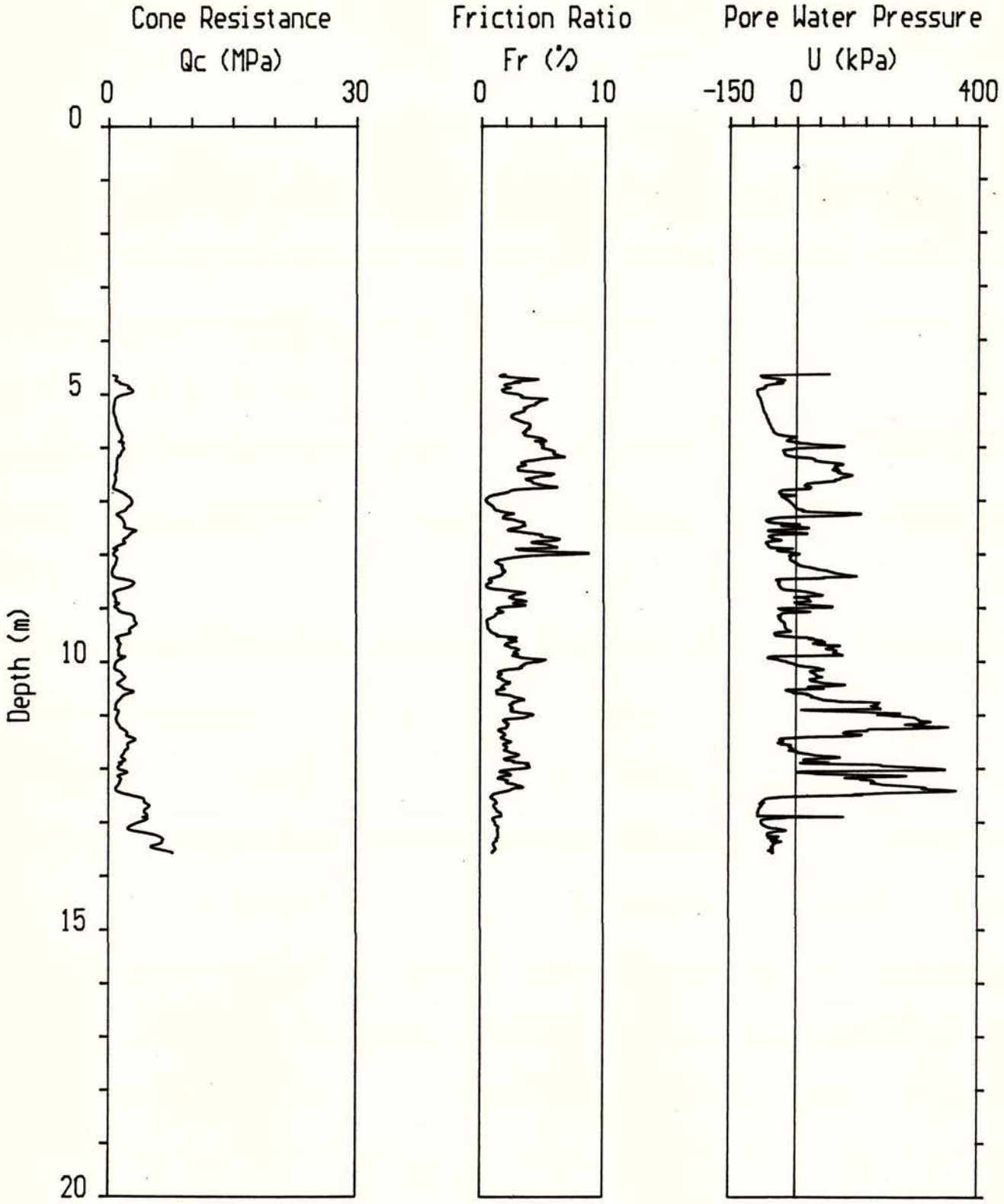
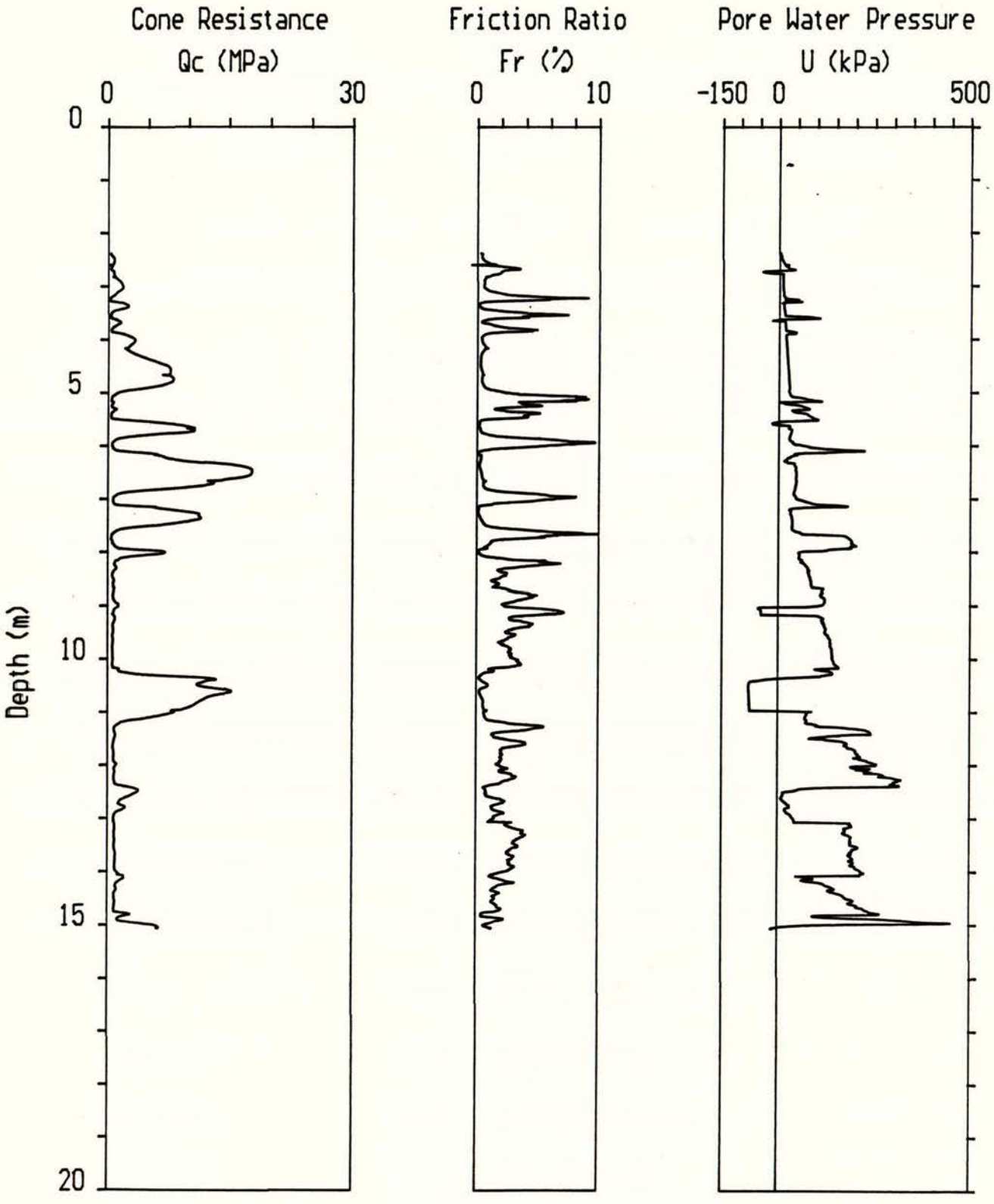


AIRPORT WATSONVILLE

Test 15 13 June 1990



AIRPORT WATSONVILLE

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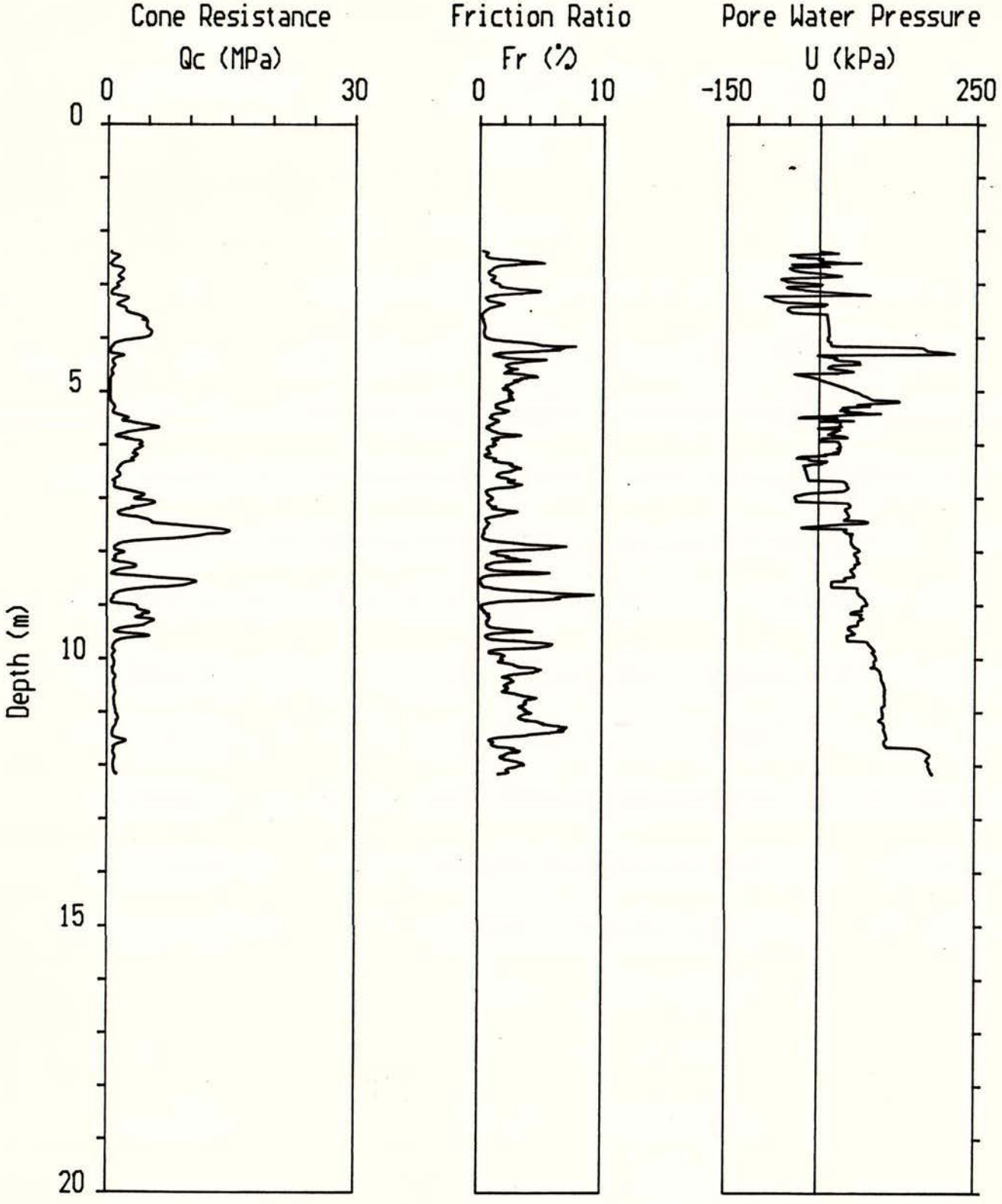

AIRPORT WATSONVILLE

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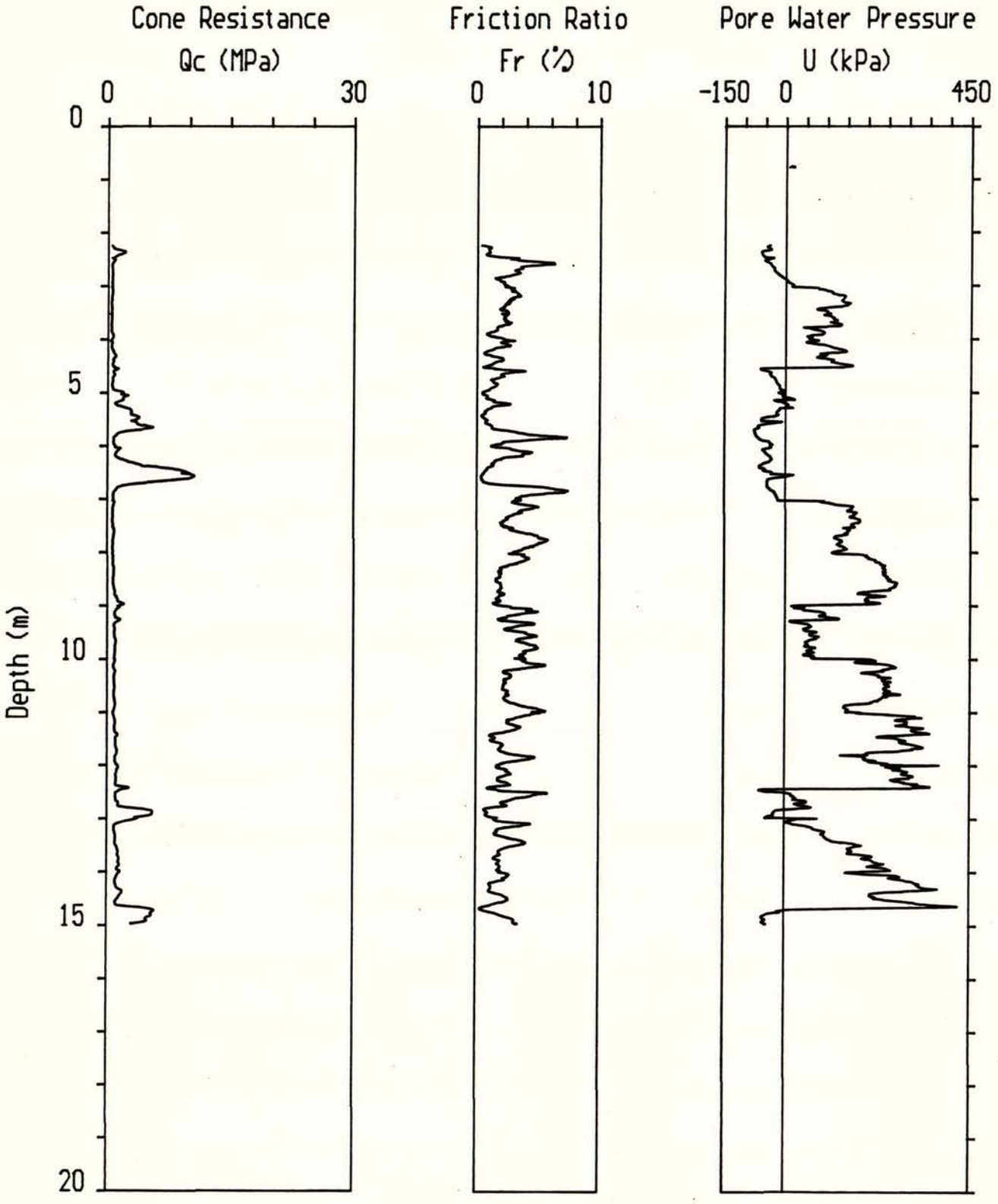

JEFFERSON

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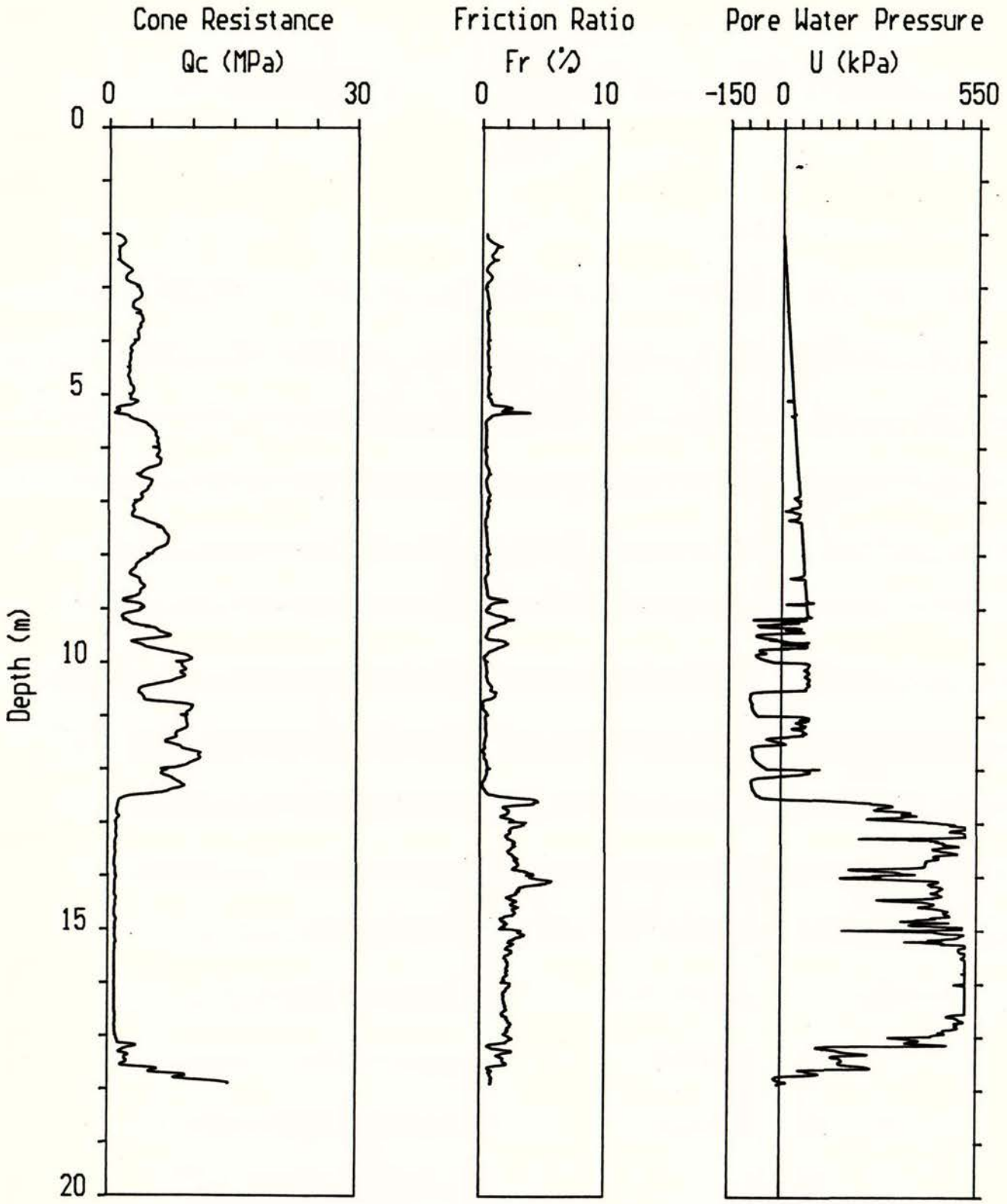

JEFFERSON

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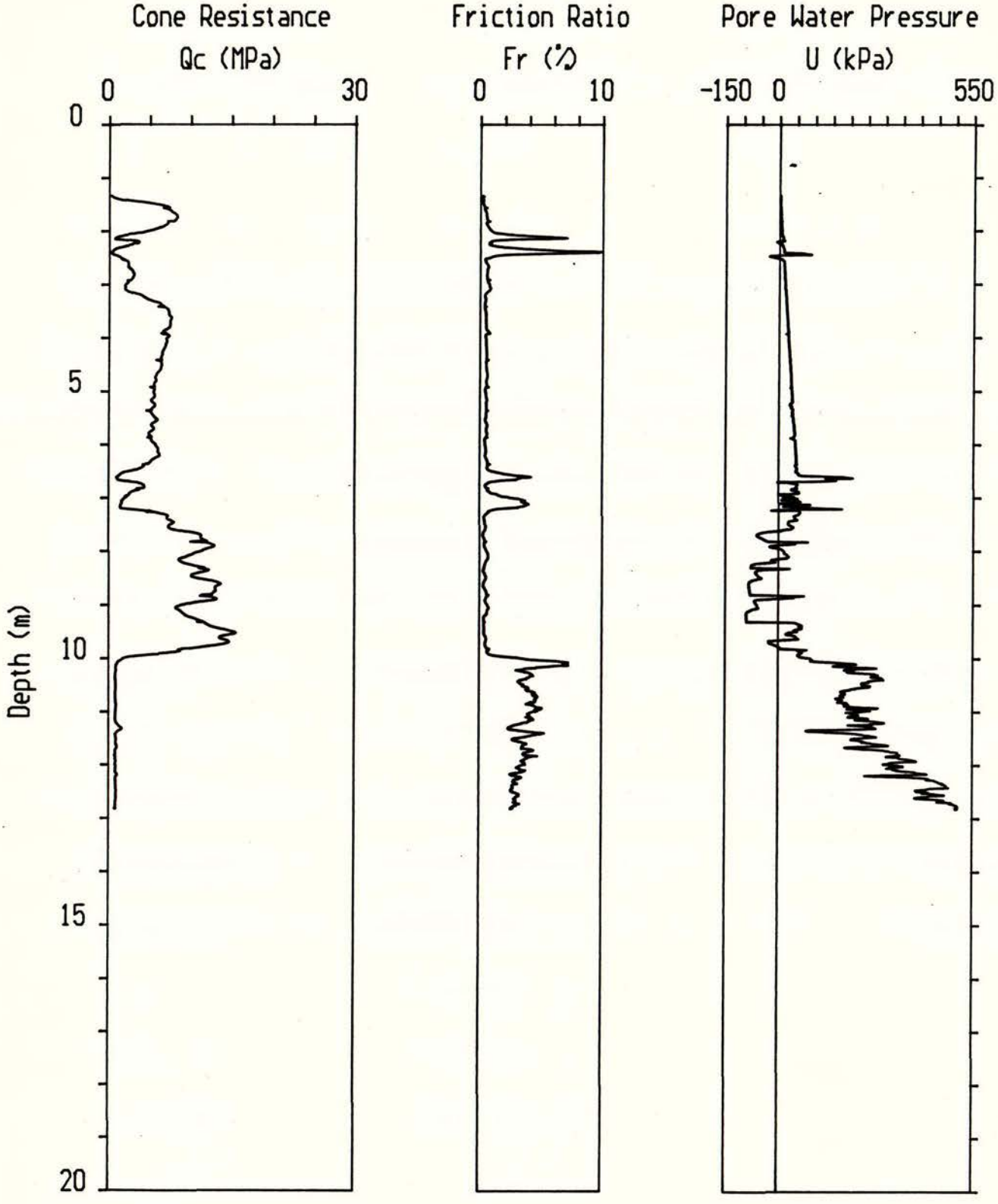

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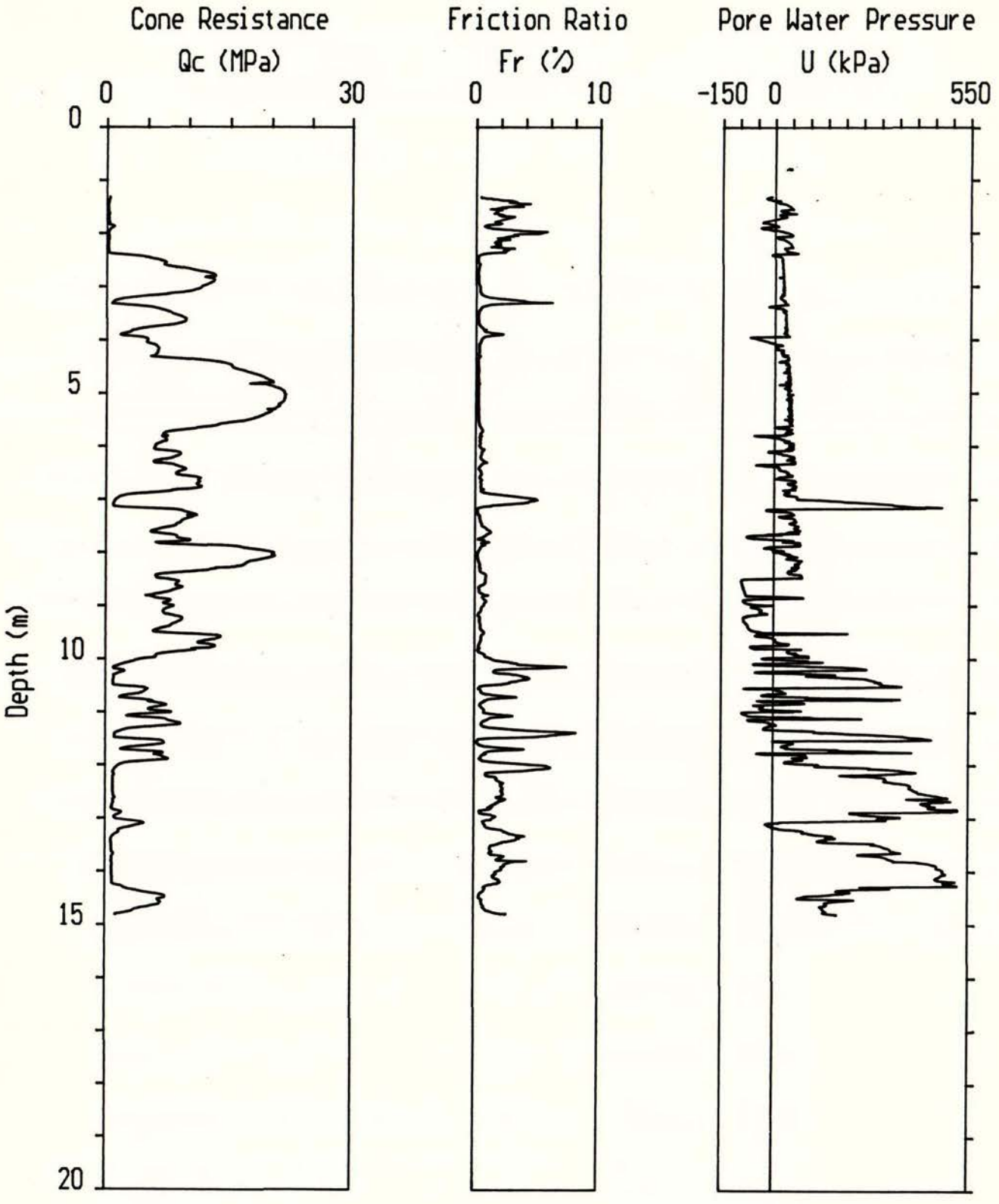

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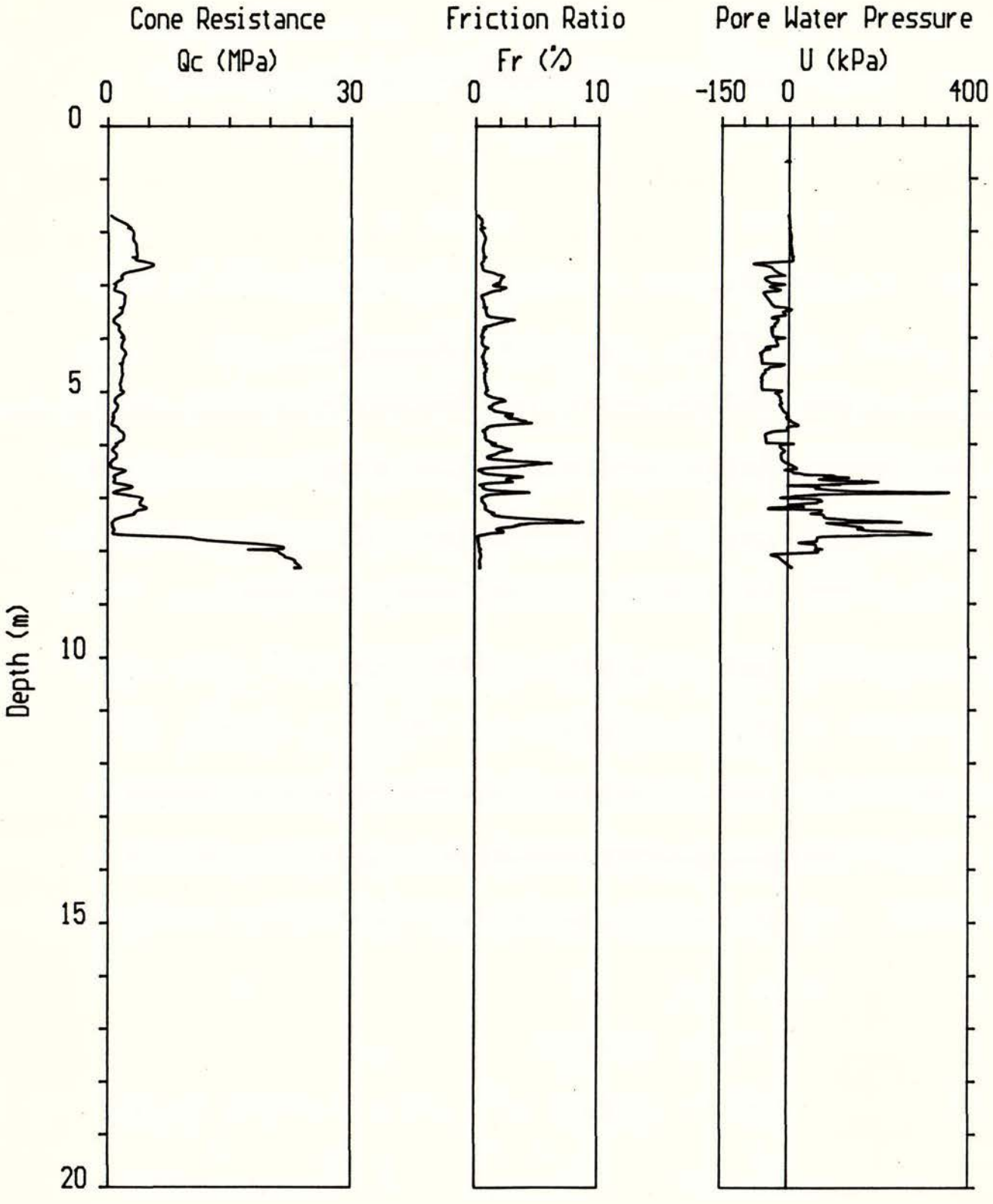

JEFFERSON

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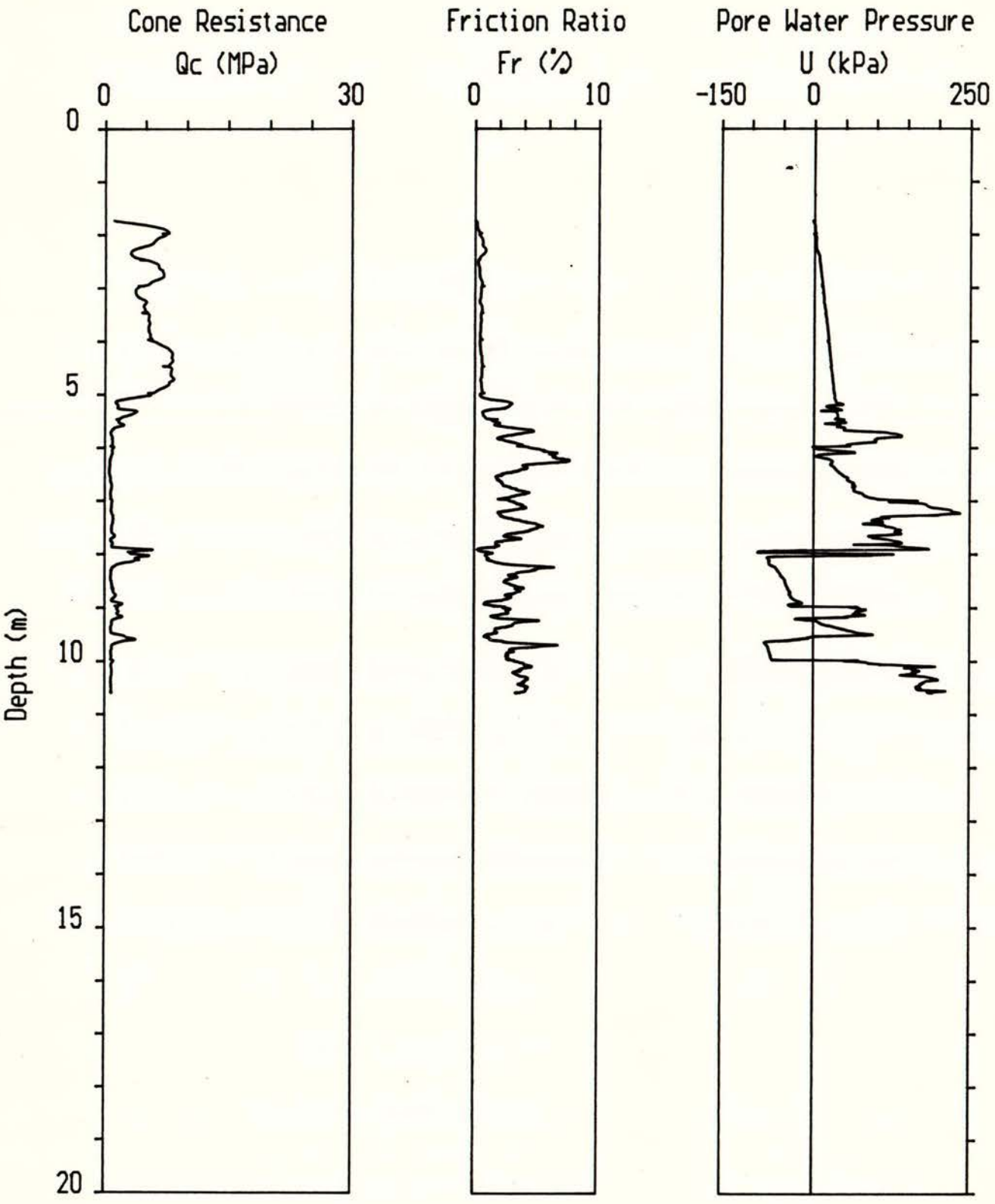

JEFFERSON

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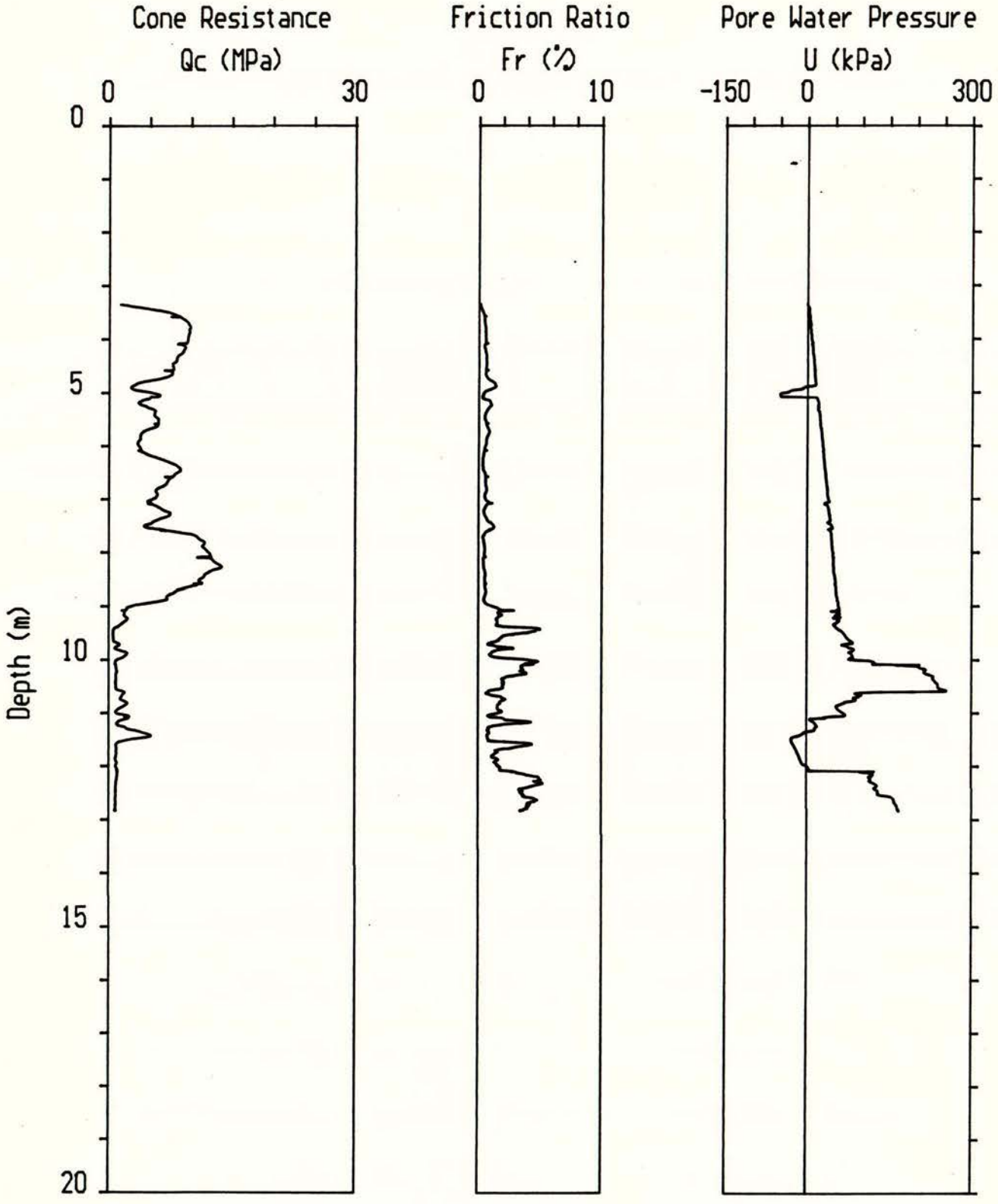

SEA MIST

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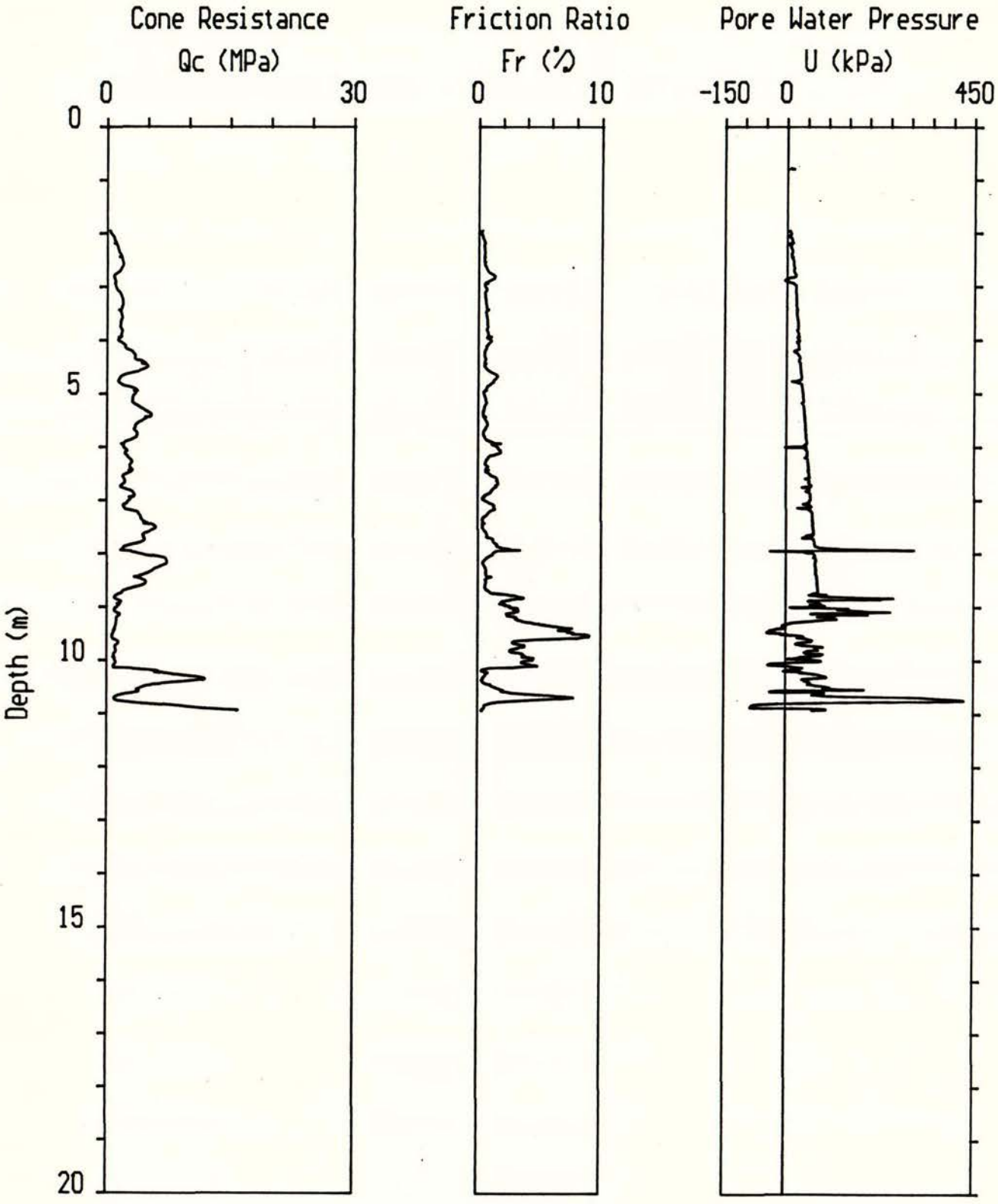

SEA MIST

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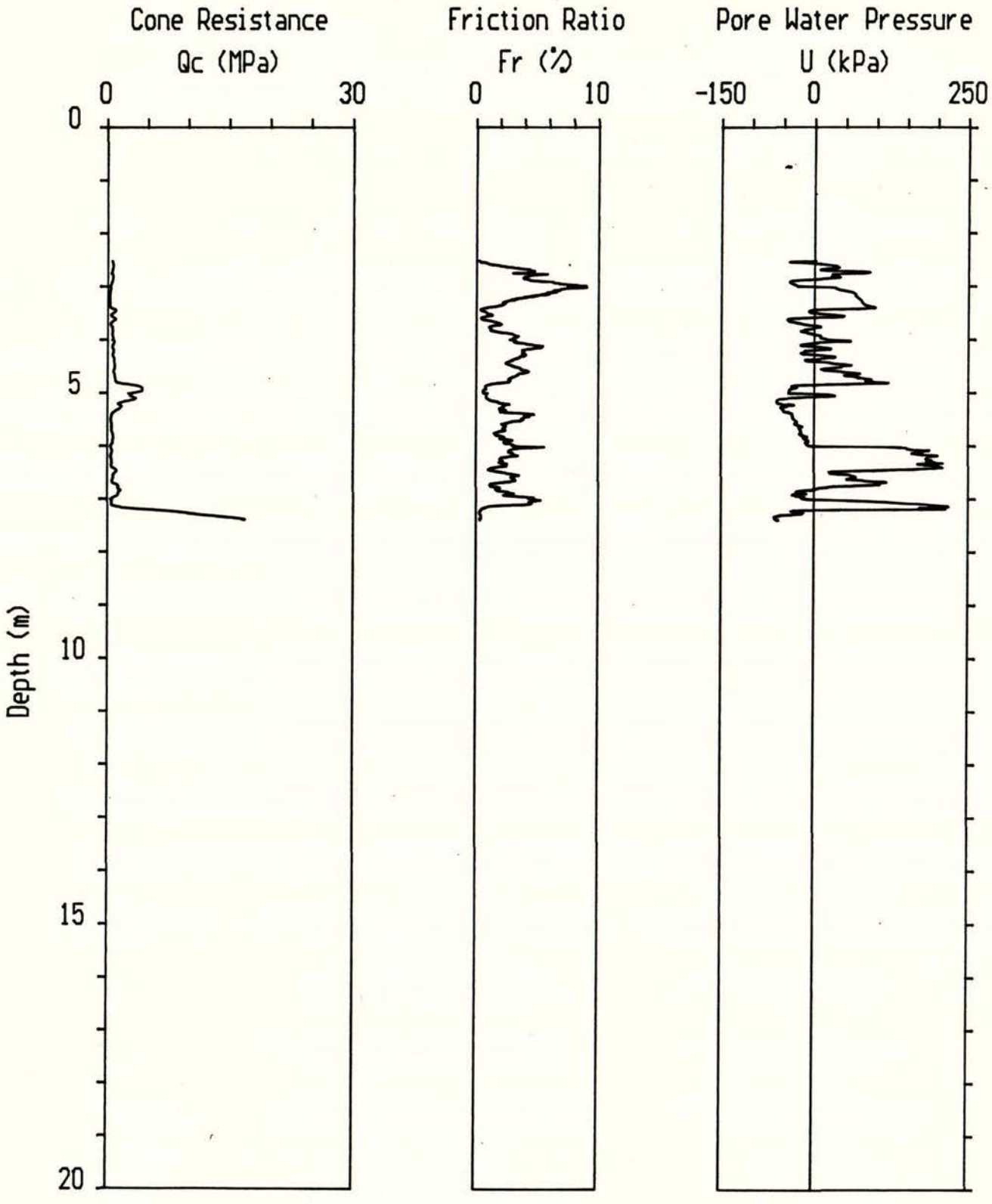

LEONARDINI

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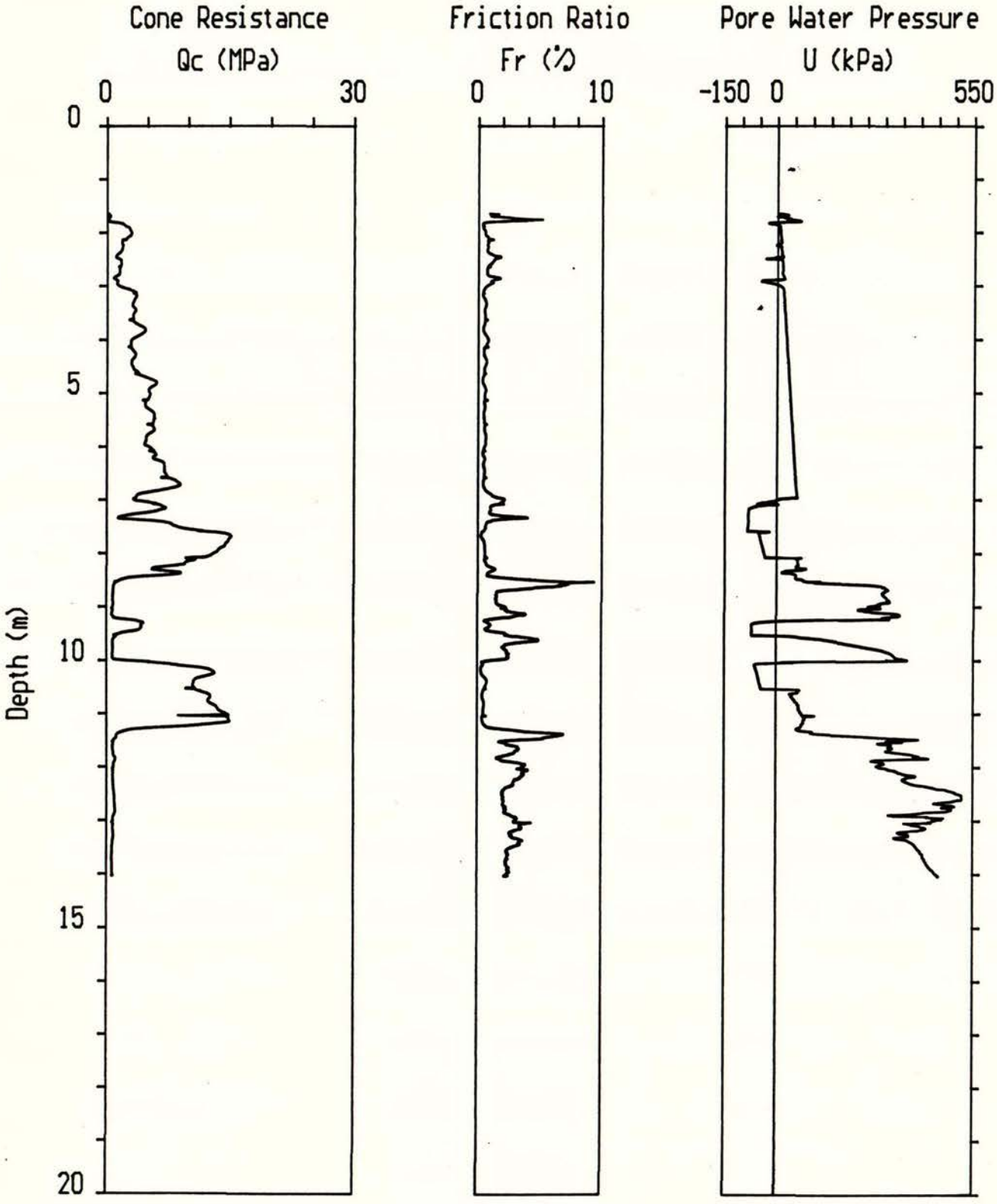

LEONARDINI

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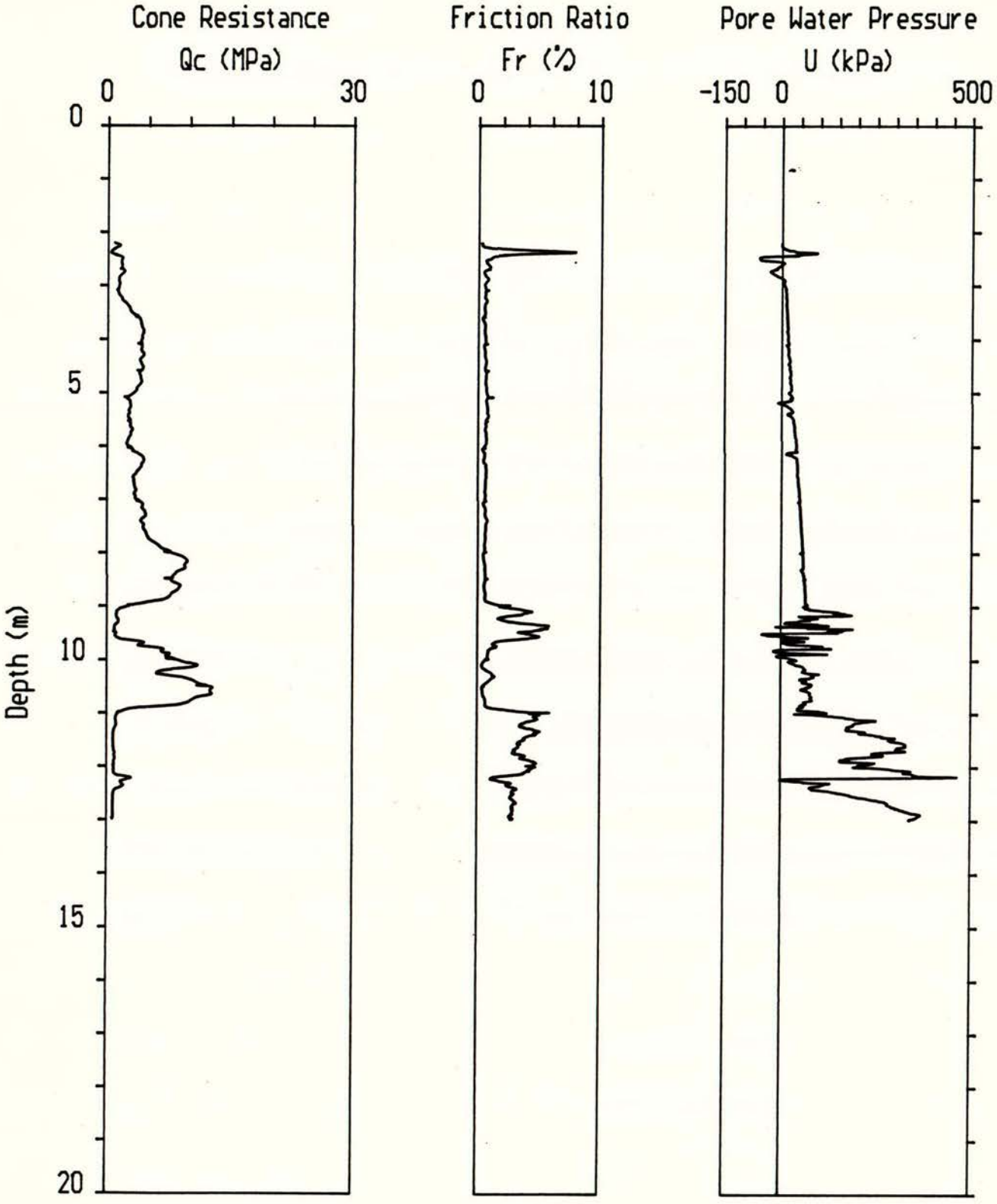

SPR BRIDGE

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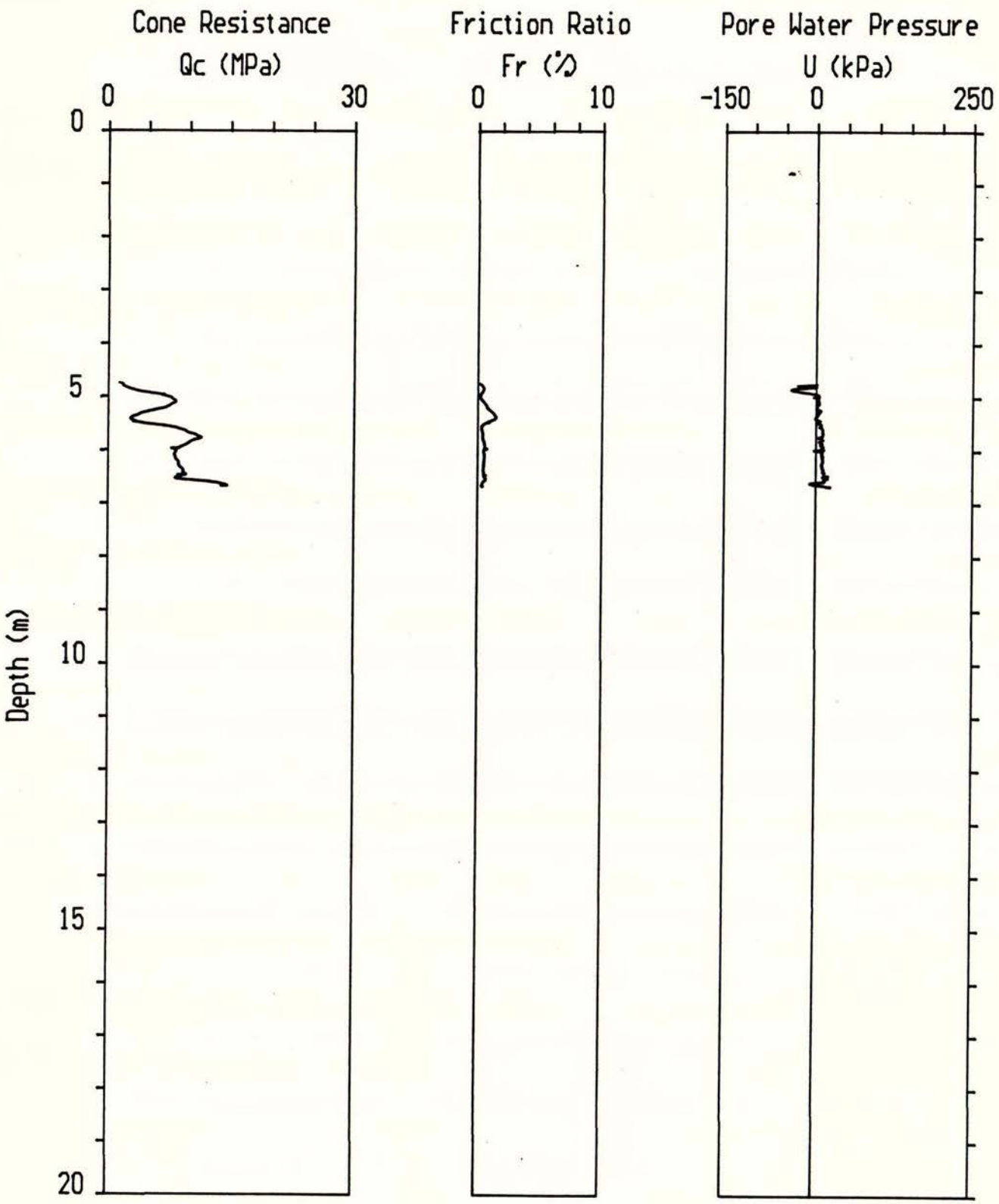

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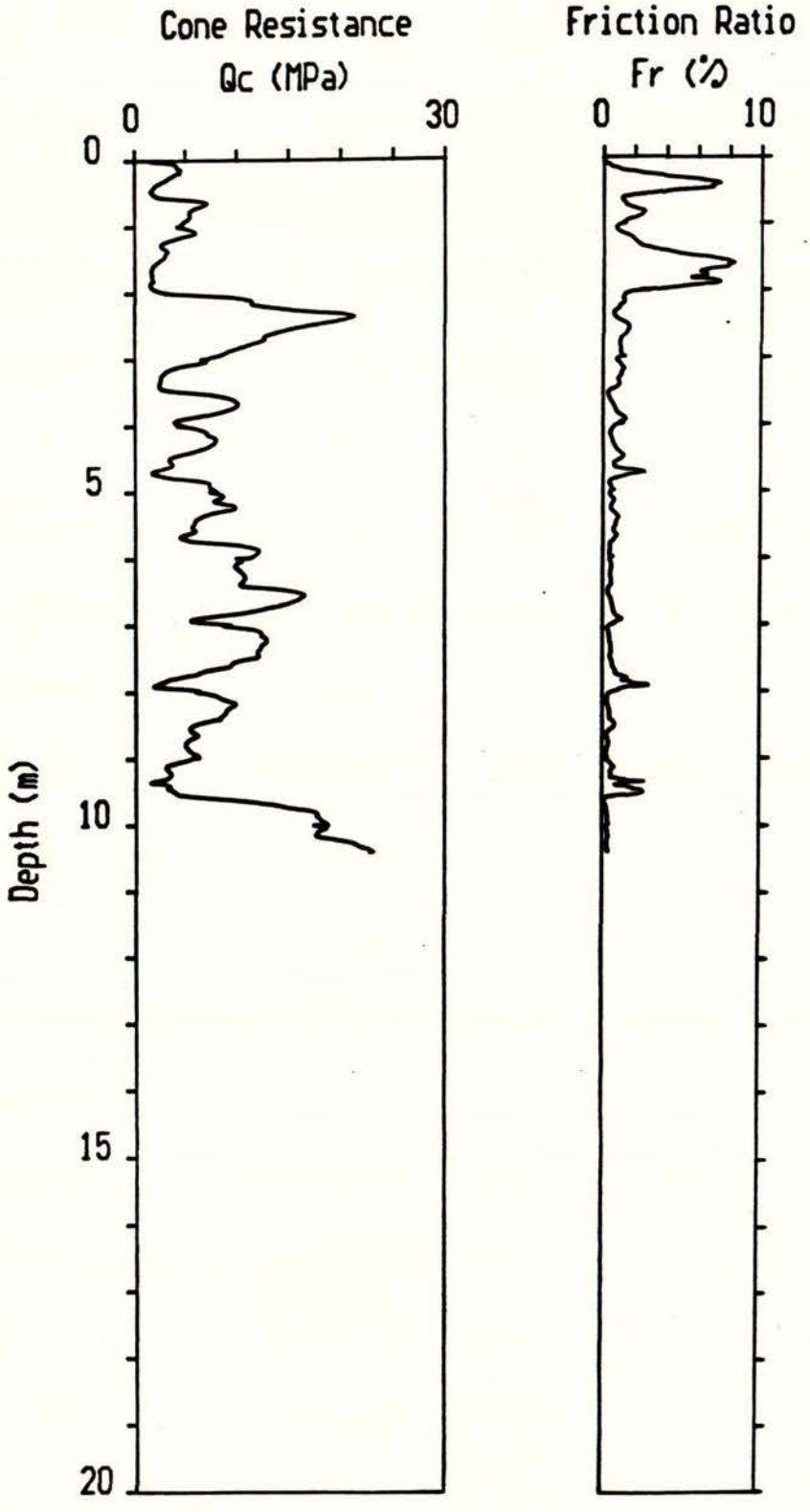

SPR BRIDGE

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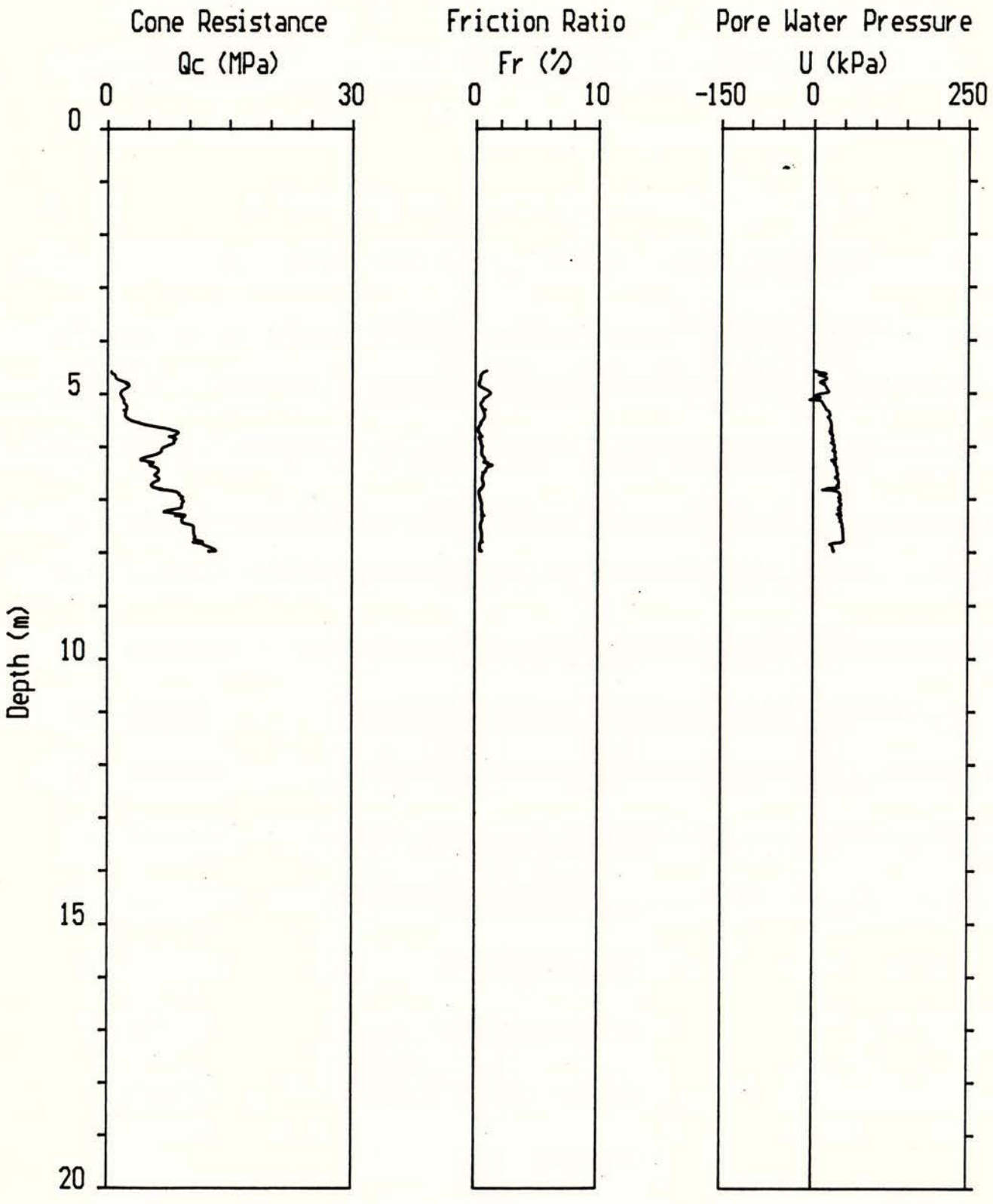

SPR BRIDGE

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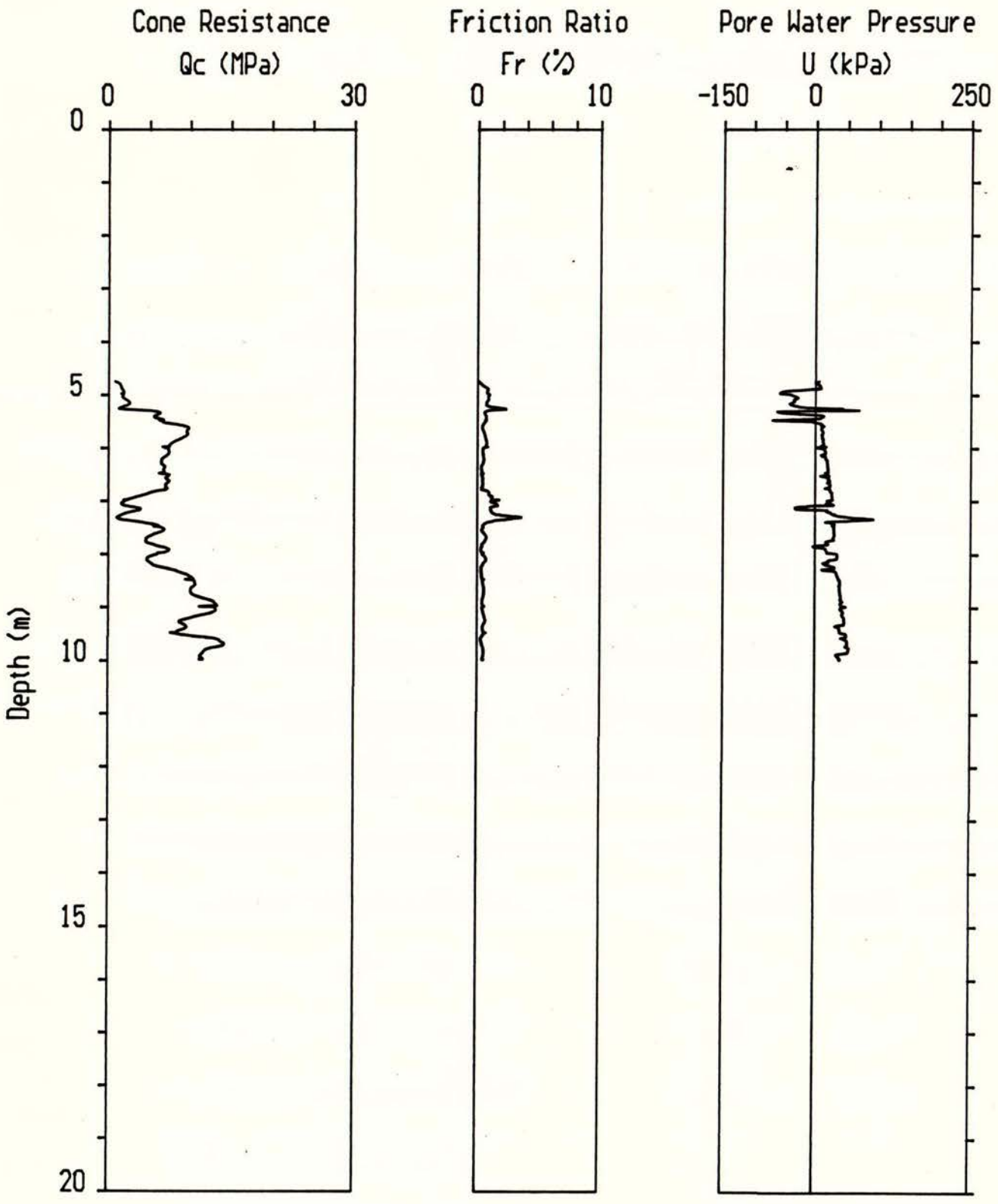
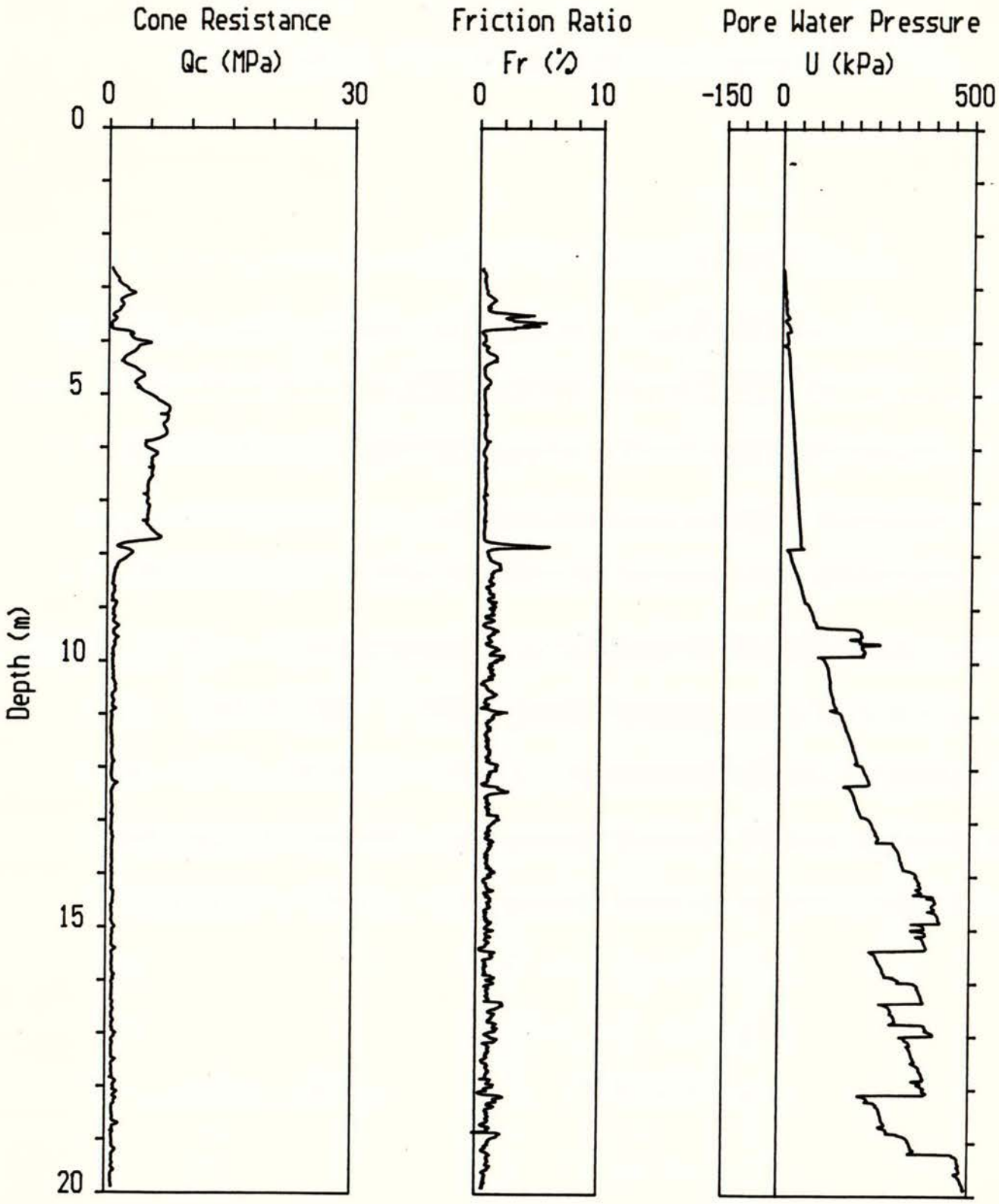


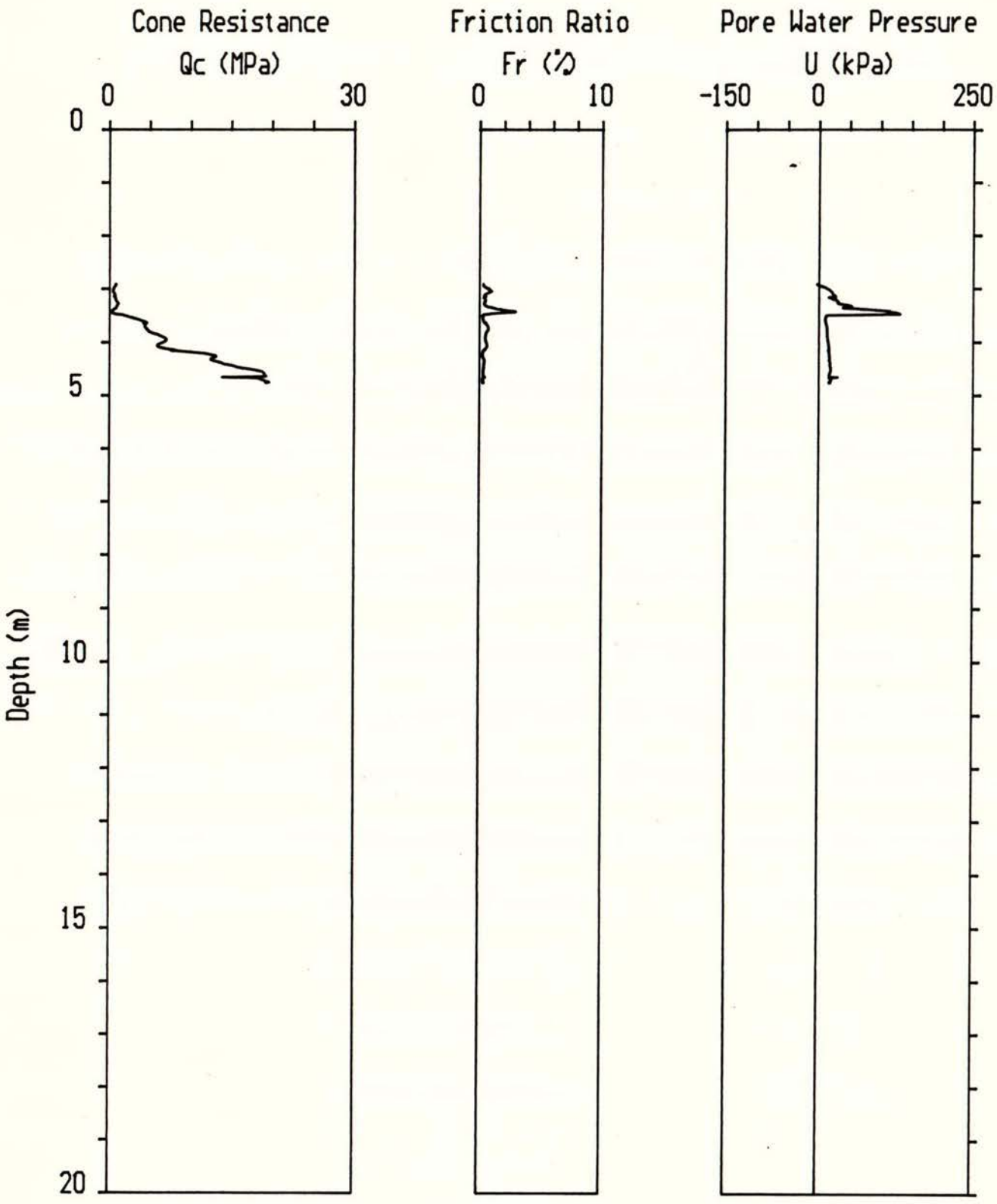
MARINA DISTRICT

Test 32 22 June 1990



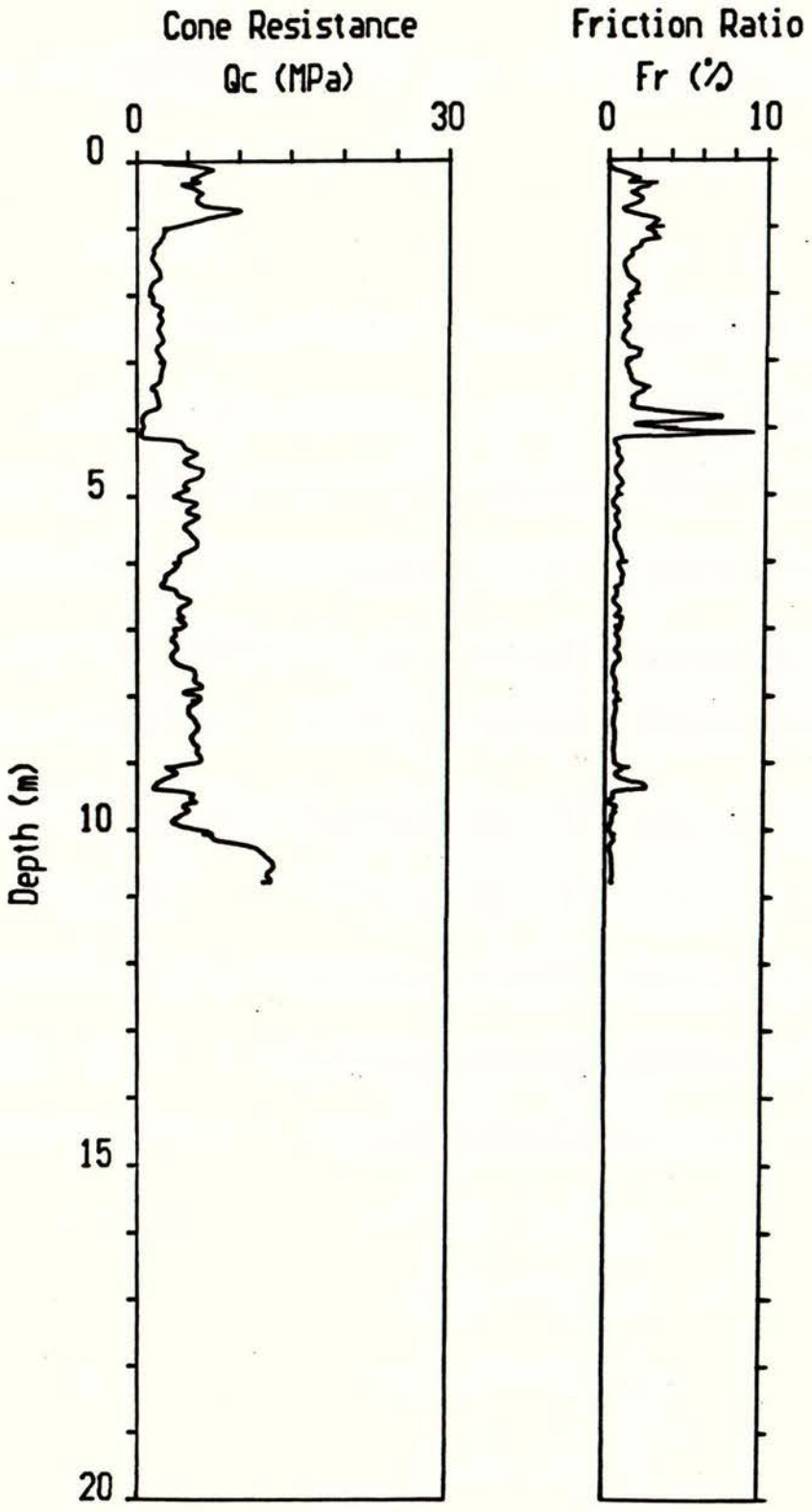
MARINA DISTRICT

Test 33 22 June 1990



SPR BRIDGE

Test 34 27 June 1990



SPR BRIDGE

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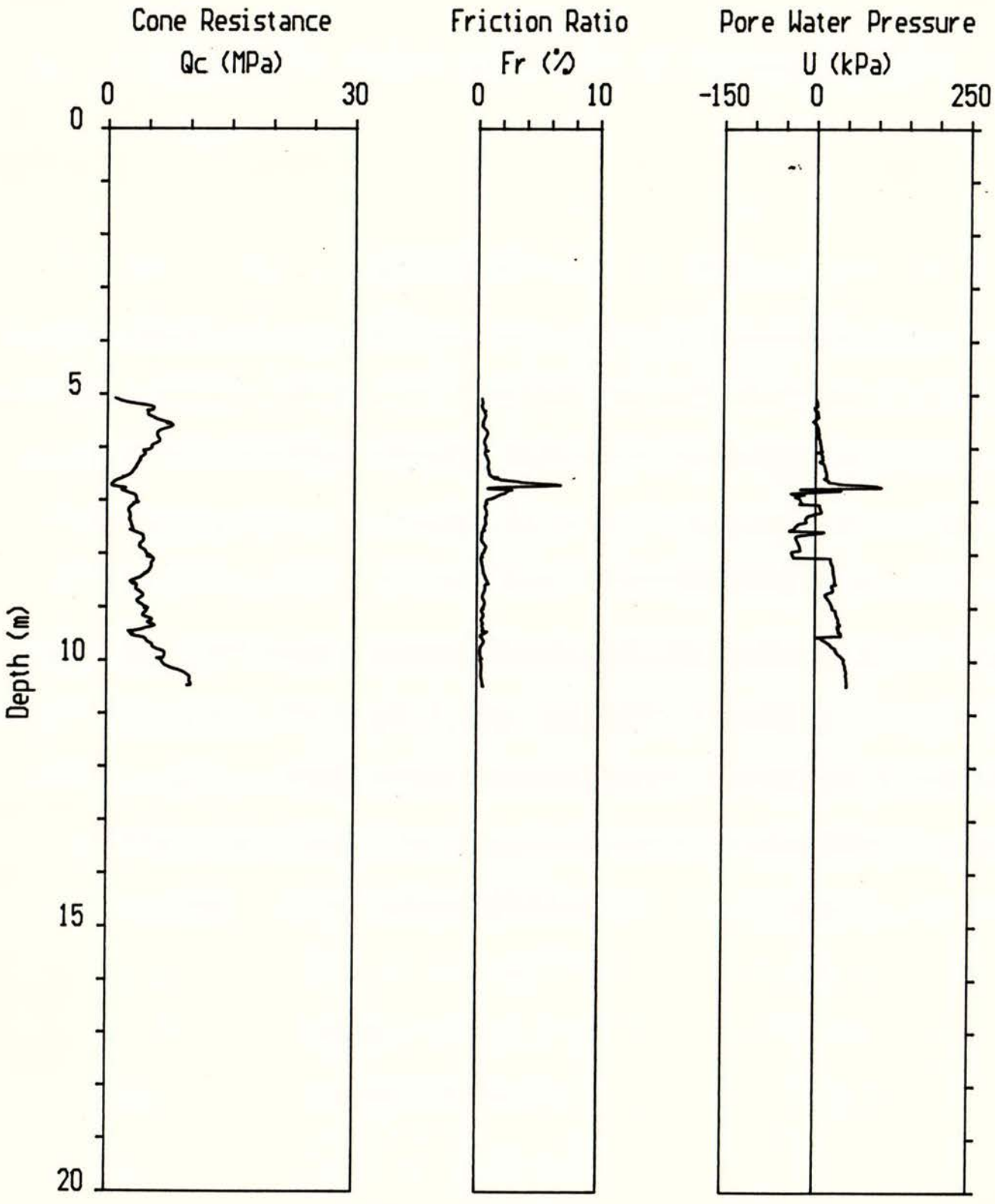
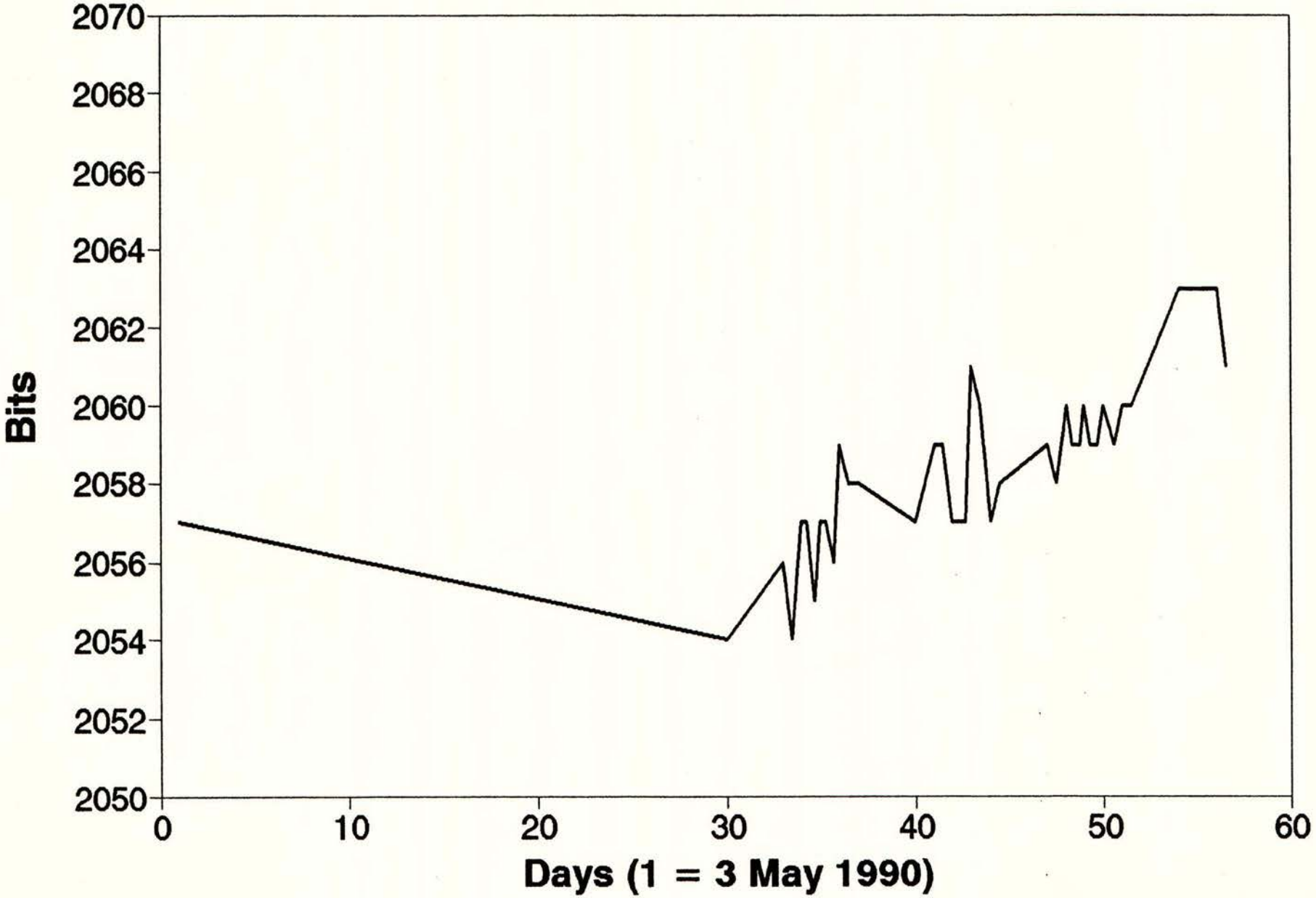
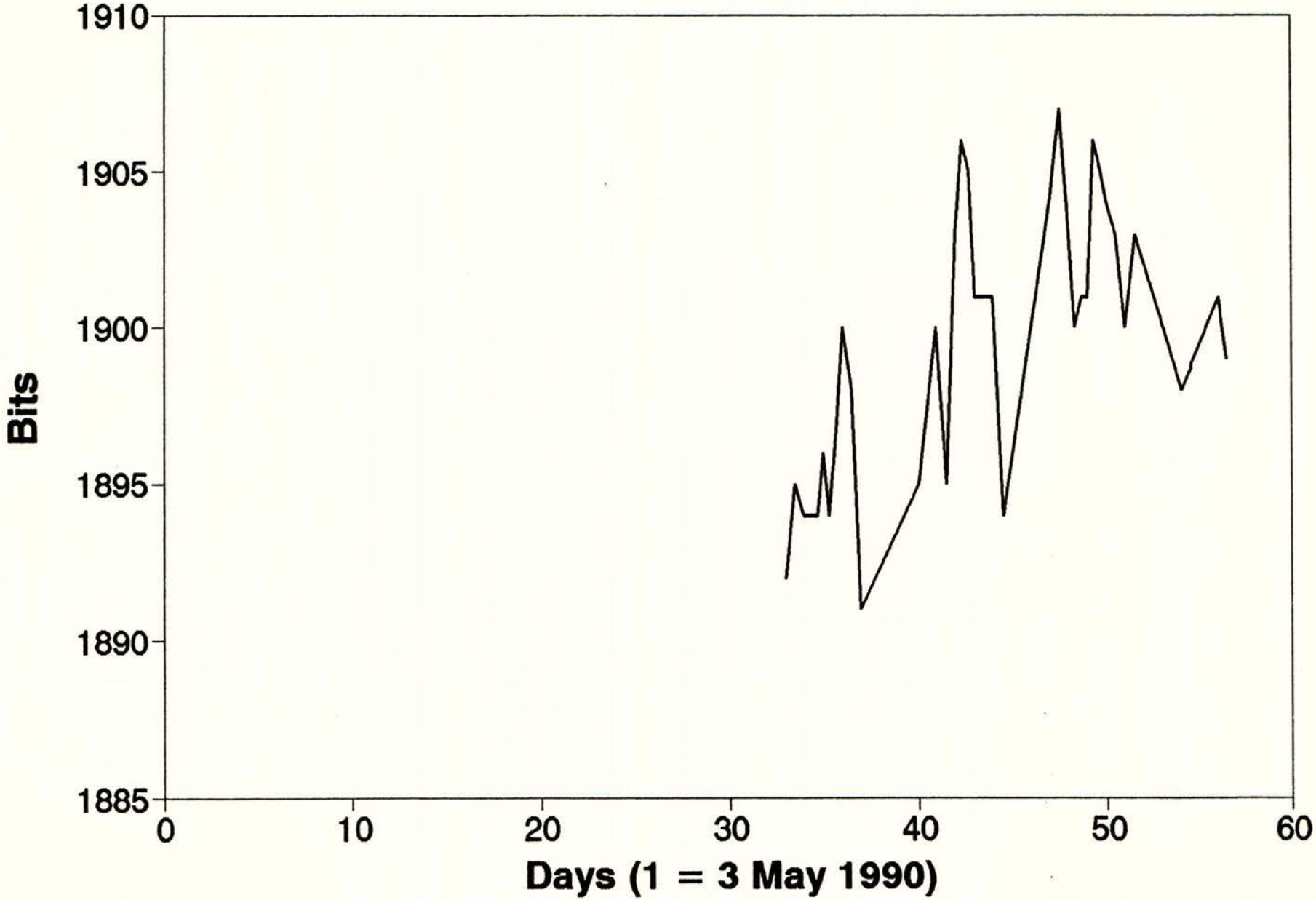


APPENDIX III

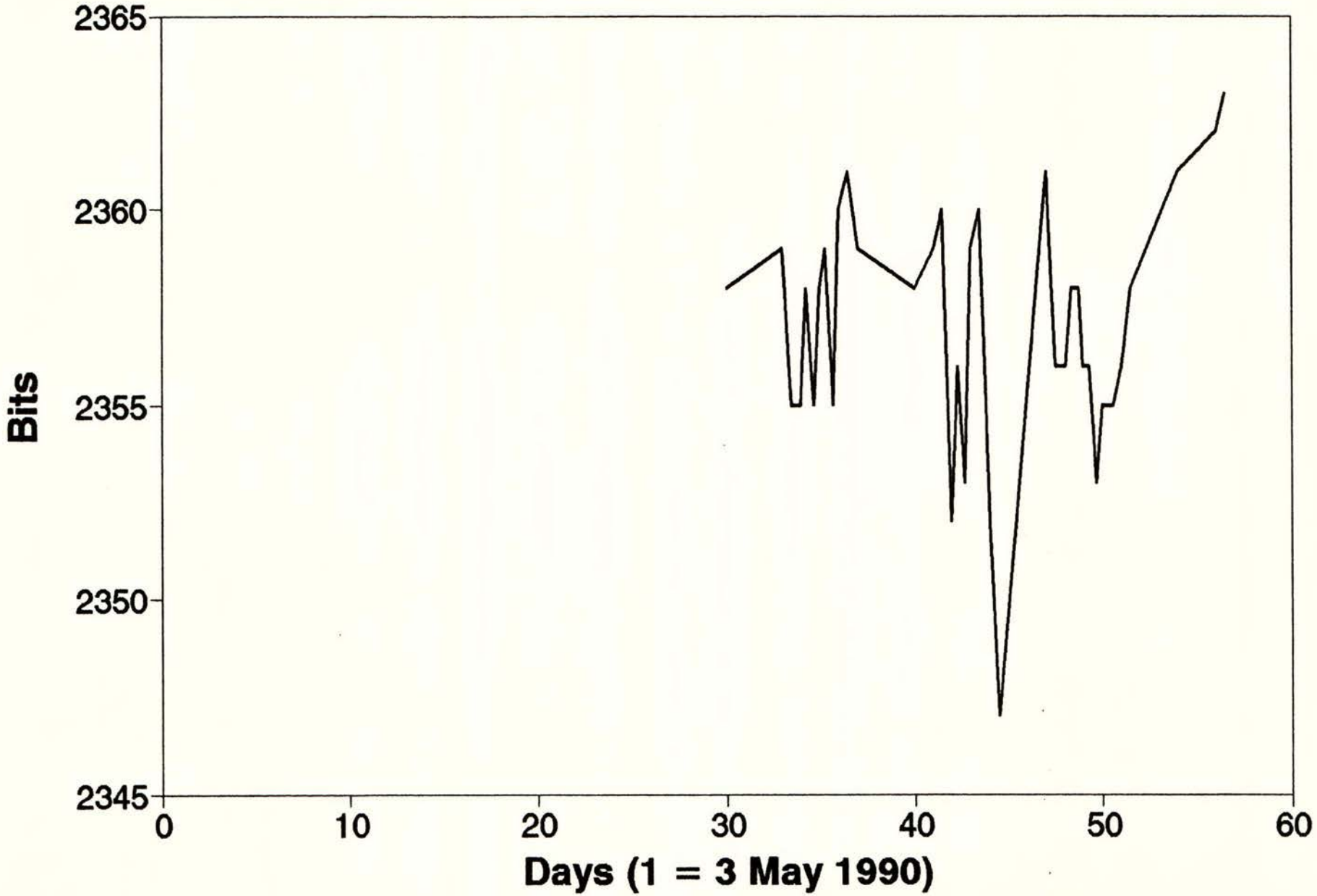
Qc Zero Variation



Qf Zero Variation



U Zero Variation



C+F Zero Variation