

# Rock Properties of Hyaloclastic Rocks

Evaluation of results and recommendation  
for further work

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Asger K. Pedersen and Christian Høier

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# Introduction

The present report gives an evaluation of the analytical results from the project "Rock Properties of Hyaloclastic Rocks" that has been carried out in collaboration between GEUS and the Atlantic Margin Group (Statoil, Enterprise Oil and Mobil). In addition to the analytical work, the project also included field studies on Nuussuaq in the summer of 1998 with participation from GEUS, Geological Museum and the Atlantic Margin Group with consultants and collaboration partners. The results from the field studies which focussed very much on the different volcanic facies and their geometries will be reported elsewhere by the Atlantic Margin Group and its consultants.

The initiation of the analytical part of the project took place following informal discussions between GEUS and the Atlantic Margin Group on problems of volcanic rocks in petroleum exploration. In particular the possibility of volcanic rocks acting as seal or reservoir, and as migration conduit to possible overlying reservoirs was discussed. These problems may be critical in the evaluation of new exploration possibilities around the Faroe Islands, in other North Atlantic areas, and in many areas on- and offshore West Greenland.

Generally there are relatively few data available in the literature on petrophysical properties of different volcanic rock types; this is the case for both standard reservoir properties, petrophysical log data and their correlation to measured core data, and acoustic data that can be used in geophysical modelling. GEUS therefore proposed to use the unique core material from Nuussuaq to get some basic data that could be useful for the Atlantic Margin Group in future exploration. The volcanic succession in the Disko–Nuussuaq area has been intensively studied through several decades (see e.g. papers by Pedersen, 1985; Pedersen et al., 1993, 1996, Larsen et al., in press and references therein) and during recent exploration nearly 2 km (!) of drill cores through the volcanics have been obtained. This gives a good chance to study the variation of petrophysical properties of different volcanic rock types and the differences between volcanic rocks with and without oil-impregnation, as these features are very common both in cores and at the surface on Nuussuaq.

## Sample material

The sample material for the present study was selected from well-described sections through volcanic rocks in the Marraat-1, GANE#1 and GANK#1 cores. In all three cases the drilling started within the volcanic succession; only the GANE#1 and GANK#1 holes actually penetrated the base of the volcanics. The location of the three drill holes is shown in Fig. 1.

Marraat-1 was drilled by GGU (funded by the Mineral Resources Administration for Greenland) in August 1993 in order to study the extent of the at that time recently discovered oil seepage and impregnation in the vicinity of the drill site. The hole is 447 m deep and the uppermost ~350 m of the hole was petrophysically logged. The drilling programme and subsequent organic geochemical studies have been reported or published by Bojesen-Koefoed et al. (in press), Christiansen et al. (1994a,b, 1996a) and Dam & Christiansen (1994).

GANE#1 was drilled by grønArctic Energy in July–August 1995 as a shallow core exploration hole. The hole is 707 m deep with the base of the volcanics situated at a depth of ~500 m. The drilling programme and subsequent sedimentological, stratigraphic and organic geochemical studies have been reported or published by Bate (1995), Bojesen-Koefoed et al. (in press), Christiansen et al. (1996b,c), Dam (1996a) and Nøhr-Hansen (1997).

GANK#1 was drilled by grønArctic Energy in August 1995 as a shallow core exploration hole. The hole is 398 m deep with the base of volcanics situated at a depth of 115 m. The drilling programme and subsequent sedimentological, stratigraphic and organic geochemical studies have been reported or published by Bojesen-Koefoed et al. (in press), Christiansen et al. (1996b,c), Dahl et al. (1995), Dam (1996b) and Nøhr-Hansen (1997).

Description of the penetrated volcanic succession (including lithological logs and distribution of oil-impregnated intervals) are included in papers by Christiansen et al. (1994b, 1996a) for the Marraat-1 core and have been reported separately for the GANE#1 and GANK#1 cores by Larsen & Pedersen (1997). Figs 2–4 show simplified lithological logs for the volcanic part of the three drill cores.

## Evaluation of results

The petrophysical measurements on the drill core samples comprise gas permeability, porosity, and grain density. The results are reported in the three enclosed GEUS Reports 1998/81, 1998/82, and 1998/83 by C. Høier from the GEUS Core Laboratory.

In the core from Marraat-1, two intervals at c. 4–30 m and 50–90 m were sampled. Plugs were taken with approximate distances of 0.3 m, and in total 212 plugs covering a combined stratigraphic thickness of c. 66 m were analysed.

In the core from GANE-1, three intervals at c. 4–10 m, 145–165 m, and 455–465 m were sampled. Plugs were taken with approximate distances of 0.3 m, and in total 104 plugs covering a combined stratigraphic thickness of c. 36 m were analysed.

In the core from GANK-1, an interval at c. 82–101 m was sampled. Plugs were taken with approximate distances of 0.3 m, and in total 54 plugs covering a stratigraphic thickness of c. 18 m were analysed.

The results are summarised in the accompanying tables (see appendix) where also divisions into geological units, short descriptions, and various comments are given. The analytical data are from GEUS Reports 1998/81, 1998/2 and 1998/83. Some missing measurements, especially of gas permeability, are caused by breakage of the plugs during treatment. Selected intervals are plotted in Figs 5 and 6.

The Marraat-1 succession represents 24 subaerial lava flows, many of which have massive central parts and vesicular tops and bases. The vesicles are partly filled with calcite, agate, clay, and zeolite minerals. The massive parts of the lava flows have generally lower permeabilities, lower porosities, and higher densities than the vesicular parts. This relation is clearly seen in the core logs when the flow boundaries are indicated, and in Figure 5: many individual lava flows have higher densities and lower porosities in the massive central parts which are usually located closer to the flow base than to the flow top. Particularly good examples of this are seen in flows 14–20. The same pattern is seen in the gamma-densities and gamma-porosities of the wireline log from Marraat-1 (see Dam & Christiansen, 1994, appendices). Fig. 5 shows that lava flows 21–25 have lower densities and higher porosities and permeabilities than the overlying flows. Flows 21–25 are more thoroughly vesicular than the overlying flows, and they also have a slightly different chemical composition, being more siliceous than the other basalts.

The GANE-1 succession consists of clast-rich hyaloclastites which at two levels are interbedded with volcanoclastic sandstone and siltstone, both horizons with scattered carbonate-shelled fossil fragments (Fig. 2). The two sediment horizons are not oil impregnated, but the hyaloclastites underlying each sediment horizon are thoroughly oil impregnated, with bleeding oil. Perhaps surprisingly, the porosities in the siltstone “seal” horizon are significantly *higher* than in the underlying hyaloclastites; however, the permeabilities are quite low (unfortunately, 4 plugs from this interval fragmented during treatment). The porosities and permeabilities of the volcanoclastic sandstone are not significantly different from those of the hyaloclastites themselves; the densities are somewhat lower.

The GANK-1 succession consists of matrix-rich, fine-clastic hyaloclastites and, at the bottom, volcanoclastic sandstone. The sandstone has higher porosities and permeabilities, and lower densities, than the hyaloclastites.

The results from the three drill cores show that the physical properties are systematically related to the rock types. In general, densities decrease, and porosities and permeabilities increase, in the succession massive lava → vesicular lava → coarse, clast-rich hyaloclastite → fine, matrix-rich hyaloclastite → volcanoclastic sandstone → volcanoclastic siltstone. This is shown in Table 1 where medians are given, not averages, because the numbers are not normal-distributed.

**Table 1. Medians of physical properties of volcanic rocks from West Greenland**

<b>Rock type</b> (number of samples)	<b>Permeability</b>	<b>Porosity</b>	<b>Grain density</b>
Massive lava (35)	0.037	4.144	2.874
Vesicular lava (128)	0.066	8.791	2.792
Coarse hyaloclastite (83)	0.185	5.872	2.720
Fine hyaloclastite (37)	0.265	5.280	2.627
Volcanoclastic sandstone (21)	0.334	7.259	2.579
Volcanoclastic siltstone (8)	0.213	16.446	2.588
<b>All samples</b>	<b>0.076</b>	<b>6.814</b>	<b>2.758</b>

In a number of cases, the permeability and porosity measurements show outliers with very high numbers. These can in some cases be explained by hair-thin cracks in the rocks, but in some cases the rocks are not visibly different from the rest. Examples of outliers are indicated in bold types in the accompanying tables, with some comments.

The volcanic rocks measured are aphyric and plagioclase-phyric basalts with compositions similar to many common basalts from the North Atlantic igneous province. Only the lowest flow sampled in the Marraat-1 core (unit 26) consists of the olivine-rich picritic rock type characteristic of the Vaigat Formation. The picritic flow clearly has higher porosities and permeabilities than the other rocks, but there are only 5 samples of this rock type.

## **Oil impregnation**

The Marraat-1 data table and Fig. 5 clearly show that oil impregnation is concentrated in the vesicular parts of the lava flows. There are somewhat higher permeabilities associated with the oil-impregnated intervals. This can be gleaned from Fig. 5 and seen from the statistics: the oil-impregnated intervals have a median permeability of 0.079, while that of the oil-free intervals is 0.045.

In the GANE-1 core, a similar relation seems to hold between oil-impregnated and oil-free intervals, but all permeabilities are much higher in the hyaloclastites and sediments than in the lavas (Fig. 6). However, the oil content in the GANE-1 rocks is correspondingly much higher than in the Marraat-1 rocks which never show complete oil saturation as seen in two intervals in the GANE-1 core.

## Conclusions and recommendations for further work

The present study has provided some unique data that give a first possibility of quantifying petrophysical properties of volcanic rocks, especially the porosity and permeability. The study therefore gives some indications about the critical parameters for evaluating whether volcanic rocks can act as reservoirs or seals.

The data demonstrate that significant differences are found from one volcanic rock type to the other, and that these differences may also control the distribution of hydrocarbons. Based on these results, GEUS recommends the below-mentioned topics for future studies that could be relevant for petroleum exploration in volcanic terrains, and where the Nuusuaq core material and outcrop data could be particularly useful. The various projects could – depending on the necessity for further data and results – be initiated during different phases of coming exploration, depending on actual problems:

- Follow up using a larger number of samples including other volcanic rock types in order to get better statistical numbers
- Comparison of analytical results with petrophysical logs from the Marraat-1 hole
- Detailed studies of the oil-impregnated parts of the volcanic succession with considerations about present and past oil saturations, and the loss of hydrocarbons by leakage, during drilling, and in the laboratory
- Studies of healed and open fractures in volcanics, their geometry and control on migration through the volcanics
- Detailed studies of the generation and timing of secondary minerals (especially zeolite zonations) and their use for interpretation of the reservoir properties, thermal history and use in basin modelling
- Acoustic properties of the volcanic rocks, analysing different lithologies with examples of different porosities and permeabilities
- Thermal properties of the volcanic rocks, especially thermal conductivity measurements that are important for basin modelling

*Acknowledgements.* This report is the result of an exclusive study carried out by GEUS for the Atlantic Margin Group (Statoil, Enterprise Oil and Mobil) with Dave Ellis as coordinator. The cores and original descriptions that formed the background for the study are based on many years of studies by GEUS and the Geological Museum, University of Copenhagen. These earlier studies have benefitted from financial support by GGU/GEUS, EFP, the former Mineral Resources Administration for Greenland and the Greenland Home Rule.

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## Figures and appendix

**Fig. 1.** Map of northern Disko and Nuussuaq showing position of drill sites and location of oil seeps.

**Fig. 2.** Simplified stratigraphic and geophysical log of the Marraat-1 core. Based on Larsen & Pedersen (unpubl. data) and geophysical formation evaluation of the borehole (see appendix in Dam & Christiansen (1994)).

**Fig. 3.** Simplified log of the volcanic succession in GANE#1 (after Larsen & Pedersen, 1997).

**Fig. 4.** Simplified log of the volcanic succession in GANK#1 (after Larsen & Pedersen, 1997).

**Fig. 5.** Part of the Marraat-1 core (from lava flow unit 13 to 26) showing petrophysical values: Porosity (%), Grain density ( $\text{g/cm}^3$ ) and Permeability (mD). Oil-impregnated intervals are shown with hatched lines in the permeability diagram.

**Fig. 6.** Part of the GANE#1 core (from unit 5 to unit 8) showing petrophysical values: Porosity (%), Grain density ( $\text{g/cm}^3$ ) and Permeability (mD). Oil-impregnated intervals are shown with hatched lines in the permeability diagram. It should be noted that core box no. 49 (154.4–157.5 m) is missing.

**Fig. 7.** Part of the GANK#1 core (from lava flow unit 3 to unit 8) showing petrophysical values: Porosity (%), Grain density ( $\text{g/cm}^3$ ) and Permeability (mD).

**Appendix 1.** Annotated petrophysical data from Marraat-1, GANE#1 and GANK#1. See original data in enclosed reports.

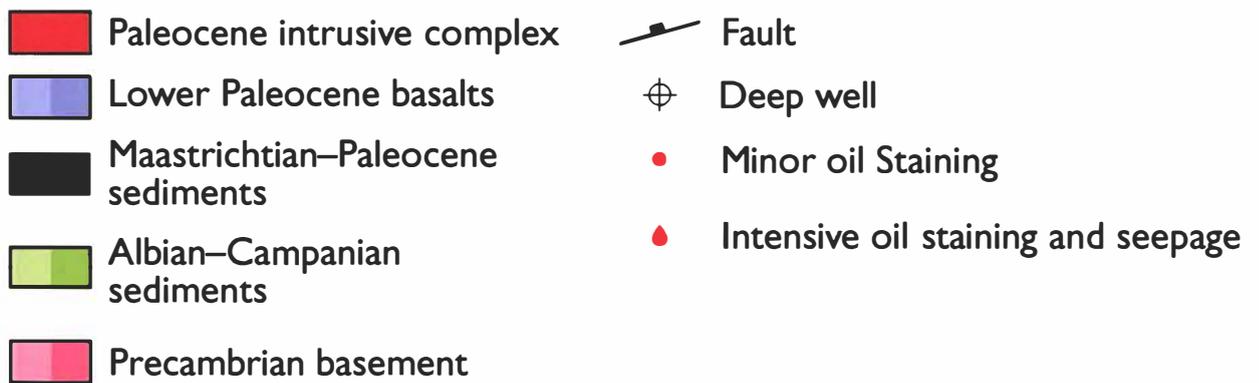
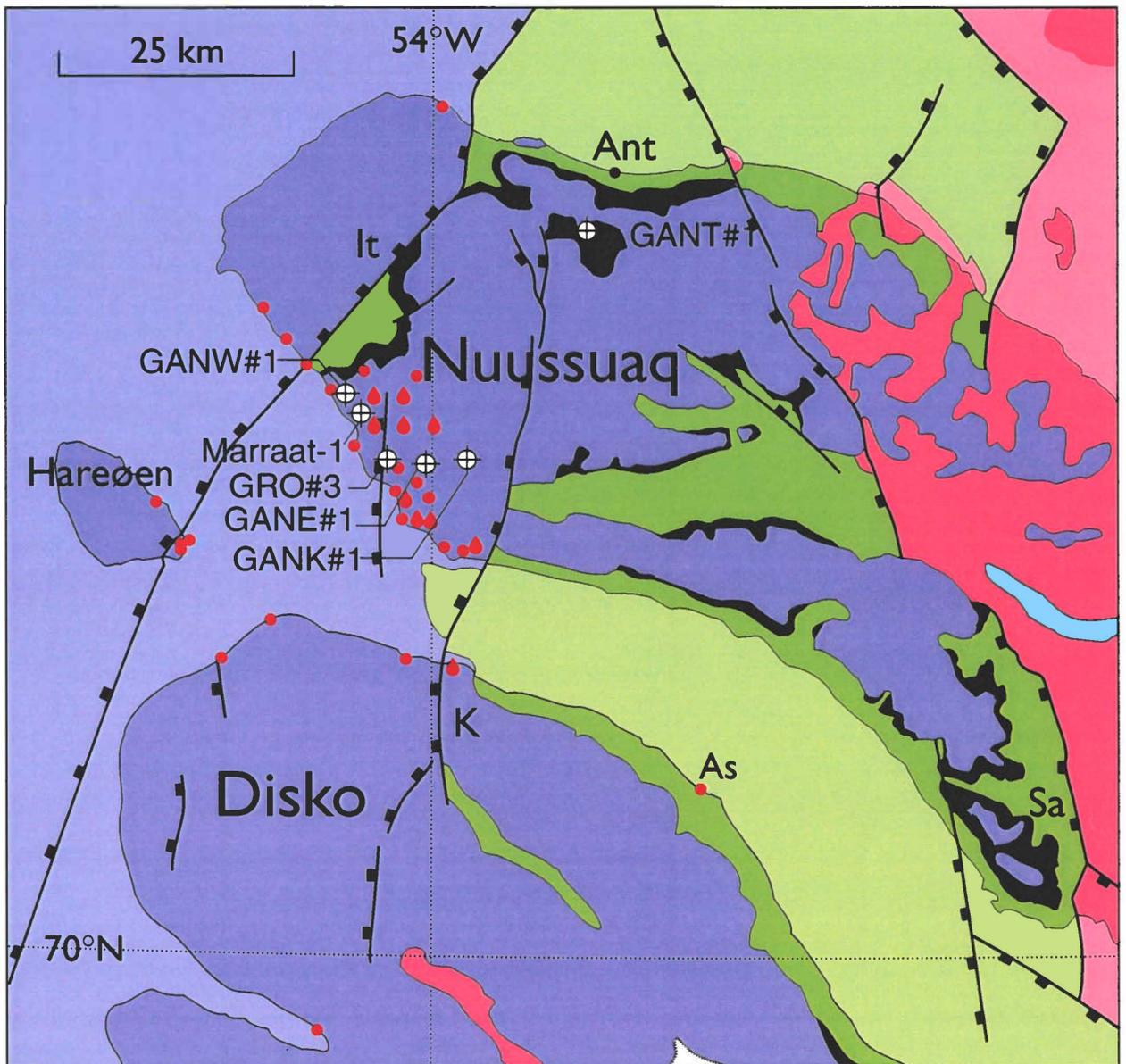


Fig. 1



# GAN#1

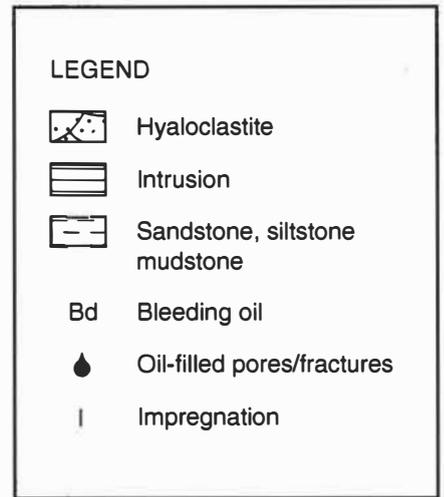
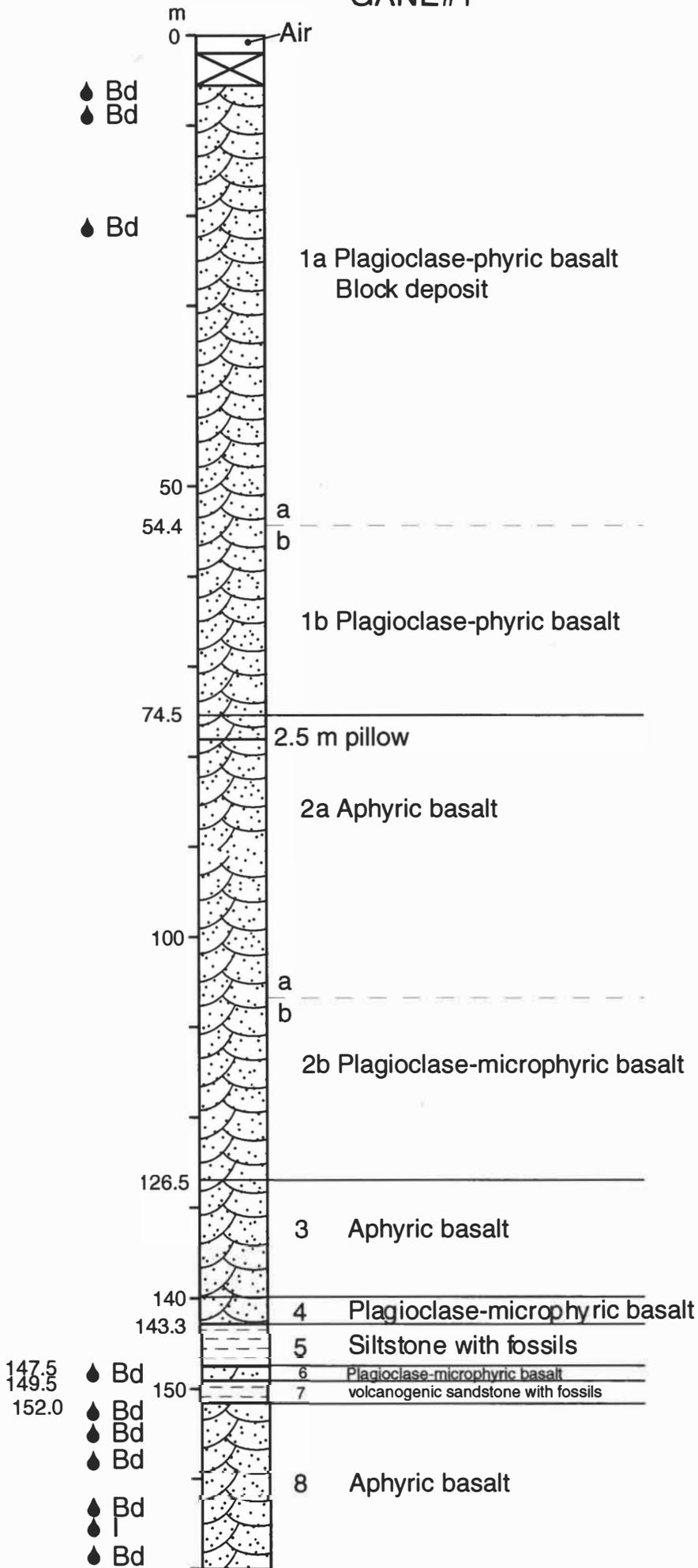


Fig. 3

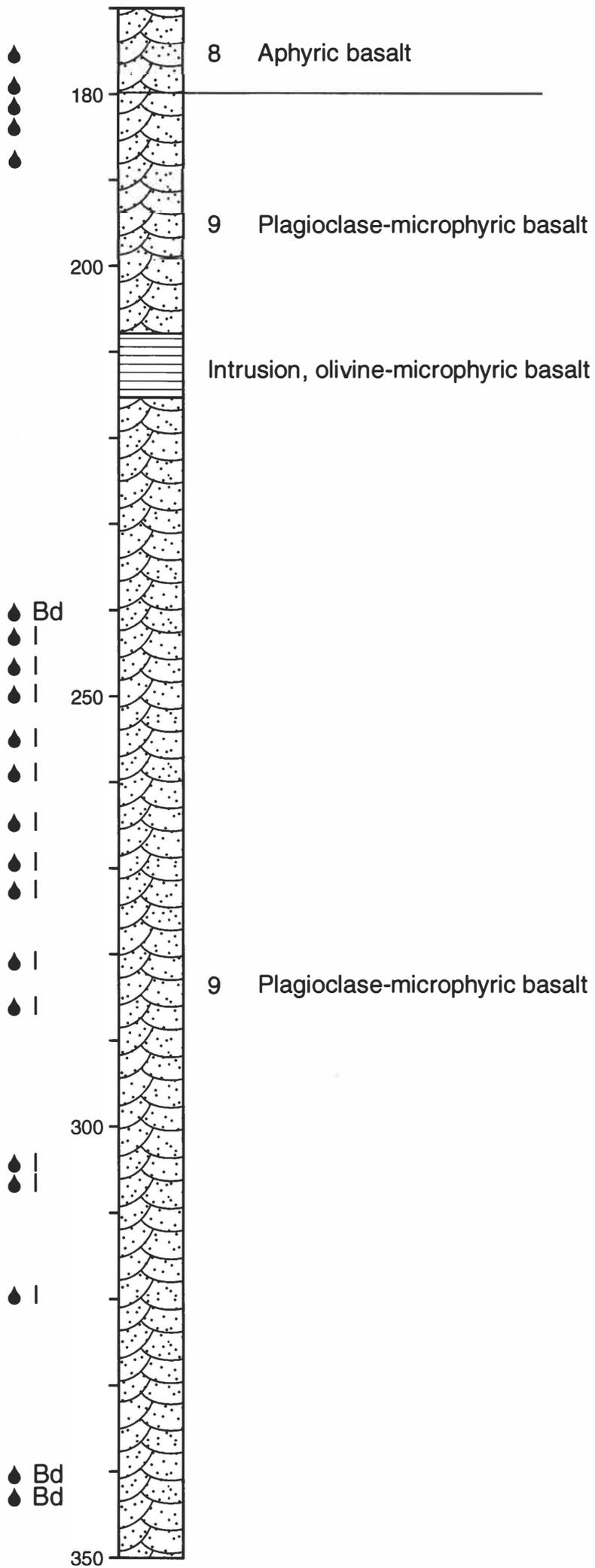


Fig. 3, cont.

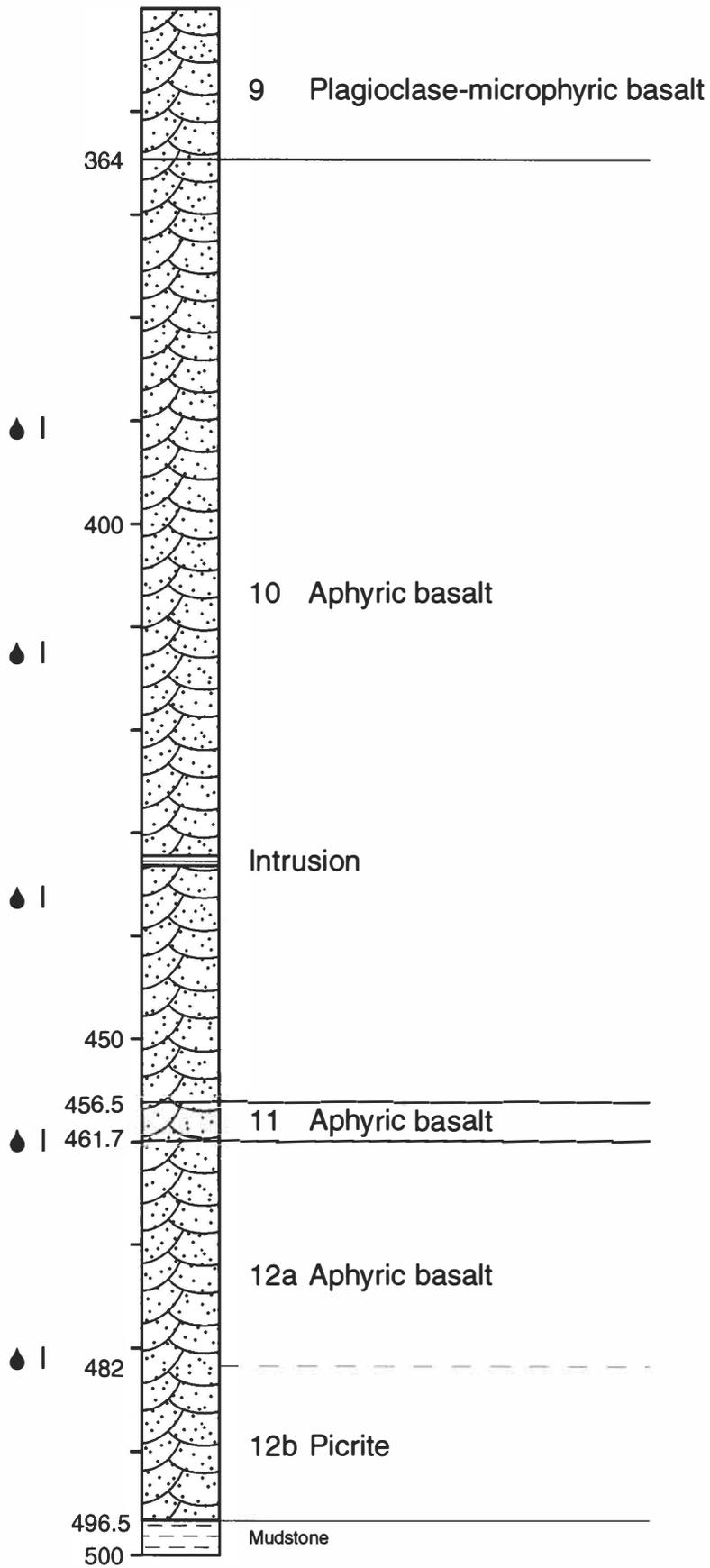


Fig. 3, cont.

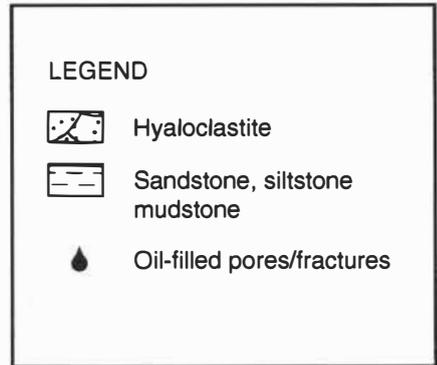
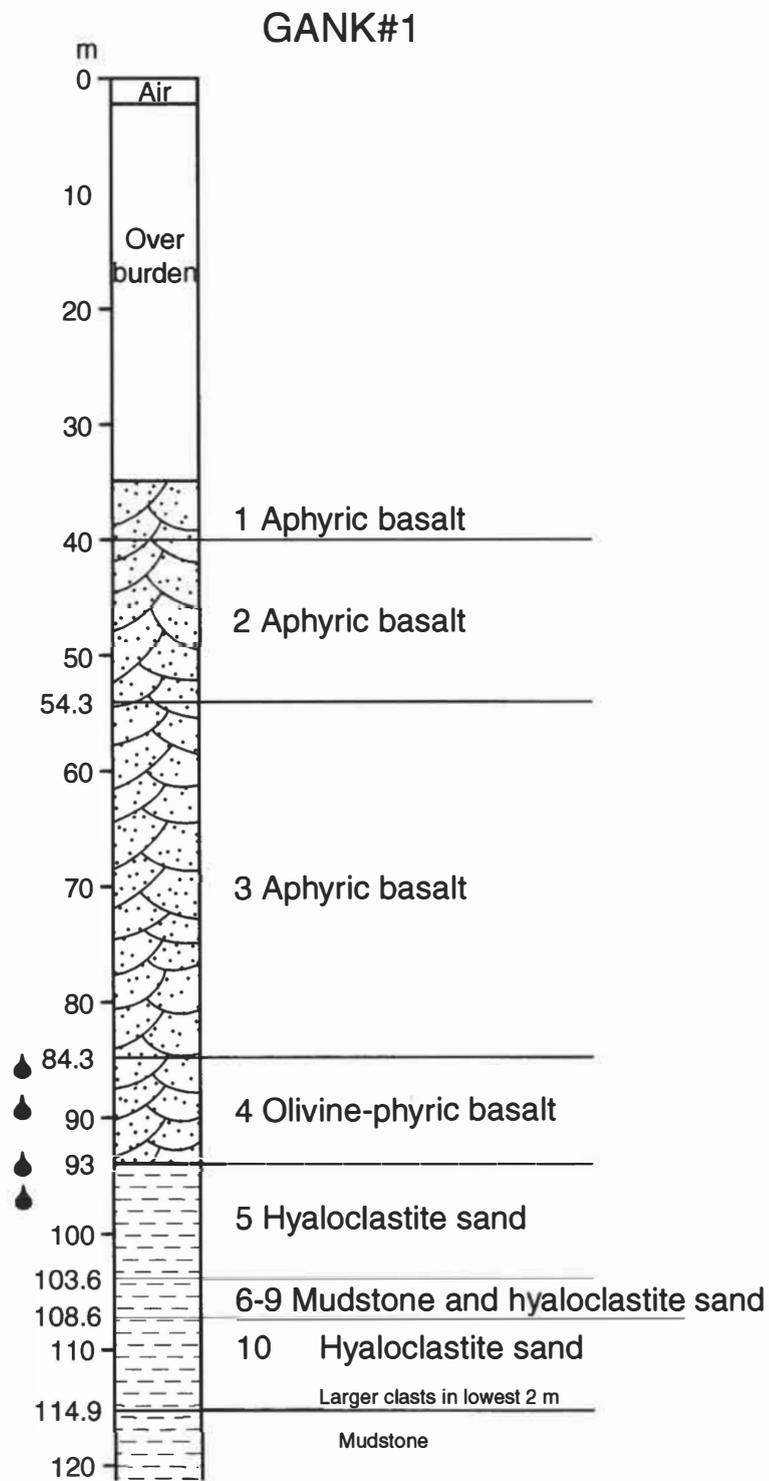


Fig. 4

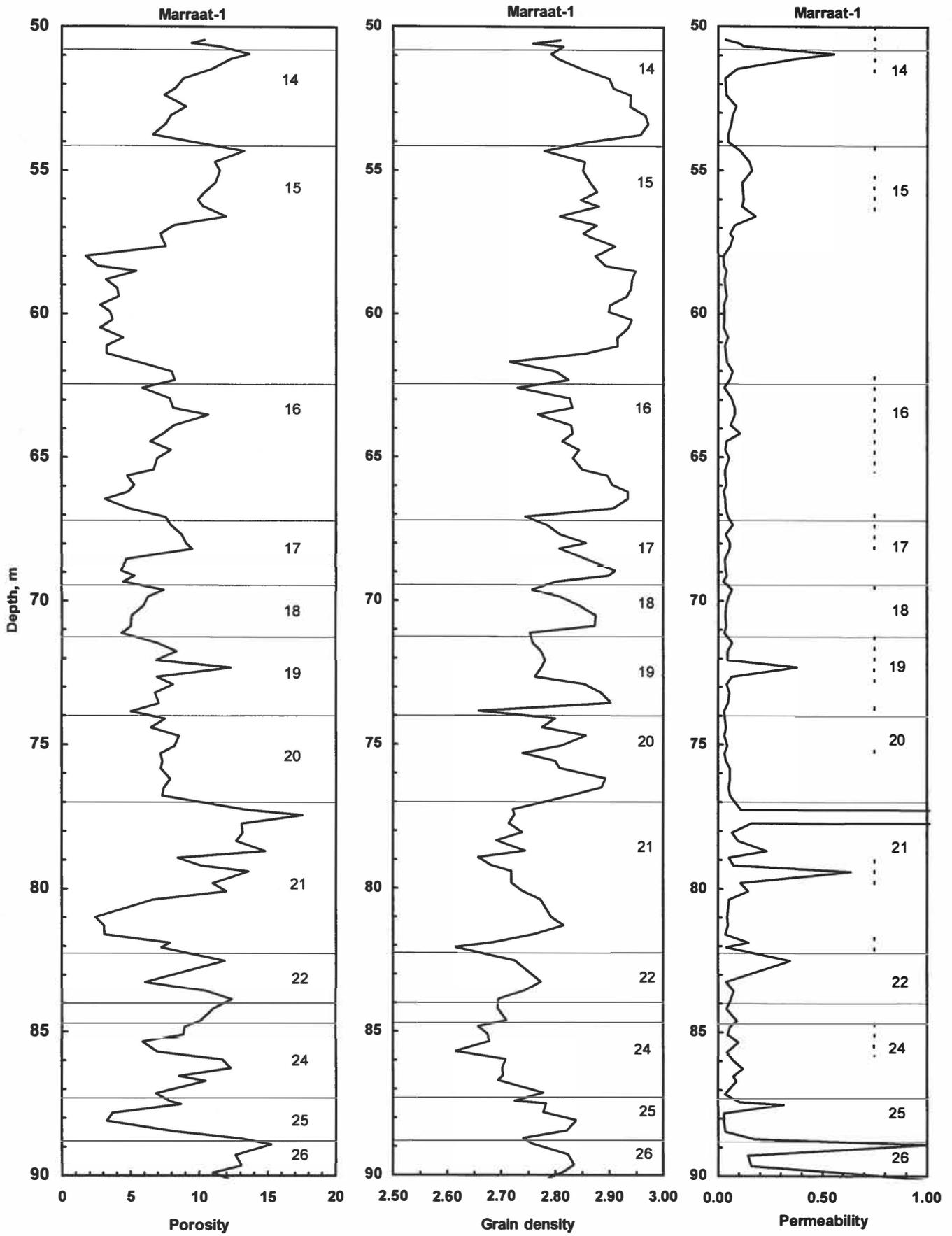


Fig. 5

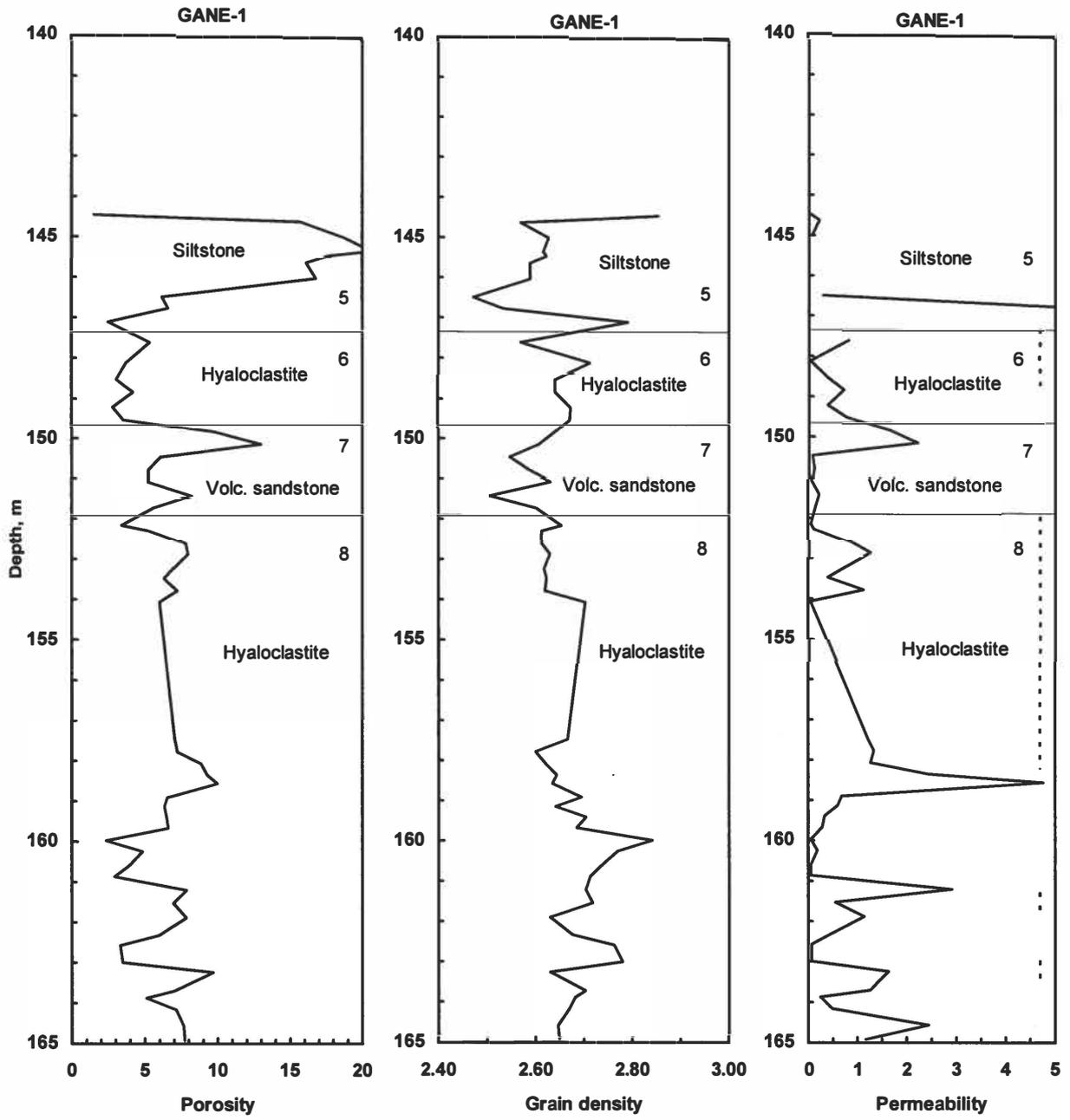


Fig. 6

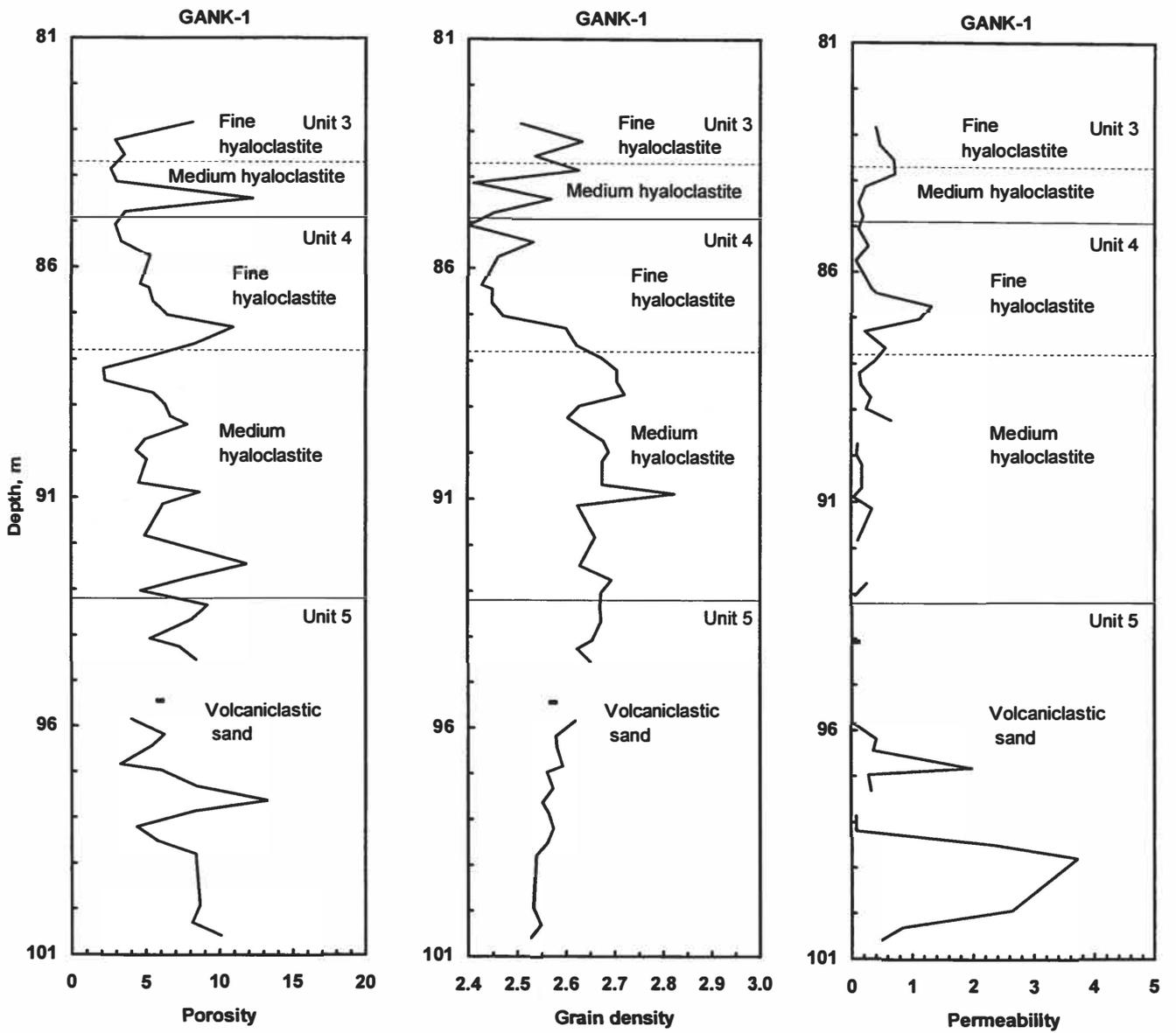


Fig. 7

**Appendix 1:**

**Annotated petrophysical data from Marraat-1, GANE#1 and GANK#1.**

**WELL Marraat-1**

Sample	Depth, m	Gas perm.	Porosity	Gr. dens.	Oil impregnation			
351	4,16	0,030	3,33	2,663		Unit 1	Basalt lava flow	>1.2 m thick
352	4,49	0,019	0,79	2,643			Vesicular upper part.	
353	5,06	0,691	0,43	2,805	← Massive		Widespread oil impregnation	
354	5,33	1,662	<b>34,56</b>	2,766	← No difference			
355	5,56	0,015	0,84	2,831		Unit 2	Basalt lava flow	6.0 m thick
356	5,87	0,021	1,61	2,815			Massive, vesicle-poor.	
357	6,15	0,016	2,52	2,833			Only little oil impregnation.	
358	6,49	0,089	3,71	2,809				
359	6,88	0,538	2,98	2,859				
360	7,21	0,023	2,33	2,828				
361	7,18	0,018	2,27	2,821				
362	7,30	0,094	1,99	2,852				
363	7,77	0,419	2,56	2,850				
364	8,11	0,757	4,52	2,843				
365	8,45	0,030	2,41	2,855				
366	8,67	1,174	2,99	2,865				
367	9,26	0,036	3,37	2,846				
368	9,31	0,014	3,36	2,841				
369	9,75	0,022	0,47	2,809				
370	10,10	0,029	2,72	2,835				
371	10,63	0,019	1,57	2,866				
372	11,02	0,100	5,72	2,765				
373	11,84	0,200	9,88	2,753		Unit 3	Basalt lava flow	3.0 m thick
374	12,02	0,227	11,64	2,819			Vesicular top and base,	
375	12,14	0,103	9,32	2,808			massive interior.	
376	12,84	0,048	6,69	2,847			Vesicle-filling: calcite, agate.	
377	13,20	0,042	5,28	2,890	← Massive		Widespread oil impregnation.	
378	14,08	0,282	13,51	2,799				
379	14,53	0,388	10,62	2,780		Unit 4	Basalt lava tongue	0.5 m thick
380	14,83	0,122	11,74	2,800			Basalt lava flow	1.9 m thick
381	15,30	0,388	14,11	2,821		Unit 5	Vesicular top and base,	
382	15,81	0,152	8,95	2,911	← Massive		massive interior.	
383	16,12		14,73	2,868			Vesicle-filling: clay, agate.	
384	16,47	0,395	14,89	2,780			Widespread oil impregnation.	
385	16,75	0,162	12,98	2,822				
386	17,03		11,68	2,928		Unit 6	Basalt lava flow	1.6 m thick
387	17,33		13,93	2,896	← Massive		Vesicular top and base,	
388	17,35	0,219	14,35	2,792			massive interior.	
389	17,60	1,429	14,64	2,843			Vesicle-filling: calcite, clay, agate.	
390	17,95		17,51	2,883	← Massive		Oil impregnation in upper half.	
391	18,28	<b>11,259</b>	17,76	2,810	← Calcite vein			
392	18,60	0,049	15,10	2,921		Unit 7	Basalt lava flow	4.2 m thick
393	18,90						Vesicular top and base,	
394	19,49	0,070	9,03	2,924			massive interior.	
395	19,55	0,044	7,92	2,937			Vesicle-filling: clay, calcite.	
396	20,11		5,12	2,903			No oil.	
397	20,36	0,018	3,64	2,924				
398	20,59		3,18	2,881				
399	20,84	0,030	2,72	2,878				
400	21,05	0,027	2,24	2,862				
401	21,15		4,53	2,868				
402	21,42	0,020	1,99	2,850				
403	21,83	0,022	2,88	2,881				
404	22,12	0,046	7,37	2,910				

Sample	Depth, m	Gas perm	Porosity	Gr. dens.	Oil impregnation			
405	22,43		8,23	2,848				
406	22,83	0,056	9,22	2,824		<b>Unit 8</b>	<b>Basalt lava flow</b>	2.7 m thick
407	23,07	0,248	10,24	2,826			Vesicular top,	
408	23,36	0,051	7,53	2,853			massive interior and base.	
409	23,64	0,072	8,35	2,886				
410	23,92	0,054	7,09	2,883				
411	24,20	0,017	2,39	2,886	} Massive			
412	24,86	0,020	2,99	2,848				
413	25,13	0,059	9,70	2,732		<b>Unit 9</b>	<b>Basalt lava tongue</b>	0.5 m thick
414	25,32	0,033	8,09	2,737			Brecciated, vesicular	
415	25,70	0,053	9,74	2,892				
416	26,25	0,034	3,46	2,744	} Massive	<b>Unit 10</b>	<b>Basalt lava flow</b>	10.9 m thick
417	26,53	0,020	1,64	2,714			Massive, vesicle-poor.	
418	26,89	0,041	8,16	2,667			Vesicles in some zones,	
419	27,15	0,038	5,34	2,607			oil impregnation in one of these	
420	27,44	0,116	13,44	2,653				
421	27,82	0,068	10,66	2,710				
422	28,10	0,046	6,40	2,639				
423	28,40	0,031	3,22	2,552				
424	28,66	0,029	5,70	2,695	} Massive			
425	29,09	0,048	3,37	2,785				
426	29,55	0,034	6,23	2,795				
427	29,81	0,028	5,48	2,831				
428	30,12	0,050	5,79	2,791				
429	50,46	0,033	10,36	2,809			<b>Basalt lava tongue</b>	0.6 m thick
430	50,57	0,099	9,41	2,758		<b>Unit 13</b>	Finely vesicular,	
431	50,68	0,121	11,51	2,815			oil impregnated.	
432	50,94	0,556	13,61	2,792				
433	51,12	0,366	12,27	2,805		<b>Unit 14</b>	<b>Basalt lava flow</b>	3.3 m thick
434	51,47	0,092	10,87	2,850			Vesicular top and base,	
435	51,80	0,033	8,86	2,899			massive interior.	
436	52,14	0,036	8,25	2,907			Oil impregnation in top zone.	
437	52,38	0,038	7,46	2,939	} Massive			
438	52,78	0,086	9,03	2,938				
439	53,09	0,069	7,93	2,966				
440	53,38	0,062	7,57	2,972				
441	53,76	0,047	6,61	2,957				
442	54,01	0,048	9,47	2,861				
443	54,32	0,105	13,26	2,780				
444	54,70	0,149	11,12	2,855		<b>Unit 15</b>	<b>Basalt lava flow</b>	8.2 m thick
445	55,00	0,162	11,48	2,851			Vesicular top and base,	
446	55,42	0,116	11,16	2,865			massive interior.	
447	55,75	0,119	10,41	2,877			Vesicle-filling: clay, calcite, agate.	
448	56,03	0,122	9,89	2,848			Scattered oil impregnation.	
449	56,25	0,115	10,27	2,880				
450	56,60	0,179	11,93	2,808				
451	56,91	0,081	8,20	2,876				
452	57,20	0,058	7,22	2,852				
453	57,33	0,072	7,26	2,866	} Massive			
454	57,64	0,057	7,57	2,910				
455	57,99	0,023	1,74	2,874				
456	58,33	0,025	2,58	2,893				
457	58,51	0,038	5,40	2,948				
458	58,80	0,028	3,20	2,942				

Sample	Depth, m	Gas perm	Porosity	Gr. dens.	Oil impregnation	
459	59,11	0,033	4,04	2,940	Unit 15, continued  Massive	
460	59,39	0,039	4,14	2,932		
461	59,69	0,025	2,79	2,901		
462	59,93	0,027	3,51	2,899		
463	60,20	0,028	3,69	2,941		
464	60,49	0,024	2,78	2,935		
465	60,83	0,046	4,45	2,915		
466	61,11	0,031	3,26	2,915		
467	61,38	0,035	3,26	2,857		
468	61,67	0,041	5,52	2,716		
469	62,01	0,068	8,02	2,802		
470	62,30	0,055	8,23	2,824		
471	62,58	0,028	5,84	2,730	Unit 16	Basalt lava flow 4.7 m thick Vesicular top and base, massive interior. Vesicle-filling: calcite, agate. Scattered oil impregnation.
472	62,94	0,063	7,87	2,827		
473	63,27	0,079	8,13	2,832		
474	63,51	0,079	10,65	2,767		
475	63,88	0,059	8,18	2,830		
476	64,17	0,104	7,38	2,833		
477	64,44	0,039	6,44	2,813	Unit 16, continued	
478	64,74	0,032	7,96	2,844		
479	65,03	0,051	6,94	2,833		
480	65,43	0,033	6,68	2,850		
481	65,64	0,032	4,75	2,896	Massive	
482	65,96	0,038	5,27	2,905		
483	66,20	0,025	4,80	2,934		
484	66,45	0,032	3,13	2,934		
485	66,78	0,034	4,88	2,907		
486	67,07	0,046	7,56	2,745		
487	67,36	0,070	7,96	2,785		
488	67,68	0,034	8,73	2,809	Unit 17	Basalt lava flow 2.4 m thick Vesicular top and base, massive interior. Vesicle-filling: calcite, agate. Scattered oil impregnation.
489	67,98	0,056	9,05	2,857		
490	68,18	0,054	9,49	2,808		
491	68,54	0,030	4,70	2,857	Massive	
492	68,95	0,034	4,31	2,909		
493	69,12	0,040	5,29	2,897		
494	69,33	0,022	4,47	2,802		
495	69,61	0,065	7,45	2,757		
496	69,86	0,048	6,26	2,808	Unit 18	Basalt lava flow 1.8 m thick Vesicular top and base, massive interior. Scattered oil impregnation.
497	70,16	0,037	5,95	2,844	Massive	
498	70,51	0,032	5,08	2,874		
499	70,88	0,037	5,02	2,873		
500	71,12	0,029	4,34	2,753		
501	71,46	0,067	6,96	2,758		
502	71,75	0,043	8,36	2,773	Unit 19	Basalt lava flow 2.6 m thick Vesicular top and base, thin massive interior zone. Widespread oil impregnation.
503	72,07	0,045	6,86	2,781	Massive	
504	72,32	0,376	12,28	2,774		
505	72,65	0,064	6,93	2,762		
506	72,91	0,040	8,11	2,853		
507	73,21	0,053	6,78	2,883		
508	73,57	0,047	7,08	2,902		
509	73,85	0,027	5,01	2,658		
510	74,10	0,031	7,53	2,799		
511	74,41	0,037	6,49	2,775	Unit 20	Basalt lava flow 3.2 m thick Vesicular top and base, thin massive interior zone. Scattered oil impregnation.
512	74,70	0,029	8,53	2,856		
513	75,05	0,043	8,20	2,811		
514	75,31	0,029	7,19	2,739		

Sample	Depth, m	Gas perm	Porosity	Gr. dens.	Oil impregnation				
515	75,58	0,037	7,33	2,799				<u>Unit 20, continued</u>	
516	75,83	0,055	7,22	2,807	} Massive				
517	76,19	0,056	7,91	2,892					
518	76,50	0,050	7,44	2,884					
519	76,77	0,057	7,32	2,829					
520	77,26	0,108	13,38	2,722					
521	77,44	<b>17,558</b>	17,51	2,725	No difference	<b>Unit 21</b>	<b>Basalt lava flow</b>	5.0 m thick	
522	77,74	0,157	13,07	2,714			Strongly vesicular top zone.		
523	78,06	0,066	13,15	2,739			Vesicular and massive in alternation.		
524	78,34	0,096	12,68	2,691	} Massive		Fractures with slickensides.		
525	78,69	0,232	14,78	2,744			Calcite veins.		
526	78,92	0,051	8,43	2,658			Vesicle-filling: calcite, clay, agate.		
527	79,19	0,074	10,07	2,682			Widespread oil impregnation.		
528	79,40	0,638	13,56	2,719					
529	79,80	0,107	10,96	2,719					
530	80,09	0,143	11,95	2,739	} Massive				
531	80,38	0,052	6,60	2,772					
532	80,99	0,043	2,45	2,792					
533	81,28	0,046	3,06	2,815					
534	81,59	0,034	3,09	2,760					
535	81,88	0,146	7,87	2,685					
536	82,04	0,039	7,26	2,614					
537	82,51	0,344	11,85	2,725					
538	83,25	0,036	6,06	2,773		<b>Unit 22</b>	<b>Basalt lava flow</b>	1.9 m thick	
539	83,56	0,074	10,51	2,743			Vesicular all through.		
540	83,86	0,060	12,36	2,695					
541	84,18	0,039	11,03	2,693		<b>Unit 23</b>	<b>Basalt lava tongue</b>	0.7 m thick	
542	84,61	0,090	10,09	2,709			Vesicular all through.		
543	84,82	0,056	8,95	2,657	} Massive				
544	85,08	0,044	8,85	2,675			<b>Unit 24</b>	<b>Basalt lava flow</b>	2.6 m thick
545	85,34	0,097	5,88	2,678				Vesicular all through.	
546	85,69	0,041	6,94	2,615				Scattered oil impregnation.	
547	85,97	0,071	11,69	2,708					
548	86,26	0,117	12,26	2,702					
549	86,53	0,073	8,54	2,703					
550	86,70	0,086	10,45	2,694					
551	87,14	0,033	6,85	2,777					
552	87,42	0,102	7,93	2,725					
553	87,51	0,313	8,68	2,782		<b>Unit 25</b>	<b>Basalt lava flow</b>	1.5 m thick	
554	87,81	0,028	3,69	2,777			Vesicular all through.		
555	88,09	0,026	3,28	2,838			No oil.		
556	88,45	0,033	8,13	2,821					
557	88,71	0,173	13,09	2,740					
558	88,91	1,000	15,23	2,757					
559	89,28	0,142	12,62	2,823		<b>Unit 26</b>	<b>Picrite lava flow</b>	4.3 m thick	
560	89,65	0,158	13,07	2,834			Vesicular all through.		
561	89,88	0,588	11,03	2,815			No oil.		
562	90,16	1,043	12,35	2,781					

**Median values:**

<b>All Marraat-1 samples</b>	<b>0,051</b>	<b>7,459</b>	<b>2,822</b>
<b>Vesicular lavas</b>	<b>0,066</b>	<b>8,855</b>	<b>2,792</b>
<b>Massive lavas</b>	<b>0,038</b>	<b>4,089</b>	<b>2,874</b>
<b>No oil impregnation</b>	<b>0,045</b>	<b>6,735</b>	<b>2,843</b>
<b>Oil-impregnated lavas</b>	<b>0,079</b>	<b>8,855</b>	<b>2,792</b>

WELL GANE-1

Sample	Depth, m	Gas perm.	Porosity	Gr. Dens.	Oil impregnation	
1051	3,79	0,150	6,34	2,741	<p><b>Unit 1 Coarse hyaloclastite</b>                      Very coarse (mass flow) deposit with frequent lava blocks up to 30-40 cm size in glassy matrix.                      Plagioclase-phyric basalt.</p>	
1052	4,05	0,094	3,82	2,735		
1053	4,31	0,023	2,80	2,774		
1054	4,73	0,181	5,94	2,704		
1055	4,99	0,182	5,30	2,723		
1056	5,29	0,063	4,19	2,720		
1057	5,7	0,155	4,12	2,727		
1058	5,89	0,069	6,17	2,754		
1059	6,71	0,083	4,48	2,748		
1060	6,98	0,079	5,55	2,751		
1061	8,56		2,76	2,851		
1062	8,88	0,146	4,72	2,721		
1063	9,22	<b>0,695</b>	<b>12,82</b>	2,670		← Sample not visibly different from others
1064	9,55	0,138	6,08	2,750		
1065	9,85	0,241	8,28	2,766		
1066	10,18	0,260	6,57	2,744		
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1067	144,46	0,019	1,51	2,854	← 50 cm clast of strongly vesicular lava.	
1068	144,63	0,213	<b>15,71</b>	2,569	<p><b>Unit 5 Siltstone</b>                      Fine-grained bedded deposit with coarser beds of hyaloclastite material, slump structures and sparse small shell fragments.</p>	
1069	145,01	0,059	<b>18,67</b>	2,627		
1070	145,35		<b>20,65</b>	2,616		
1071	145,47	0,068	<b>17,69</b>	2,622		
1072	145,64		<b>16,11</b>	2,588		
1073	146,03		<b>16,78</b>	2,589		
1074	146,49	0,287	6,16	2,471		
1075	146,77	<b>5,156</b>	6,59	2,533		
1076	147,11		2,49	2,791		← 40 cm clast of vesicular lava.
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1077	147,61	0,814	5,34	2,568	<p><b>Unit 6 Coarse hyaloclastite</b>                      Frequent up to 10 cm lava clasts.                      Aphyric basalt.                      Bleeding oil, especially in upper half.</p>	
1078	148,12	0,027	3,73	2,712		
1079	148,52	0,377	3,05	2,641		
1080	148,84	0,710	4,20	2,641		
1081	149,21	0,380	2,79	2,672		
1082	149,52	0,769	3,56	2,671		
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1083	149,83	1,634	9,73	2,639	<p>Relatively fine-grained rock with thin cracks.</p>	
1084	150,15	<b>2,219</b>	<b>13,00</b>	2,605		
1085	150,46	0,070	6,08	2,546	<p><b>Unit 7 Volcaniclastic sand</b>                      Normal grain size up to 0.5 cm, scattered lava clasts up to 10 cm. Carbonate-shelled fossil fragments, including corals. No oil.</p>	
1086	150,77	0,110	5,29	2,585		
1087	151,07	0,068	5,27	2,632		
1088	151,41	0,228	8,23	2,507		
1089	151,71	0,152	5,62	2,602		
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1090	152,14	0,058	3,46	2,654		<p><b>Unit 8 Hyaloclastite</b>                      Variable deposit with coarser and finer intervals.                      Aphyric basalt.                      Bleeding oil at 152-158.2 m.                      Oil impregnation and scattered bleeding farther down-core.</p>
1091	152,27	0,119	5,24	2,614		
1092	152,6	0,859	7,81	2,612		
1093	152,87	1,248	7,96	2,629		
1094	153,23	0,727	6,93	2,617		
1095	153,47	0,393	6,29	2,622		
1096	153,78	1,103	7,22	2,619		
1097	154,06	0,044	5,99	2,702		
1098	157,46	1,210	7,05	2,667		
1099	157,77	1,333	7,22	2,601		
1100	158,07	1,268	<b>8,84</b>	2,622	<p>Relatively fine-clastic; up to 1 cm clasts.</p>	
1101	158,35	<b>2,442</b>	<b>9,26</b>	2,645		
1102	158,56	<b>4,758</b>	<b>9,99</b>	2,636		
1103	158,9	0,680	6,55	2,695		
1104	159,13	0,599	6,32	2,642		
1105	159,39	0,332	6,48	2,705		
1106	159,66	0,286	6,59	2,685		
1107	159,97	<b>0,049</b>	<b>2,34</b>	<b>2,841</b>	← Sample is almost all solid lava clast	
1108	160,24	0,185	4,84	2,769		
1109	160,6	0,052	3,89	2,736		
1110	160,86	0,052	2,91	2,713		
1111	161,2	2,916	7,85	2,704		

Sample	Depth, m	Gas perm	Porosity	Gr. Dens.	Oil impregnation
1112	161,52	0,550	6,95	2,719	
1113	161,88	1,143	7,84	2,631	Unit 8, continued
1114	162,32	0,442	5,95	2,677	
1115	162,57	0,067	3,32	2,762	
1116	162,99	0,066	3,50	2,780	
1117	163,24	1,629	<b>9,69</b>	2,631	←  Fine-clastic
1118	163,7	1,258	6,99	2,703	
1119	163,87	0,246	5,09	2,682	
1120	164,16	0,488	7,13	2,670	
1121	164,56	2,447	7,65	2,647	← Coarse-clastic
1122	164,92	1,163	7,71	2,649	← Coarse-clastic
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1123	455,08	0,252	7,53	2,678	
1124	455,35	0,184	5,40	2,736	<b>Unit 10 Hyaloclastite</b>
1125	455,62	0,368	7,42	2,684	Medium-grained with up to 10 cm clasts.
1126	455,92	0,248	7,69	2,699	Aphyric basalt.
1127	456,24	0,041	4,00	2,755	Scattered oil impregnation.
1128	456,36	0,387	8,34	2,713	
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1129	456,69	1,962	7,94	2,746	
1130	456,98		5,69	2,842	<b>Unit 11 Coarse hyaloclastite</b>
1131	457,27	1,564	7,67	2,765	Contains frequent up to 25 cm clasts of vesicular lava.
1132	457,46		<b>15,98</b>	<b>2,835</b>	← Not visibly different. Calcite-filled vesicles.
1133	457,73	<b>0,038</b>	5,84	<b>2,836</b>	← All one vesicular lava clast. Aphyric basalt.
1134	457,98	0,435	8,60	2,717	Scattered oil impregnation.
1135	458,24	0,138	5,87	2,702	
1136	458,53	0,116	4,54	2,805	
1137	459,07	<b>0,020</b>	<b>2,45</b>	2,793	← Mainly a lava clast.
1138	459,42	0,042	3,82	2,752	
1139	459,7	0,037	3,12	2,804	
1140	459,99	<b>0,020</b>	<b>1,04</b>	<b>2,933</b>	← All one lava clast. Only few vesicles.
1141	460,45	0,644	9,84	2,717	
1142	460,76		<b>12,49</b>	2,791	← Calcite veins and fine cracks.
1143	461,09	<b>0,022</b>	<b>2,37</b>	2,742	← All one vesicular lava clast.
1144	461,36	<b>15,437</b>	<b>11,91</b>	<b>2,830</b>	← Fine cracks, much matrix.
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1145	461,88	<b>0,018</b>	1,16	<b>2,936</b>	← All one non-vesicular lava clast.
1146	462,19	0,031	3,90	2,721	<b>Unit 12 Hyaloclastite</b>
1147	462,59	0,158	6,65	2,727	Medium-to-coarse deposit with frequent 2-6 cm clasts.
1148	463,38	1,300	8,18	2,710	Aphyric basalt.
1149	463,38	0,194	6,66	2,694	Scattered oil impregnation.
1150	463,69	0,036	3,48	2,751	
1151	463,88	0,041	3,21	2,792	
1152	464,13	0,035	2,57	2,761	
1153	464,44	0,081	4,04	2,739	
1154	464,77	0,066	3,02	2,813	

**Median of all GANE-1 0,204 6,121 2,704**

**Median of hyaloclastites 0,155 5,872 2,741**

**Median of siltstones 0,213 16,446 2,588**

**Median of oil-impregnated intervals 0,211 5,993 2,704**

**WELL GANK-1**

Sample	Depth, m	Gas perm.	Porosity	Gr. Dens.				
351	82,83	0,389	8,17	2,506	<b>Unit 3</b>	<b>Fine-clastic hyaloclastite</b> Upper part bedded, clasts 1-2 cm Matrix-rich.		
352	83,22	0,454	2,96	2,632				
353	83,54	0,682	3,58	2,535				
354	83,85	0,701	2,64	2,625	Coarsening downwards: clast size increasing up to 8 cm.			
355	84,13	0,216	3,05	2,410	Bedding becomes indistinct.			
356	84,48	0,107	<b>12,27</b>	2,568	←Net-veined by mm-thin calcite veins.			
357	84,78	0,180	3,63	2,451				
358	85,06	0,107	2,96	2,400				
359	85,43	0,265	3,36	2,532	<b>Unit 4</b>	<b>Hyaloclastite</b> Upper part bedded, fine-clastic, matrix-rich. Clasts normally up to 1 cm. A few larger clasts up to 10 cm.		
360	85,75	0,060	5,28	2,460				
361	86,37	0,329	4,64	2,428				
362	86,46	0,404	5,22	2,450				
363	86,75	<b>1,301</b>	5,48	2,448				
364	87,04	<b>1,113</b>	6,46	2,472				
365	87,30	0,227	<b>10,91</b>	2,599			← Rock not visibly different.	
366	87,66	0,557	8,31	2,622				
367	87,94	0,384	5,27	2,674			Coarser deposit from c. 88 m.	
368	88,20	0,134	2,14	2,705			← Mainly clasts	
369	88,46	0,162	2,25	2,705	← Mainly clasts			
370	88,73	0,323	5,47	2,720				
371	88,98	0,246	6,29	2,627				
372	89,24	0,651	6,65	2,604				
373	89,43		7,78	2,629				
374	89,74	0,108	4,97	2,677				
375	89,98	0,090	4,36	2,687				
376	90,18	0,174	5,06	2,675				
377	90,69	0,179	4,53	2,675				
378	90,89	0,037	8,62	2,822				
379	91,14	0,342	6,15	2,624				
380	91,83	0,110	4,94	2,660				
381	92,45		<b>11,88</b>	2,629	← Cracks in rock, and hair-thin calcite veins.			
382	92,76	0,259	7,78	2,693				
383	93,03	0,067	4,65	2,673				
384	93,35		9,17	2,670				
385	93,66		8,09	2,672	<b>Unit 5</b>	<b>Volcaniclastic sand</b> Bedded; normal clast size <0.5 cm. Occasional clasts up to 3 cm. Several depositional events can be discerned by grain size variations.		
386	94,07	0,020	5,26	2,654				
387	94,25		7,26	2,623				
388	94,54		8,41	2,651				
389	95,16							
390	95,45		5,78	2,567				
391	95,75							
392	95,85	0,044	4,01	2,619			93-97 m: Disseminated calcite impregnation in matrix.	
393	96,19	0,413	6,24	2,579				
394	96,44	0,363	5,36	2,581				
395	96,84	<b>1,960</b>	3,28	2,593	← Very fine-grained.			
396	96,97	0,286	6,04	2,561				
397	97,32	0,334	8,41	2,573				
398	97,63		<b>13,26</b>	2,552	← Cracks in rock.			
399	97,86	0,084	8,28	2,565				
400	98,19	0,088	4,39	2,574				
401	98,50	<b>2,334</b>	5,80	2,562	} Very fine-grained.			
402	98,79	<b>3,719</b>	8,37	2,539				
403	99,93	<b>2,640</b>	8,64	2,533				
404	100,30	0,844	8,13	2,547				
405	100,58	0,489	<b>10,10</b>	2,529	← Rock not visibly different.			
<b>Median of all GANK-1</b>		<b>0,286</b>	<b>5,775</b>	<b>2,599</b>				
<b>Median of hyaloclastite</b>		<b>0,246</b>	<b>5,219</b>	<b>2,625</b>				
<b>Median of volc. sand</b>		<b>0,388</b>	<b>7,676</b>	<b>2,573</b>				