Grain Size Distribution and Heavy Minerals Content of Marine Sands in Federal Waters Offshore of Virginia

Authors:
C. R. Berquist, Jr.[1]
William L. Lassetter[1]
Mary H. Goodwyn[2]

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By:
[1]Virginia Department of Mines, Minerals and Energy
Division of Geology and Mineral Resources
900 Natural Resources Drive
Charlottesville, VA 22903

[2]Virginia Institute of Marine Science
College of William and Mary
1375 Greate Road
Gloucester Point, VA 23062

U.S. Department of the Interior
Bureau of Ocean Energy Management
Leasing Division Marine Minerals Program
Sterling, VA 20166

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Table of Contents

Tables

Figures

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ABSTRACT

Marine sediment samples collected in 2013 in the offshore Virginia Wind Energy Area (WEA) were analyzed for grain size statistics and heavy minerals content. These analyses provide valuable geotechnical and economic information that is relevant to the identification of potential offshore sand borrow areas for beach re-nourishment, an objective of the BOEM-Virginia State Cooperative Agreement M14AC00013. The sediments were collected as seafloor grab and vibracore samples at locations ranging from about 3.5 nautical miles from shore out to about 35 nautical miles within the WEA. Water depths ranged from about 11 meters to 34 meters MLLW (mean lower low water). A total of 73 large-volume sediment samples were dried, screened and sieved for textural analysis, and of these 60 were processed through a three-turn Humphrey Spiral concentrator to separate the total heavy minerals (THM) fraction for laboratory mineralogical analysis. Thirteen additional grab samples were processed for THM only. The heavy minerals of interest in this study are characterized by specific gravity greater than about 2.9 and include ilmenite ($FeTiO_3$), rutile (TiO_2), leucoxene (altered ilmenite), monazite ($(Ce,La,Nd,Y,Dy,Sm,Th)(PO_4)$), and zircon ($(Zr,Hf,U)(SiO_4)$). These minerals have economic value as sources of titanium- and zirconium-oxides, rare earth elements and thorium that could provide significant cost benefits if co-recovered during sand mining operations for coastline protection projects.

Grain size analysis indicated most samples consist of medium- to coarse sand with low percentages of mud averaging less than 2% and gravel less than 2.5%. The THM fractions for all samples averaged 0.93% by weight, but there were notable enrichments in samples with higher percentages of fine-grain sediments. In 6 samples where the total sand fraction consisted mainly of fine- to very-fine sand, THM averaged 2.63% by weight with a maximum value of 4.10%. Lab results from Mineral Liberation Analyzer (MLA) scans indicated garnet, titanium-bearing minerals, and amphibole to be the most abundant components of the THM concentrates. On a mass percent basis, ilmenite and rutile averaged about 18.21% and 1.49%, respectively in the concentrates. Minerals containing rare earth elements (REE), such as monazite and apatite were generally low in abundance, although REE-bearing zircon ranged as high as 5.73% and averaged 2.21% for all samples.

The lab results for these samples will expand the catalog of offshore data that is available to help identify beach-quality sand resources for dredging operations and coastal restoration projects. The heavy minerals analyses compliment data from earlier offshore mineral assessments that showed very promising potential for economic deposits of coexisting industrial minerals. THM concentrations were generally lower than those reported by Berquist and Hobbs (1988) and Berquist et al., (1990) for 390 sediment samples from Virginia's offshore region (average THM = 3.3% with a maximum value of 14.7%), but also underscored the importance of the

depositional environment on the distribution of heavy mineral sands. Based upon the minimum economic threshold concentration of about 2% THM for heavy mineral sand deposits in coastal environments worldwide (Van Gosen et al., 2014), additional data gathering is warranted to better understand the tonnage potential, key depositional factors, and mineralogical compositions of Virginia's offshore sand resources.

INTRODUCTION

The Virginia Department of Mines, Minerals and Energy (DMME) - Division of Geology and Mineral Resources (DGMR) has for many years worked cooperatively with the U.S. Bureau of Ocean Energy Management (BOEM) to identify sand resources on Virginia's Outer Continental Shelf (OCS) suitable for beach nourishment and other coastal protection and restoration projects. These resources serve a vital role in sustaining economic growth and the vitality of popular tourist destinations such as Chincoteague Island and Virginia Beach. Marine mineral projects have also protected important coastal infrastructure including NASA's Wallops Flight Facility at Wallops Island, and facilities at Naval Station Oceana, Dam Neck Annex.

In May 2014, DGMR and BOEM began a partnership as part of State Cooperative Agreement M14AC00013 on the project entitled, *Hurricane Sandy Coastal Recovery and Resiliency – Resource Identification, Delineation, and Management Practices*. The project study area encompasses the OCS region in Federal waters from 3 nm (nautical miles) to 8 nm offshore (Figure 1).

Concurrent studies in the Virginia offshore Wind Energy Area (WEA) provided an opportunity to leverage ongoing sample collection activities to gain access to marine sediment samples. Through an agreement with the WEA environmental contractors, DGMR acquired large-volume sand samples for geotechnical and mineralogical analysis. Additional seafloor grab and vibracore samples were made available from a related ongoing research project, the Virginia Offshore Wind Technology Advancement Project (VOWTAP). These marine samples were collected over a large geographic region in Federal waters and represent a valuable asset in the effort to identify potential sand resources for coastal resiliency projects.

Previous studies on Virginia's OCS have also recognized the potential economic value of marine mineral resources. Sand and gravel deposits contain known economic concentrations of heavy minerals such as ilmenite ($FeTiO_3$), rutile (TiO_2), zircon ($ZrSiO_4$), monazite ($CePO_4$), among others. In a study that included the analysis of 390 sediment samples from vibracore and grab samples, Berquist et al., (1990) reported a substantial number of samples that contained concentrations of one or more economic minerals that were equal to or greater than cut-off grades in onshore deposits that are currently being mined from Pliocene-age beach sands in Dinwiddie and Greenville Counties, Virginia (DMME, 2015). Increasing demand for construction aggregate and the depletion of Virginia's available onshore resources that meet required specifications may also soon result in greater interest in offshore aggregate resources.

Although relatively untested to date, Virginia's OCS region likely contains valuable deposits of industrial minerals including high-purity silica sand, phosphate, aluminum-rich sillimanite minerals, and rare earth elements. These minerals are currently produced from similar continental shelf marine deposits in Australia, Canada, and Japan.

PURPOSE AND RELEVANCE

Federal funding from the BOEM-Virginia Hurricane Sandy State Cooperative provided the means to complete grain size and heavy mineral analyses for existing marine sand samples that had been recently collected in the offshore WEA area. The work was conducted through a partnership between BOEM, DGMR, and the Virginia Institute of Marine Science (VIMS). This report presents DGMR's findings in partial fulfilment of the work product deliverables for Cooperative Agreement M14AC00013. The results provide the foundation for continuing investigations that will identify and delineate sand resources for coastal recovery and resiliency. Recognizing that recovery of "value-added" mineral resources as part of beach restoration programs could potentially provide economic offsets to the costs of future dredging projects in Virginia, it is anticipated that recommendations from this assessment may inform BOEM's policy decisions as the demand for non-traditional marine mineral resources increases.

METHODS AND ANALYSES

Acquisition of seafloor grab and vibracore samples from Virginia's Wind Energy Area

Virginia's offshore Wind Energy Area (WEA) includes 20 OCS lease blocks, encompassing an area of about 476 km^2 (135 nm). The western boundary of the WEA is about 45 km (25 nm) east of Cape Henry, Virginia Beach (Figure 1). Fugro Consultants, Inc. (Fugro) was contracted in early 2013 to perform a desktop geologic assessment together with geophysical and geotechnical surveys over the WEA to support future leasing and development of offshore wind resources (McNeilan et al., 2013). As part of the data gathering activities, Fugro collected 73 large-volume samples of seafloor sediments at the request of DGMR for the purposes of assessing grain size distribution and heavy mineral content in the WEA and also along a regional tie line to the Chesapeake Bay Bridge Tunnel. Fugro shipped the samples in 5-gallon buckets to DGMR in Williamsburg where they were received and entered into the DGMR repository in July 2013. The locations of the samples are shown in Figure 1, and Table 1 provides the DGMR repository number, sample identification, coordinates and water depth.

Additional marine sediment samples were acquired in 2014 with ongoing data collection activities associated with the Virginia Offshore Wind Technology Advancement Project (VOWTAP). As part of this renewable energy technology research partnership that included Dominion Resources, Inc., DMME, the National Renewable Energy Laboratory (NREL), the Virginia Coastal Energy Research Consortium (VCERC), among other project partners, Tetra Tech Inc. (Tetra Tech) conducted sediment sampling and geophysical surveys in the planned wind turbine demonstration area of the WEA as well as along the proposed cable route back to Camp Pendleton, Virginia Beach.

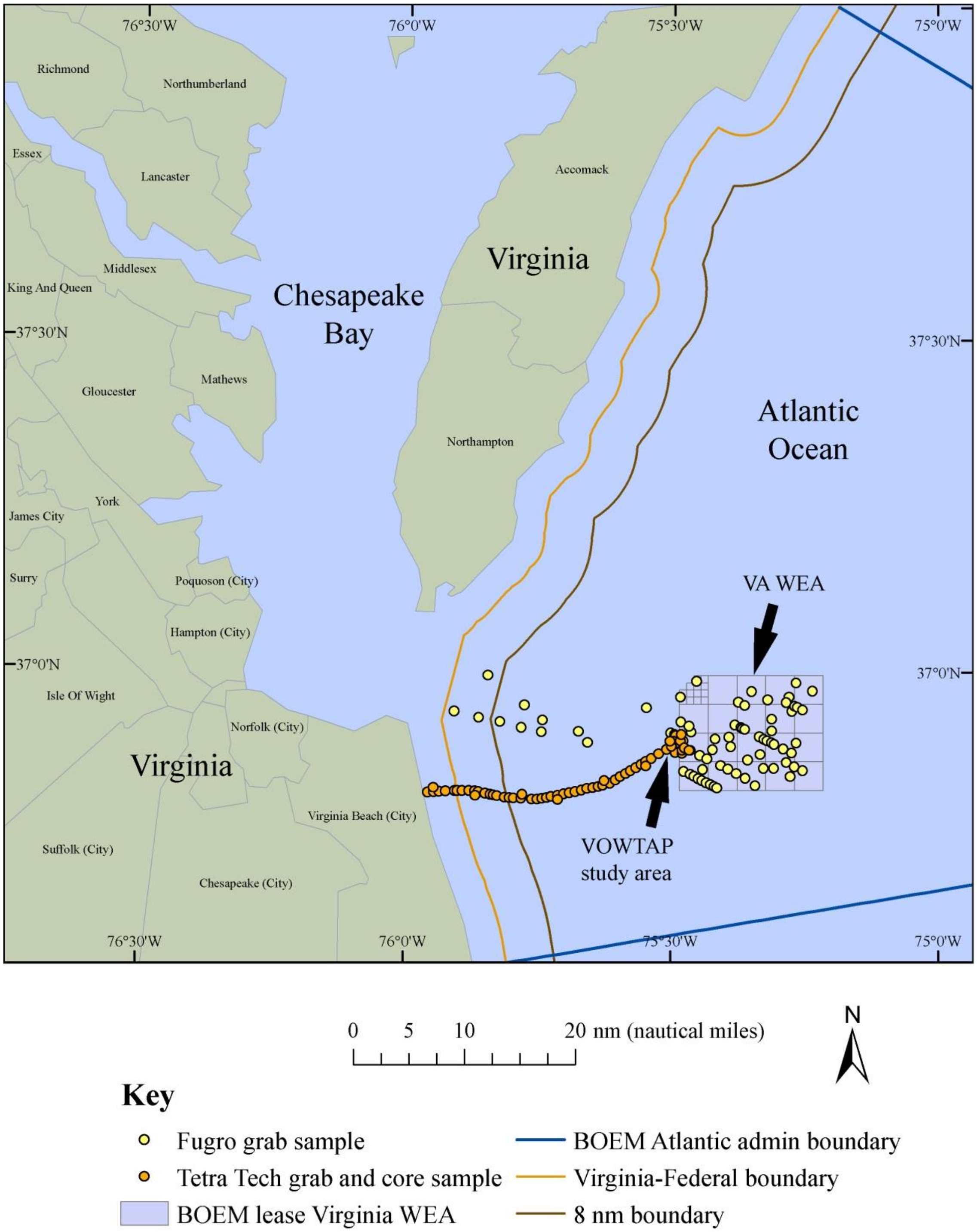

Figure 1. Project location map showing 3 nm and 8 nm boundaries, the location of the BOEM-Virginia Wind Energy Area (WEA), and sediment samples collected by Fugro (WEA) and Tetra Tech (VOWTAP).

In September 2014 following the completion of grain size and other geotechnical analyses for the VOWTAP project, Tetra Tech provided DGMR with 69 grab samples and 90 bagged sample intervals from 17 vibracore locations. Sample locations and the results of grain size analyses are available in the final VOWTAP report (Tetra Tech, 2014). Thirteen of the grab samples were selected for heavy mineral analysis for the present study. The locations are shown in Figure 1 and Table 1 provides additional information about the samples.

Table 1. List of marine sediment samples acquired from Fugro (F) and Tetra Tech (TT) with DGMR repository number, sample ID, location information, and type of lab analysis.

Repository number (R-)	**Sample ID**	**Longitude (dec deg W)**	**Latitude (dec deg N)**	**Water depth m (ft) MLLW**	**Type Analysis** **gsa= grain size** **hm= heavy mins**
10942	GS-101-01(F)	-75.50086	36.90829	21.9 (71.9)	gsa, hm
10943	GS-103-01(F)	-75.46263	36.90925	28.6 (93.8)	gsa
10945	GS-106-01(F)	-75.44050	36.85358	22.0 (72.2)	gsa, hm
10946	GS-106-02(F)	-75.42242	36.88313	22.1 (72.5)	gsa, hm
10947	GS-107-01(F)	-75.39185	36.90221	24.8 (81.4)	gsa, hm
10948	GS-107-02(F)	-75.34927	36.97122	28.8 (94.5)	gsa
10949	GS-109-03(F)	-75.31925	36.95871	28.9 (94.8)	gsa, hm
10950	GS-110-02(F)	-75.35657	36.86815	24.7 (81.0)	gsa, hm
10951	GS-111-01(F)	-75.33302	36.87578	25.2 (82.7)	gsa
10952	GS-111-02(F)	-75.31118	36.91132	27.1 (88.9)	gsa
10953	GS-111-03(F)	-75.27962	36.96234	28.0 (91.9)	gsa
10954	GS-112-01(F)	-75.34267	36.82908	23.4 (76.8)	gsa
10955	GS-112-03(F)	-75.32693	36.85518	25.3 (83.0)	gsa
10956	GS-112-04(F)	-75.27402	36.94142	26.8 (87.9)	gsa
10957	GS-114-01(F)	-75.28377	36.86421	30.2 (99.1)	gsa, hm
10958	GS-114-02(F)	-75.26577	36.89311	32.7 (107.3)	gsa
10959	GS-115-01(F)	-75.26884	36.85814	28.0 (91.9)	gsa, hm
10960	GS-116-01(F)	-75.25369	36.85214	28.9 (94.8)	gsa, hm
10961	GS-201-01(F)	-75.47641	36.85030	27.4 (89.9)	gsa, hm
10962	GS-201-02(F)	-75.46439	36.84554	23.9 (78.4)	gsa
10963	GS-201-04(F)	-75.45720	36.84271	21.5 (70.5)	gsa, hm
10964	GS-201-05(F)	-75.44919	36.83955	21.5 (70.5)	gsa, hm
10965	GS-201-06(F)	-75.44238	36.83662	21.1 (69.2)	gsa, hm
10966	GS-201-07(F)	-75.43409	36.83353	25.3 (83.0)	gsa, hm
10967	GS-201-08(F)	-75.42640	36.83029	24.2 (79.4)	gsa, hm
10968	GS-201-09(F)	-75.41916	36.82749	24.4 (80.1)	gsa, hm
10969	GS-201-10(F)	-75.41401	36.82549	25.5 (83.7)	gsa
10970	GS-202-01(F)	-75.46455	36.88186	28.4 (93.2)	gsa, hm
10971	GS-202.02(F)	-75.44687	36.87465	27.7 (90.9)	gsa, hm
10972	GS-202-03(F)	-75.43334	36.86935	23.0 (75.5)	gsa, hm

Repository number (R-)	**Sample ID**	**Longitude (dec deg W)**	**Latitude (dec deg N)**	**Water depth m (ft) MLLW**	**Type Analysis** **gsa= grain size** **hm= heavy mins**
10973	GS-202-04(F)	-75.40738	36.85906	25.7 (84.3)	gsa, hm
10974	GS-202-05(F)	-75.39410	36.85382	28.4 (93.2)	gsa, hm
10975	GS-202-06(F)	-75.37804	36.84739	24.4 (80.1)	gsa, hm
10976	GS-202-07(F)	-75.36105	36.84053	23.5 (77.1)	gsa, hm
10977	GS-203-01(F)	-75.48169	36.92485	26.2 (86.0)	gsa, hm
10978	GS-203-02(F)	-75.46659	36.91876	26.1 (85.6)	gsa, hm
10979	GS-203-03(F)	-75.41746	36.89931	26.8 (87.9)	gsa, hm
10980	GS-203-04(F)	-75.38826	36.88768	28.4 (93.2)	gsa, hm
10981	GS-203-05(F)	-75.30768	36.85573	30.9 (101.4)	gsa, hm
10982	GS-203-06(F)	-75.27673	36.84315	26.2 (86.0)	gsa, hm
10983	GS-204-01(F)	-75.48295	36.96169	22.9 (75.1)	gsa, hm
10984	GS-204-05(F)	-75.38045	36.92069	28.6 (93.8)	gsa, hm
10985	GS-204-06(F)	-75.36949	36.91655	28.5 (93.5)	gsa, hm
10986	GS-204-07(F)	-75.36633	36.91507	25.8 (84.6)	gsa, hm
10987	GS-204-08(F)	-75.36233	36.91368	23.9 (78.4)	gsa, hm
10988	GS-204-09(F)	-75.33501	36.90278	26.3 (86.3)	gsa, hm
10989	GS-204-10(F)	-75.32594	36.89898	24.6 (80.7)	gsa, hm
10990	GS-204-11(F)	-75.32023	36.89678	23.8 (78.1)	gsa, hm
10991	GS-204-12(F)	-75.31209	36.89367	25.5 (83.7)	gsa, hm
10992	GS-204-13(F)	-75.30684	36.89159	30.2 (99.1)	gsa, hm
10993	GS-204-14(F)	-75.28975	36.88486	30.1 (98.8)	gsa, hm
10994	GS-204-15(F)	-75.27391	36.87824	29.4 (96.5)	gsa, hm
10995	GS-205-01(F)	-75.45307	36.98584	22.0 (72.2)	gsa, hm
10996	GS-205-03(F)	-75.37455	36.95464	28.7 (94.2)	gsa, hm
10997	GS-205-04(F)	-75.36231	36.94961	28.0 (91.9)	gsa, hm
10998	GS-205-05(F)	-75.31136	36.92951	29.6 (97.1)	gsa, hm
10999	GS-206-02(F)	-75.28436	36.95460	27.9 (91.5)	gsa, hm
11000	GS-206-03(F)	-75.26879	36.94882	26.9 (88.3)	gsa, hm
11001	GS-206-04(F)	-75.26403	36.94690	27.0 (88.6)	gsa, hm
11002	GS-206-05(F)	-75.25388	36.94301	34.3 (112.5)	gsa, hm
11003	GS-207-01(F)	-75.26604	36.98374	29.8 (97.8)	gsa, hm
11004	GS-207-02(F)	-75.23544	36.97164	32.6 (107.0)	gsa
11005	GS-500-01(F)	-75.90762	36.93857	11.8 (38.7)	gsa, hm
11006	GS-500-02(F)	-75.86097	36.92956	11.5 (37.7)	gsa, hm
11007	GS-500-03(F)	-75.82090	36.92336	12.7 (41.7)	gsa, hm
11008	GS-500-04(F)	-75.78086	36.91542	14.6 (47.9)	gsa, hm
11009	GS-500-05(F)	-75.74325	36.90868	15.7 (51.5)	gsa, hm
11010	GS-500.06(F)	-75.65673	36.89296	21.1 (69.2)	gsa, hm
11011	GS-501-01(F)	-75.67408	36.90964	19.7 (64.6)	gsa, hm
11012	GS-501-02(F)	-75.54706	36.94561	23.8 (78.1)	gsa

Repository number (R-)	Sample ID	Longitude (dec deg W)	Latitude (dec deg N)	Water depth m (ft) MLLW	Type Analysis gsa= grain size hm= heavy mins
11013	GS-502-03(F)	-75.84461	36.99286	12.7 (41.7)	gsa, hm
11014	GS-502-04(F)	-75.77613	36.94874	12.3 (40.4)	gsa, hm
11015	GS-502-05(F)	-75.74128	36.92633	14.6 (47.9)	gsa, hm
11031	Ref-002(TT)	-75.86700	36.81215	13.82 (45.3)	hm
11032	GS-021(TT)	-75.90069	36.81946	11.01 (36.1)	hm
11033	GS-022(TT)	-75.89147	36.81952	10.98 (36.0)	hm
11034	GS-023(TT)	-75.87816	36.81944	14.01 (46.0)	hm
11035	GS-024(TT)	-75.86786	36.81905	14.79 (48.5)	hm
11036	GS-025(TT)	-75.86131	36.81794	15.77 (51.7)	hm
11037	GS-026(TT)	-75.84834	36.81544	16.03 (52.6)	hm
11038	GS-027(TT)	-75.83873	36.81415	15.65 (51.3)	hm
11039	GS-028(TT)	-75.83258	36.81293	15.85 (52.0)	hm
11040	GS-029(TT)	-75.82635	36.81175	16.17 (53.0)	hm
11041	GS-030(TT)	-75.81243	36.80933	16.12 (52.9)	hm
11042	GS-031(TT)	-75.80282	36.80897	16.60 (54.5)	hm
11043	GS-032(TT)	-75.79487	36.80842	18.41 (60.4)	hm

Sample preparation for grain size and heavy mineral analysis

A total of 73 wet sediment samples received from Fugro in sealed 5-gallon buckets were processed for grain size analysis in the VIMS Sediment Lab located in Gloucester. The work was initiated in November 2014. Appendix C provides a cross-reference to mesh size, grain size scales, and sediment classification terms used in this report. The total sample weights, minus the bucket, ranged from 12.7 kg up to 26.6 kg. From each bucket a representative subsample weighing approximately 150 g was taken for textural analysis using sieving methods in accordance with ASTM Standard D422, “Particle-Size Analysis of Soils”. The remainder of the bulk sample was wet sieved through ASTM 10- and 230-mesh sieves and allowed to dry in large open-air plastic containers in the lab. Due to the large size of the samples and amount of contained water, sample air-drying times averaged about two weeks. The dry sieved gravel fraction (>10-mesh) was placed in a labelled bag and the dry sand fraction (<10-mesh) was placed back in the original bucket. The dry weight of both fractions was recorded for calculating the dry weight percent of the total sample. The bulk sand fraction was transported to the VIMS Seawater Research Lab for heavy mineral separation using DGMR’s Humphrey Spiral.

The 150 g subsamples were wet sieved through stacked ASTM standard 10-mesh and 230-mesh sieves, and the water passing through the sieve set was collected for drying and determination of mud weight percent content (<230-mesh). The sand fraction was air dried and sieved using a Ro-Tap sieve shaker for 10 minutes. The sieve set included the ASTM standard mesh sizes 10, 20, 40, 60, 100 and 230. Each particle size fraction was weighed separately and recorded. The sample was then recombined and labelled for archive in the DGMR repository.

Grain size statistics were evaluated for the sand fraction particle distribution using the base two logarithmic phi (ϕ) scale. Plotting the arithmetic-scaled cumulative weight percent curve against the ϕ scale, the ϕ size at 16%, 50%, and 84% were taken directly from the curve. The mean sand grain size (ϕ_M) was calculated as the average of the three values:

$$\phi_M = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$$

Heavy mineral concentrates were prepared from the bulk sand fractions by passing the entire sample through the DGMR three-turn Humphrey Spiral. The sample was introduced into the top of the spiral under a steady, low pressure stream of water (Figure 2). The heavy minerals (grains with specific gravity generally greater than about 2.9) migrated to the inside of the spiral while the lighter materials (shell, quartz, phosphate, etc.) were carried in the water stream toward the outside. A splitter at the bottom of the spiral was adjusted in the water stream as needed to ensure the separation of the heavy minerals. The concentrate was then washed into the top of the spiral to eliminate as much quartz and lighter weight minerals as possible. The concentrates were dried and weighed. A 100 g split was submitted to Activation Laboratories, Ltd. located in Ancaster, Ontario for mineral identification. There the samples were further concentrated using heavy liquid separation methods. Mineral identifications were completed using the QEMSCAN scanning electron microscope Mineral Liberation Analysis (MLA) method. The remaining concentrates were archived in the DGMR repository. Lighter fraction sands were discarded.

Figure 2. Washing a large volume sediment sample into the top hopper of the three-turn Humphrey Spiral for heavy mineral separation.

RESULTS

Grain size analysis

The results of grain size analysis for 73 Fugro seafloor grab samples indicated that most were composed of good quality medium to coarse sand that would be well suited for coastal resiliency projects (Figure 3). Overall, the sediments averaged 95.84% sand, 2.40% gravel, and 1.75% mud fractions (Table 2). For the sieved sand fractions, grain size (ϕ) statistics were evaluated by the graphic method using the cumulative weight percent curve (Appendix A, Figure 4). The mean ϕ value (ϕ_M) for all samples was 1.0 confirming the visual observation of medium- to coarse sand (Figure 5). Figure 4 also shows a separate cumulative weight percent curve for 6 samples that contained unusually large fractions of fine to very fine sand. The individual ϕ_M values for these samples ranged from 2.2 up to 3.5, averaging 3.0 overall. These finer grain samples were of notable interest concerning the associated heavy mineral content discussed in the next section.

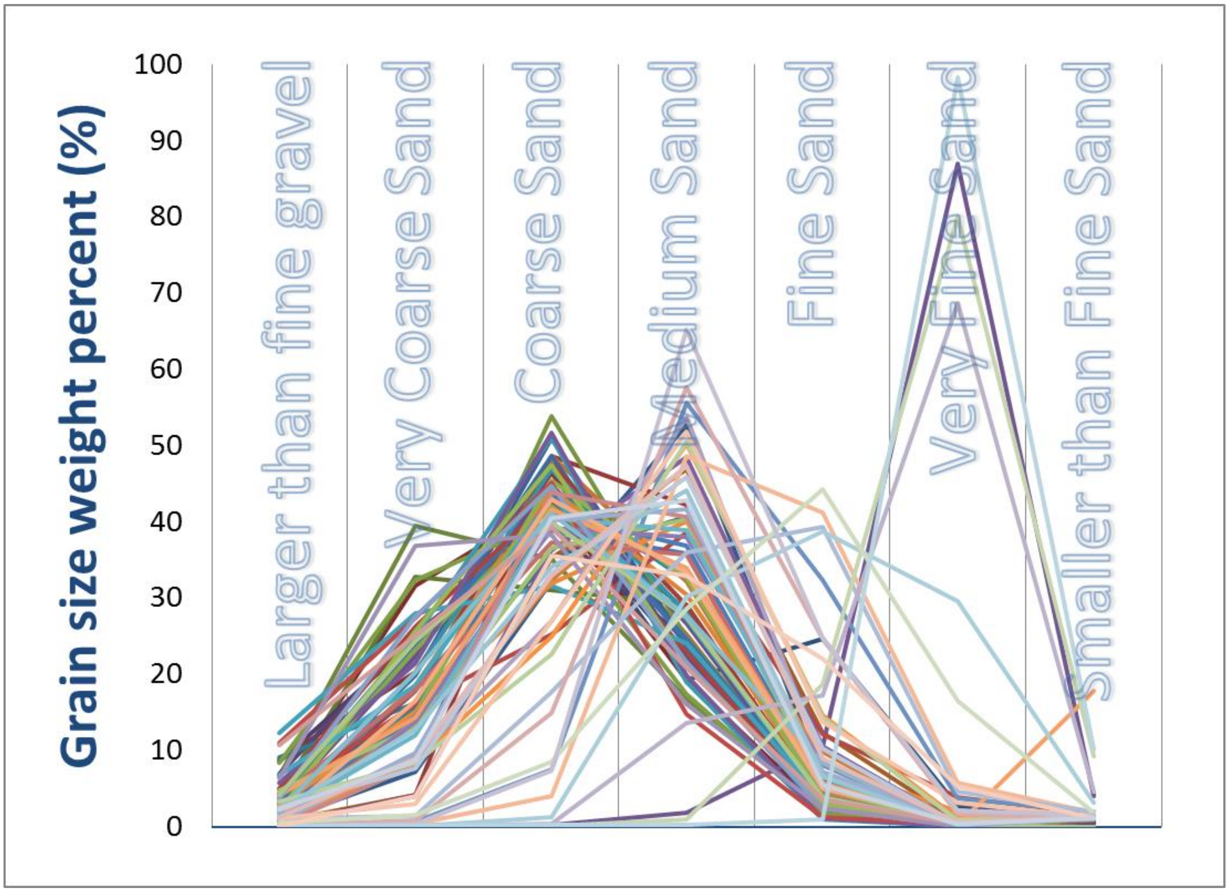

Figure 3. Grain size weight percent distribution for all samples (n=73).

Table 2. Grain size statistics and total heavy mineral (THM) content for Fugro samples. Samples without reported THM were not submitted for mineral analysis. All samples containing THM >1.85% are color-highlighted.

Sample ID	**Gravel %**	**Sand %**	**Mud %**	**Sand fraction ϕ_M**	**THM %**
GS-101-01	0.16	98.39	1.45	1.2	1.17
GS-103-01	0.60	98.46	0.93	0.3	
GS-106-01	1.80	96.84	1.36	0.4	0.37
GS-106-02	10.33	88.73	0.95	0.3	0.34
GS-107-01	4.11	94.71	1.18	0.8	2.01
GS-107-02	1.12	97.78	1.10	1.2	
GS-109-03	0.97	97.83	1.20	1.1	0.99
GS-110-02	16.84	82.52	0.64	0.3	0.27
GS-111-01	3.29	96.33	0.38	0.2	
GS-111-02	2.21	96.63	1.17	0.4	
GS-111-03	5.41	93.99	0.60	0.5	
GS-112-01	3.25	96.16	0.59	0.5	
GS-112-03	0.77	98.29	0.94	0.6	
GS-112-04	0.63	98.62	0.74	1.0	
GS-114-01	0.63	98.02	1.34	0.7	0.60
GS-114-02	1.20	98.27	0.53	0.5	
GS-115-01	0.32	98.73	0.95	0.8	0.48
GS-116-01	1.69	97.39	0.92	0.8	0.51
GS-201-01	1.39	97.28	1.33	0.5	0.47
GS-201-02	2.10	96.79	1.11	0.7	
GS-201-04	5.72	93.34	0.94	0.2	0.25
GS-201-05	1.47	97.51	1.01	0.5	0.20
GS-201-06	2.25	96.29	1.46	0.6	0.54
GS-201-07	0.90	97.61	1.48	1.1	0.41
GS-201-08	2.56	96.32	1.13	0.5	0.41
GS-201-09	1.66	97.47	0.86	0.4	0.38
GS-201-10	1.68	97.29	1.03	0.6	
GS-202-01	0.20	95.72	4.08	3.5	2.14
GS-202-02	3.60	95.25	1.15	0.4	0.24
GS-202-03	1.05	97.62	1.34	0.7	0.41
GS-202-04	1.69	96.80	1.51	0.7	0.61
GS-202-05	2.99	95.33	1.68	1.0	0.49
GS-202-06	1.92	96.86	1.22	0.7	0.54
GS-202-07	3.66	95.12	1.22	0.4	0.42
GS-203-01	2.25	96.68	1.07	0.3	0.47
GS-203-02	2.24	96.61	1.15	0.9	0.65
GS-203-03	1.91	97.01	1.08	0.8	0.48

Sample ID	**Gravel %**	**Sand %**	**Mud %**	**Sand fraction ϕ_M**	**THM %**
GS-203-04	14.57	84.12	1.30	0.2	0.67
GS-203-05	1.31	97.20	1.48	0.5	0.49
GS-203-06	0.13	98.55	1.32	1.1	0.84
GS-204-01	7.28	91.82	0.90	0.6	0.93
GS-204-05	0.29	98.33	1.38	1.2	0.97
GS-204-06	0.12	97.86	2.02	1.8	1.05
GS-204-07	2.83	95.83	1.34	0.7	1.28
GS-204-08	2.01	96.71	1.29	0.8	1.42
GS-204-09	0.33	98.48	1.19	0.9	0.54
GS-204-10	1.24	97.51	1.25	0.9	0.98
GS-204-11	1.37	80.87	17.76	0.8	0.60
GS-204-12	1.64	97.22	1.14	0.4	0.60
GS-204-13	0.27	98.33	1.40	1.0	0.64
GS-204-14	2.42	97.58	0.00	0.5	0.72
GS-204-15	3.36	95.32	1.31	0.2	0.24
GS-205-01	1.59	97.12	1.30	0.7	0.65
GS-205-03	2.04	96.90	1.06	0.8	0.63
GS-205-04	0.24	98.39	1.37	1.0	0.36
GS-205-05	17.69	81.02	1.29	0.3	0.52
GS-206-02	2.90	95.95	1.14	1.2	1.16
GS-206-03	1.69	97.27	1.04	1.1	1.12
GS-206-04	3.83	94.76	1.41	1.0	1.15
GS-206-05	0.04	98.09	1.87	1.9	1.28
GS-207-01	0.91	97.14	1.95	1.7	0.87
GS-207-02	0.09	98.82	1.09	1.6	
GS-500-01	0.07	90.65	9.27	3.4	1.85
GS-500-02	0.01	95.32	4.66	3.1	4.10
GS-500-03	0.03	96.89	3.08	2.5	3.14
GS-500-04	1.61	97.07	1.32	1.3	1.70
GS-500-05	1.97	96.61	1.41	1.1	1.00
GS-500-06	1.26	97.48	1.26	1.07	1.79
GS-501-01	0.55	97.61	1.84	2.2	2.41
GS-501-02	0.04	98.48	1.48	1.7	
GS-502-03	0.03	89.85	10.12	3.5	2.12
GS-502-04	0.55	98.39	1.06	1.4	1.06
GS-502-05	2.48	96.43	1.08	1.0	0.83
MAX	17.69	98.82	17.76	3.5	4.10
MIN	0.01	80.87	0.00	0.2	0.20
AVG	2.40	95.84	1.75	1.0	0.93
SD	3.40	3.86	2.44	0.8	0.70

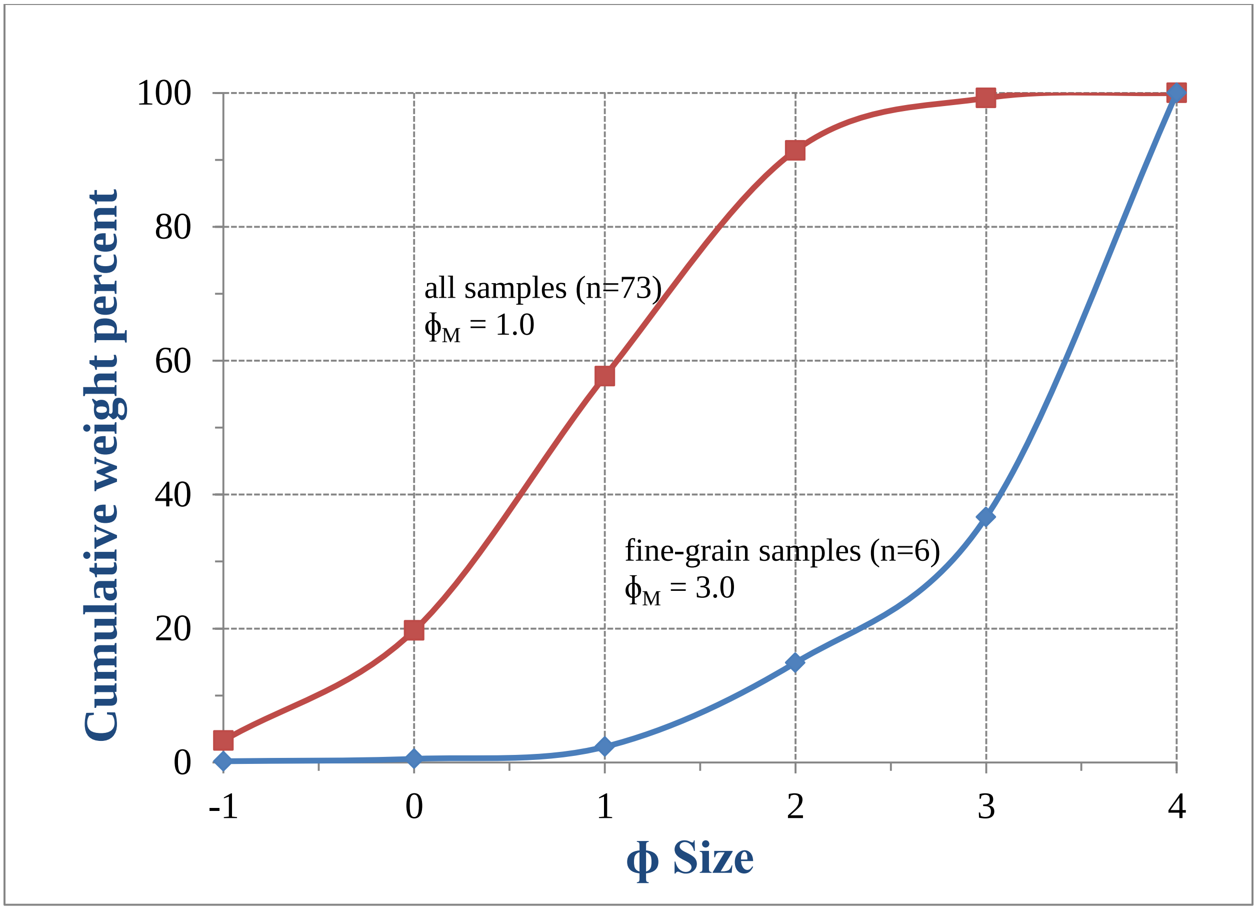

Figure 4. Representative cumulative weight percent curves for all samples (n=73) and very fine grain sand samples only (n=6).

a) GS-107-01 $\phi_M = 0.8$

b) GS-202-01 $\phi_M = 3.5$

Figure 5. Sieved sand fractions; both samples contained THM > 2%.

Total heavy minerals

The results of analysis for total heavy mineral (THM) content as a percent of the total sample weight in 60 Fugro samples are shown in Table 2. Results for 13 Tetra Tech samples were not available at the time this report was finalized and will be provided in a future report to BOEM.

The THM fractions for the Fugro samples ranged from 0.20% up to as high as 4.10% by weight, averaging 0.93% overall. Notable THM enrichments greater than 1.85% were found in seven samples (color-highlighted in Table 2), which included the six samples with the largest fractions of very fine grain sand shown in Figure 4. The positive correlation between higher THM content and higher weight percent of very fine sand in all samples is shown graphically in Figure 6. Although this study was constrained by the relatively small number of samples and limited geographic extent of sampling near the WEA, the apparent link between higher THM content and depositional settings that favors finer grain sandy sediments might be an important economic guide on the OCS.

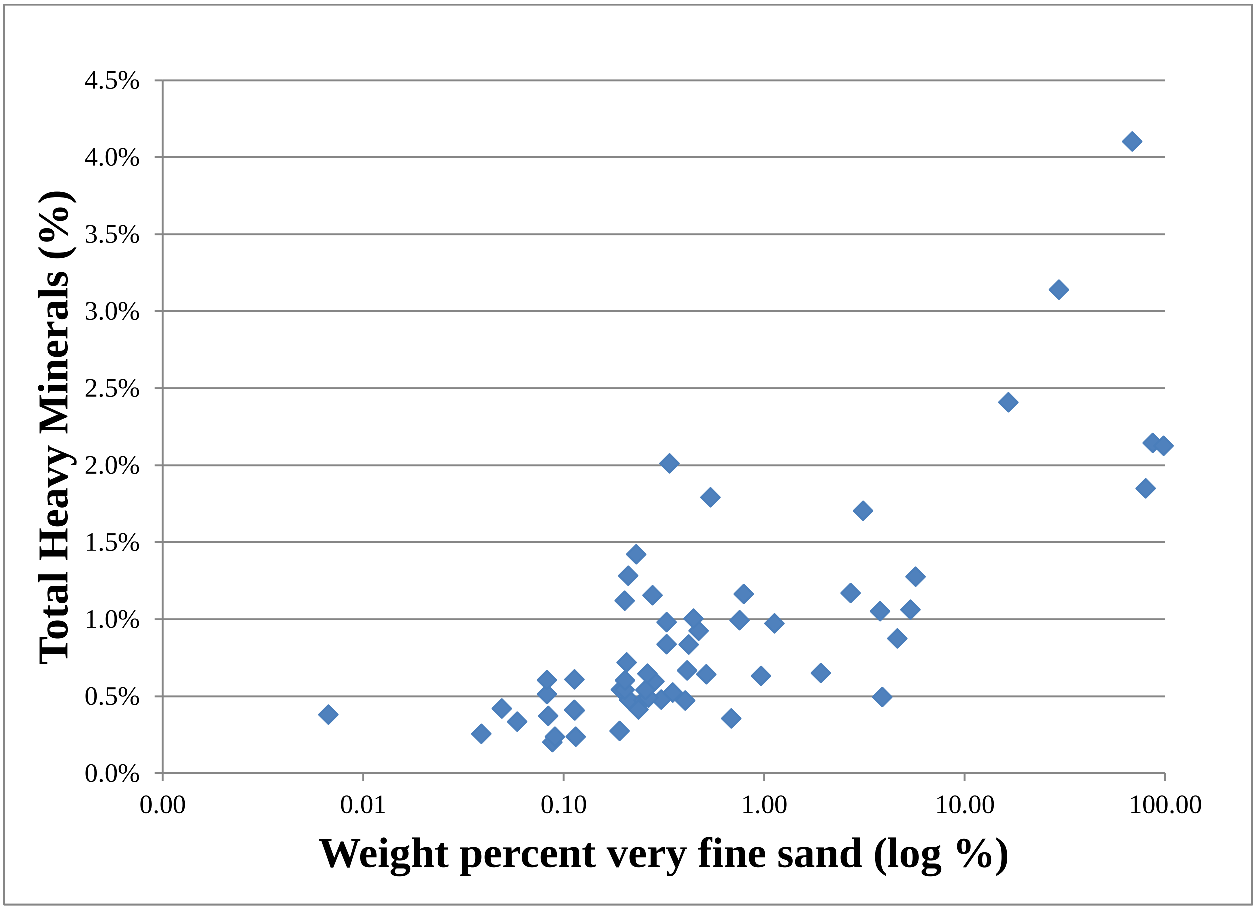

Figure 6. Total heavy mineral content versus the weight percent (log scale) of the very fine sand fraction (ϕ >3) for all samples (n=60).

Heavy mineral composition

The complete laboratory results from Activation Laboratories for the Mineral Liberation Analyzer (MLA) scans performed on 60 heavy mineral concentrates are included in Appendix B. The report provides details concerning modal mineralogy, size distribution and mineral mapping of representative particles. Table 3 presents a summary of the main heavy minerals considered of economic importance and weight percent statistics for each sample. In general, the most abundant components of the THM concentrates are garnet, titanium-bearing ilmenite, and amphibole minerals. On a mass percent basis, ilmenite and rutile averaged 18.21% and 1.49%, respectively in the concentrates. Minerals containing rare earth elements (REE), such as monazite and apatite were generally low in abundance, although REE-bearing zircon ranged as high as 5.73% and averaged 2.21% for all samples.

Table 3. Summary of the modal mineralogy of economic heavy minerals reported in weight percent of the total heavy mineral concentrate (wt % THM). THM is reported as weight percent of total sample.

Sample ID	THM Wt %	Ilmenite Wt % THM	Rutile Wt % THM	Leucoxene Wt % THM	Magnetite Wt % THM	Zircon Wt % THM	Monazite Wt % THM	Amphibole Wt % THM	Staurolite Wt % THM	Garnet Wt % THM
GS-101-01	1.17	12.78	1.01	1.24	0.17	1.78	0.00	21.90	4.13	27.79
GS-106-01	0.37	18.70	2.57	1.15	1.93	1.75	0.00	10.63	6.93	24.39
GS-106-02	0.34	18.85	1.57	1.33	1.13	2.44	0.00	8.75	7.93	20.73
GS-107-01	2.01	23.04	1.15	1.11	3.35	2.28	0.07	12.15	3.89	21.88
GS-109-03	0.99	17.82	1.37	1.47	3.09	2.11	0.13	15.46	3.98	21.29
GS-110-02	0.27	32.92	3.18	2.33	1.07	3.01	0.01	6.50	4.57	22.36
GS-114-01	0.60	21.35	1.17	1.44	1.05	2.28	0.00	13.62	3.61	26.65
GS-115-01	0.48	11.90	1.35	0.94	0.91	1.11	0.01	19.10	3.33	17.54
GS-116-01	0.51	24.20	2.33	1.25	1.63	3.77	0.07	13.76	2.99	24.32
GS-201-01	0.47	16.33	1.41	1.15	1.25	1.42	0.03	18.88	4.55	25.57
GS-201-04	0.25	19.22	1.18	1.73	1.29	2.21	0.06	10.70	4.84	21.39
GS-201-05	0.20	24.13	1.96	1.09	1.23	2.39	0.07	12.30	3.15	25.93
GS-201-06	0.54	20.90	1.45	1.61	1.84	2.25	0.00	11.81	4.21	22.05
GS-201-07	0.41	11.51	0.95	1.16	0.77	1.72	0.00	19.91	1.98	14.72
GS-201-08	0.41	14.83	1.30	0.71	0.55	2.72	0.00	14.28	7.48	21.85
GS-201-09	0.38	23.34	1.52	1.48	1.22	2.87	0.04	11.47	4.57	24.96
GS-202-01	2.14	14.61	1.88	1.43	1.13	3.49	0.25	30.12	0.41	21.09
GS-202-02	0.24	12.37	1.87	1.36	0.03	1.22	0.00	8.50	11.13	22.22
GS-202-03	0.41	16.78	1.35	0.86	1.69	1.51	0.00	16.12	4.97	25.98
GS-202-04	0.61	21.76	2.12	1.18	2.67	1.91	0.05	12.95	4.17	21.75
GS-202-05	0.49	19.56	1.25	1.02	0.16	1.65	0.02	9.91	7.43	20.22
GS-202-06	0.54	27.98	1.84	0.86	0.68	4.47	0.37	12.80	2.20	18.80
GS-202-07	0.42	21.29	2.38	1.07	0.53	1.50	0.00	10.42	9.02	24.14
GS-203-01	0.47	12.10	0.93	0.55	0.14	1.31	0.00	20.51	3.59	24.05
GS-203-02	0.65	15.64	1.30	0.93	1.36	1.12	0.04	19.92	3.25	20.75
GS-203-03	0.48	21.37	1.91	0.88	2.35	2.70	0.08	13.18	4.96	21.69

Sample ID	**THM** Wt %	**Ilmenite** Wt % THM	**Rutile** Wt % THM	**Leucoxene** Wt % THM	**Magnetite** Wt % THM	**Zircon** Wt % THM	**Monazite** Wt % THM	**Amphibole** Wt % THM	**Staurolite** Wt % THM	**Garnet** Wt % THM
GS-203-04	0.67	31.22	2.02	0.84	0.67	5.73	0.06	3.44	8.70	23.20
GS-203-05	0.49	17.19	1.55	1.02	1.25	1.62	0.00	12.02	4.79	18.25
GS-203-06	0.84	11.47	1.41	0.94	0.81	0.94	0.00	19.38	3.22	19.51
GS-204-01	0.93	10.77	0.78	0.76	0.10	1.53	0.04	19.46	7.59	33.21
GS-204-05	0.97	23.32	1.39	1.02	3.16	2.53	0.10	14.88	2.93	20.37
GS-204-06	1.05	10.89	1.22	1.13	1.22	0.98	0.07	26.41	1.54	19.07
GS-204-07	1.28	20.87	1.02	0.85	3.79	2.60	0.03	12.29	3.51	22.02
GS-204-08	1.42	20.26	1.02	0.98	2.79	1.21	0.04	12.94	2.81	20.37
GS-204-09	0.54	24.60	1.62	1.12	1.58	2.06	0.01	12.56	3.70	21.52
GS-204-10	0.98	21.06	1.78	1.02	2.72	2.19	0.05	13.59	4.29	24.14
GS-204-11	0.60	19.28	1.33	0.83	1.75	1.60	0.00	14.70	5.28	19.79
GS-204-12	0.60	21.93	1.55	1.07	2.15	2.24	0.10	10.60	5.28	24.96
GS-204-13	0.64	23.02	1.12	0.93	2.14	2.15	0.08	12.97	3.93	23.41
GS-204-14	0.72	18.90	1.53	1.08	1.39	2.22	0.07	13.25	5.29	23.25
GS-204-15	0.24	15.21	1.35	0.93	0.57	1.94	0.00	11.05	3.91	19.01
GS-205-01	0.65	16.59	0.92	1.11	0.18	1.88	0.05	24.45	4.10	25.40
GS-205-03	0.63	15.24	0.99	0.77	2.02	1.46	0.02	20.51	3.69	20.55
GS-205-04	0.36	14.83	1.23	1.02	2.24	0.86	0.03	20.83	2.60	22.63
GS-205-05	0.52	19.11	1.57	1.27	1.63	3.78	0.06	10.28	5.99	20.14
GS-206-02	1.16	17.99	1.39	1.01	2.17	1.03	0.13	18.59	4.45	21.48
GS-206-03	1.12	19.55	1.43	0.77	1.52	2.32	0.08	19.09	2.90	23.18
GS-206-04	1.15	22.80	1.41	0.80	2.27	3.15	0.06	13.38	5.42	23.57
GS-206-05	1.28	13.77	1.54	1.20	1.11	1.33	0.02	27.81	1.58	18.80
GS-207-01	0.87	17.55	1.51	0.98	0.83	1.85	0.04	24.56	2.06	22.58
GS-500-01	1.85	14.72	1.59	1.14	2.49	2.78	0.12	30.72	0.58	20.67
GS-500-02	4.10	17.38	1.55	0.91	1.76	3.71	0.10	26.80	1.35	20.91
GS-500-03	3.14	16.53	1.49	1.14	0.61	3.37	0.21	26.96	1.45	22.51
GS-500-04	1.70	11.35	1.10	0.75	0.08	1.62	0.03	20.17	4.74	26.06

Sample ID	**THM** Wt %	**Ilmenite** Wt % THM	**Rutile** Wt % THM	**Leucoxene** Wt % THM	**Magnetite** Wt % THM	**Zircon** Wt % THM	**Monazite** Wt % THM	**Amphibole** Wt % THM	**Staurolite** Wt % THM	**Garnet** Wt % THM
GS-500-05	1.00	11.20	1.33	0.69	0.02	2.16	0.04	16.89	6.72	29.28
GS-500-06	1.79	25.27	1.70	1.02	1.09	2.62	0.03	11.39	3.77	23.89
GS-501-01	2.41	12.05	1.56	1.11	0.17	2.57	0.10	33.89	1.18	18.76
GS-502-03	2.12	11.85	1.68	1.38	1.96	2.88	0.15	31.20	0.41	20.04
GS-502-04	1.06	14.61	1.42	1.65	0.25	2.17	0.16	32.39	1.60	21.69
GS-502-05	0.83	15.11	1.25	0.72	0.03	2.24	0.05	16.04	6.54	30.05
MAX	4.10	32.92	3.18	2.33	3.79	5.73	0.37	33.89	11.13	33.21
MIN	0.20	10.77	0.78	0.55	0.02	0.86	0.00	3.44	0.41	14.72
AVG	0.93	18.21	1.49	1.09	1.36	2.21	0.06	16.85	4.19	22.47
SD	0.70	5.03	0.43	0.30	0.93	0.91	0.07	6.90	2.20	3.15

DISCUSSION

The apparent positive correlation between higher THM content greater than 1.85% and higher percentages of very fine sand noted earlier may indicate a depositional setting that is favorable for concentrating heavy minerals. It is noteworthy that during the heavy mineral separation procedure, soft-sediment worm tubes were observed in many samples while wet sieving and spiraling. These tubes are likely attributed to *Spiochaetopterus costarum* (Jennifer Dreyer, Virginia Institute of Marine Science, personal communication) (Figure 7).

Figure 7. Worm tubes attributed to Spiochaetopterus costarum found in very-fine sandy sediments containing higher THM values.

Although speculative at this stage in the investigation, it is possible that the presence of worms and their tubes increases the roughness of the seafloor causing a similar effect on sediment transport along the seafloor as a carpet or “miner’s moss” would have in a gold sluice (Figure 8). Additional work and sampling to study this phenomenon may include examinations of archived sediment core and grab samples stored in the DGMR repository for the co-presence of worm tubes and heavy minerals. The review of existing side-scan sonar images in areas with samples containing heavy minerals may also help identify seafloor roughness patterns that could be helpful in the interpretation of the depositional setting.

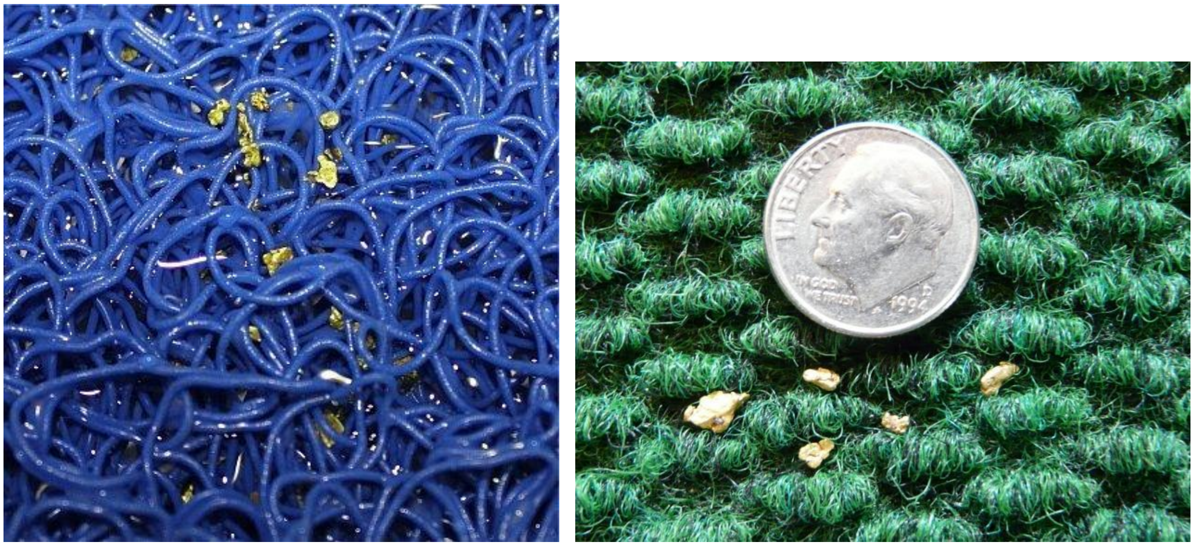

Figure 8. Photographs of “miner’s moss” and ribbed carpet with trapped gold.

CONCLUSIONS

The results of this study provide valuable new information concerning grain size characteristics and heavy mineral concentrations in sand deposits on Virginia’s outer continental shelf. Regarding the heavy mineral content in OCS sands, the present results together with those published earlier by Berquist et al., (1990) and Luepke (1990) indicate concentrations of one or more economic minerals that are well above the provisional 2% THM cut-off grade (Van Gosen et al., 2014) of onshore deposits currently being mined from Pliocene-age beach sands in Dinwiddie and Greenville Counties, Virginia (DMME, 2015). The distribution of these existing samples shows that heavy minerals are relatively common offshore of central Virginia Beach, Chincoteague and the southern half of the Eastern Shore (Figure 9).

Future studies will include mapping the abundance of both THM and individual minerals of economic interest such as ilmenite, altered hi-titanium enriched ilmenite, zircon, and monazite. Although relatively untested to date, Virginia’s OCS region likely contains valuable deposits of industrial minerals including high-purity silica sand, phosphate, aluminum-rich sillimanite minerals, and rare earth elements. Continued activities focused on gathering geologic and geophysical data in key target areas using vibracore logs and grab sample descriptions and analyses will provide the means to estimate the lateral and thickness extents of potential sand and co-existing economic mineral resources. Equally important, this data is expected to identify favorable depositional environments, sediment transport processes, and mineral concentrating processes on the seafloor that can serve as exploration guides.

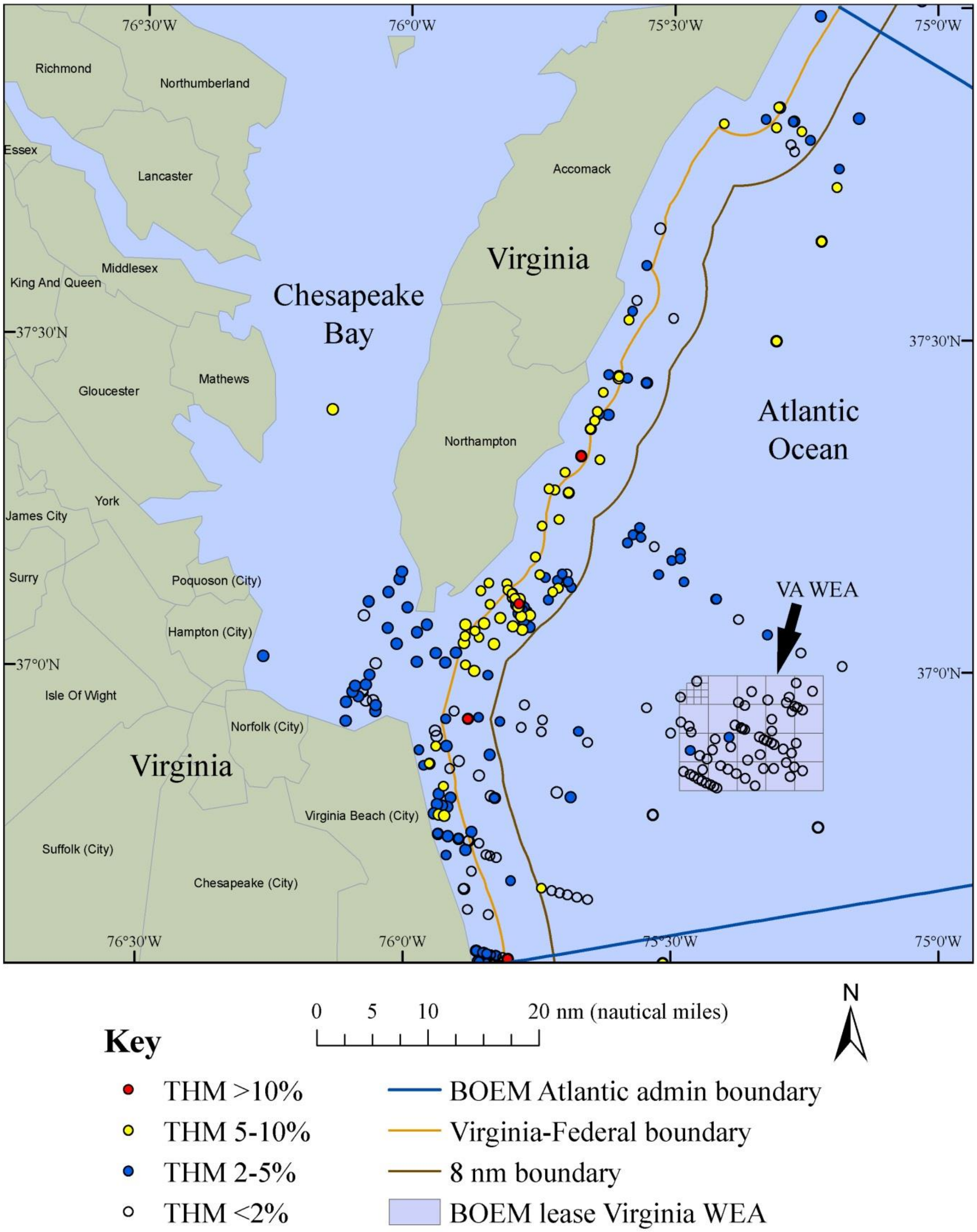

Figure 9. Map showing sample locations from Berquist et al., (1990), Luepke (1990), and the present study analyzed for total heavy minerals (THM) offshore of Virginia.

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CITED AND RELEVANT REFERENCES

Berquist, C.R., Jr., and C.H. Hobbs, III, 1986, Assessment of economic heavy minerals of the Virginia inner shelf: Virginia Division of Mineral Resources Open-File Report 86-1.

Berquist, C.R., Jr. and C.H. Hobbs, III, 1988, Study of economic heavy minerals of the Virginia Inner Continental Shelf: Virginia Division of Mineral Resources Open-File Report 88-4, 149 pp.

Berquist, C.R., Jr., C.T Fischler, L.J. Calliari, S.M. Dydak, H. Ozalpasan, and S.A. Skrabal, 1990, Heavy-mineral concentrations in sediments of the Virginia Inner Continental Shelf: *in* Berquist, C.R., Jr. [ed.], 1990, Heavy-mineral studies – Virginia inner continental shelf, Virginia Division of Mineral Resources Publication 103, 124 pp.

Diaz, R.J., G.L. Wikel, A.G. Browder, J.P. Y-Maa, D.A. Milligan, C.S. Hardaway, C.O. Tallent, J.E. McNinch, H.K. Ha, J.A. Nestlerode, and C.H. Hobbs, III, 2006, Field testing of a physical/biological monitoring methodology for offshore dredging and mining operations: Prepared for U.S. Department of the Interior, Minerals Management Service, Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, Virginia.

DMME (Department of Mines, Minerals and Energy), 2012, Sand resource evaluation on Virginia’s outer continental shelf – Final Technical Report: Prepared for U.S. Bureau of Ocean Energy Management, Cooperative Agreement M10AC20021 for the performance period Sept 14, 2010 to Oct 31, 2011: 19p.

DMME, 2015, Annual production data reported to DMME: Division of Mineral Mining databases.

Kimball, S.M. and J.K. Dame, 1989, Geotechnical evaluation of sand resources of the inner shelf of southern Virginia: Virginia Institute of Marine Science Final Report to the City of Virginia Beach, VA.

Kimball, S.M., J.K. Dame, C.H. and Hobbs, III, 1991, Investigation of isolated sand shoals on the inner shelf of southern Virginia: Virginia Institute of Marine Science Final Report.

Luepke, G., 1990, Economic heavy minerals in sediments from an offshore area east of Cape Charles, Virginia: U.S. Geological Survey Open File Report 90-451, 10 pp.

McNeilan, T.W., K.R. Smith, and J.E. Fisher, 2013, Regional geophysical survey and interpretive report: Virginia Wind Energy Area offshore southeastern Virginia: Prepared by Fugro Consultants, Inc., for U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Herndon. OCS Study BOEM 2013-220, 240 pp.

Tetra Tech, Inc., 2014, Marine site characterization survey report, Virginia Offshore Wind Technology Advancement Project (VOWTAP): Prepared for Dominion Resources, Glen Allen, VA, submitted December 2013, revised February 2014 and June 2014, 758 pp.

Van Gosen, B.S., D.L. Fey, A.K. Shah, P.L. Verplanck, and T.M. Hoefen, 2014, Deposit model for heavy-mineral sands in coastal environments: U.S. Geological Survey Scientific Investigations Report 2010-5070-L, 51 p., *http://dx.doi.org/10.3133/sir20105070L*.

APPENDIX A. Grain size scales and sieve sizes for sediment classification.

Phi (ϕ)	millimeters (mm)	inches (in)	ASTM No. (U.S. Standard)	Size Class (Wentworth, 1922)
≥ -8	>256	> 10.1		boulders
-6 to -8	64-256	2.5 – 10.1		cobbles
-5 to -6	32 – 64	1.26 – 2.5		very coarse pebbles
-4 to -5	16 - 32	0.63 – 1.26		coarse pebbles
-3 to -4	8 – 16	0.31 – 0.63		medium pebbles
-2 to -3	4 – 8	0.157 – 0.31 5		fine pebbles
-1 to -2	2 – 4	0.079 – 0.157	10	granules (gravel) very fine pebbles
0 to -1	1 – 2	0.039 – 0.079	18	very coarse sand
0.25	0.84	0.033	20	
1 to 0	0.5 – 1	0.020 – 0.039	35	coarse sand
1.25	0.42	0.017	40	
2 to 1	0.25 – 0.5	0.010 – 0.020	60	medium sand
2.75	0.149	0.0059	100	
3 to 2	0.125 – 0.25	0.0049 – 0.010	120	fine sand
4 to 3	0.0625 – 0.125	0.0025 – 0.0049	230	very fine sand
5 to 4	0.031 – 0.0625	0.0012 – 0.0025		coarse silt (mud)
6 to 5	0.0156 – 0.031	0.0006 – 0.0012		medium silt
7 to 6	0.0078 – 0.0156	0.0003 – 0.0006		fine silt
8 to 7	0.0039 – 0.0078	0.00015 – 0.0003		very fine silt
>8	<0.0039	<0.00015		clay

APPENDIX B. Results of sieve analysis of sand fractions in Fugro samples; cumulative weight percent distribution by ϕ size.

Sample ID	ϕ size - cumulative weight percent retained						interpreted from curve			calculated
	-1	0.25	1.25	2	2.75	4	ϕ_{16}	ϕ_{50}	ϕ_{84}	ϕ_M
GS-101-01	0.21	9.18	53.36	72.63	97.30	100.00	0.2	0.9	2.45	1.2
GS-103-01	4.27	35.88	78.42	97.66	99.89	100.00	-0.6	0.3	1.2	0.3
GS-106-01	4.19	37.04	68.03	97.22	99.92	100.00	-0.6	0.4	1.5	0.4
GS-106-02	8.57	33.09	75.64	97.64	99.94	100.00	-0.65	0.4	1.25	0.3
GS-107-01	2.60	18.90	54.24	94.84	99.66	100.00	-0.15	0.85	1.65	0.8
GS-107-02	0.73	4.85	40.07	86.93	99.20	100.00	0.4	1.2	1.9	1.2
GS-109-03	0.82	8.10	40.31	93.08	99.24	100.00	0.3	1.2	1.75	1.1
GS-110-02	8.79	29.16	75.59	97.37	99.81	100.00	-0.6	0.45	1.125	0.3
GS-111-01	6.58	46.04	81.18	97.99	99.90	100.00	-0.75	0.1	1.1	0.2
GS-111-02	6.88	32.28	71.45	96.02	99.77	100.00	-0.6	0.45	1.4	0.4
GS-111-03	9.17	25.41	68.20	96.57	99.79	100.00	-0.5	0.6	1.45	0.5
GS-112-01	3.82	27.20	72.04	97.27	99.88	100.00	-0.4	0.5	1.4	0.5
GS-112-03	2.49	22.39	73.37	97.11	99.84	100.00	-0.125	0.55	1.3	0.6
GS-112-04	0.39	4.54	53.12	95.36	99.82	100.00	0.3	0.9	1.65	1.0
GS-114-01	0.84	16.83	70.66	95.46	99.72	100.00	0	0.6	1.4	0.7
GS-114-02	4.91	27.36	74.96	97.16	99.83	100.00	-0.4	0.5	1.3	0.5
GS-115-01	0.79	16.43	60.84	93.27	99.79	100.00	0	0.75	1.65	0.8
GS-116-01	1.30	15.76	64.47	96.70	99.92	100.00	0	0.7	1.55	0.8
GS-201-01	3.77	26.07	74.64	98.23	99.75	100.00	-0.	0.5	1.25	0.5
GS-201-02	1.95	19.82	67.51	96.56	99.99	100.00	-0.15	0.6	1.5	0.7
GS-201-04	8.33	40.66	80.83	98.25	99.96	100.00	-0.75	0.2	1.1	0.2
GS-201-05	3.05	25.46	70.39	97.09	99.91	100.00	-0.35	0.55	1.4	0.5
GS-201-06	2.09	22.21	69.05	97.06	99.81	100.00	-0.25	0.6	1.4	0.6
GS-201-07	1.20	10.26	42.58	89.88	99.76	100.00	0.25	1.2	1.8	1.1
GS-201-08	4.19	27.97	71.63	96.35	99.89	100.00	-0.45	0.5	1.4	0.5
GS-201-09	5.00	31.24	74.23	97.18	99.99	100.00	-0.55	0.45	1.3	0.4
GS-201-10	3.21	26.39	68.51	96.05	99.87	100.00	-0.4	0.6	1.5	0.6

Sample ID	**ϕ size - cumulative weight percent retained**						**interpreted from curve**			**calculated**
	-1	**0.25**	**1.25**	**2**	**2.75**	**4**	**ϕ_{16}**	**ϕ_{50}**	**ϕ_{84}**	**ϕ_{M}**
GS-202-01	0.19	0.34	0.63	2.49	13.01	100.00	3.1	3.5	3.8	3.5
GS-202-02	3.91	28.90	80.02	98.98	99.89	100.00	-0.4	0.4	1.15	0.4
GS-202-03	2.12	20.63	64.87	95.38	99.89	100.00	-0.2	0.65	1.55	0.7
GS-202-04	3.25	21.19	60.03	95.93	99.89	100.00	-0.25	0.75	1.6	0.7
GS-202-05	4.10	20.20	45.40	84.02	96.11	100.00	-0.25	1.15	2.0	1.0
GS-202-06	2.83	17.82	63.31	95.95	99.80	100.00	-0.1	0.7	1.55	0.7
GS-202-07	5.72	27.16	78.89	98.78	99.95	100.00	-0.4	0.45	1.15	0.4
GS-203-01	12.30	40.32	71.99	96.03	99.60	100.00	-0.8	0.3	1.4	0.3
GS-203-02	2.74	17.80	49.71	89.77	98.08	100.00	-0.1	1.0	1.75	0.9
GS-203-03	2.08	16.52	57.57	94.38	99.69	100.00	0	0.8	1.6	0.8
GS-203-04	11.01	38.45	83.64	98.38	99.59	100.00	-0.8	0.25	1.0	0.2
GS-203-05	2.03	27.74	75.25	96.73	99.74	100.00	-0.4	0.5	1.25	0.5
GS-203-06	0.42	4.41	40.73	89.18	99.67	100.00	0.4	1.2	1.8	1.1
GS-204-01	6.75	25.34	68.39	95.73	99.53	100.00	-0.4	0.55	1.5	0.6
GS-204-05	0.46	9.01	33.94	84.22	98.87	100.00	0.4	1.3	2.0	1.2
GS-204-06	0.12	0.78	8.24	63.86	96.20	100.00	1.2	1.75	2.55	1.8
GS-204-07	3.94	21.97	59.25	94.93	99.79	100.00	-0.25	0.75	1.6	0.7
GS-204-08	4.79	17.82	54.39	94.71	99.77	100.00	-0.1	0.9	1.65	0.8
GS-204-09	0.46	14.27	53.52	91.62	99.74	100.00	0.1	0.9	1.75	0.9
GS-204-10	1.60	13.66	54.23	93.11	99.67	100.00	0.1	0.9	1.7	0.9
GS-204-11	4.17	18.46	60.06	94.03	99.80	100.00	-0.1	0.75	1.6	0.8
GS-204-12	3.67	31.20	75.91	97.46	99.92	100.00	-0.5	0.4	1.25	0.4
GS-204-13	0.17	8.25	52.06	92.66	99.49	100.00	0.25	0.95	1.7	1.0
GS-204-14	4.12	28.42	68.28	95.90	99.79	100.00	-0.45	0.55	1.5	0.5
GS-204-15	6.40	43.21	81.46	97.56	99.91	100.00	-0.75	0.2	1.15	0.2
GS-205-01	2.19	22.53	63.57	91.29	99.74	100.00	-0.25	0.65	1.65	0.7
GS-205-03	1.09	17.59	60.61	93.93	99.03	100.00	-0.1	0.75	1.6	0.8
GS-205-04	0.62	10.30	50.44	92.06	99.31	100.00	0.2	1.0	1.75	1.0
GS-205-05	10.67	35.84	75.15	96.03	99.65	100.00	-0.75	0.4	1.25	0.3

Sample ID	**ϕ size - cumulative weight percent retained**						**interpreted from curve**			**calculated**
	-1	**0.25**	**1.25**	**2**	**2.75**	**4**	**ϕ_{16}**	**ϕ_{50}**	**ϕ_{84}**	**ϕ_{M}**
GS-206-02	3.30	11.64	34.29	84.86	99.21	100.00	0.25	1.3	1.95	1.2
GS-206-03	1.33	10.29	37.28	91.05	99.80	100.00	0.25	1.25	1.8	1.1
GS-206-04	2.08	14.85	49.01	93.15	99.72	100.00	0.1	1.1	1.75	1.0
GS-206-05	0.04	0.42	4.44	53.07	94.30	100.00	1.25	1.9	2.65	1.9
GS-207-01	1.10	2.51	20.12	56.09	95.37	100.00	0.8	1.8	2.6	1.7
GS-207-02	0.24	1.00	15.97	73.66	98.29	100.00	1	1.6	2.25	1.6
GS-500-01	0.04	0.14	0.30	1.26	19.93	100.00	2.9	3.4	3.8	3.4
GS-500-02	0.04	0.12	0.48	14.09	31.36	100.00	2.15	3.3	3.75	3.1
GS-500-03	0.10	0.23	1.48	31.67	70.42	100.00	1.55	2.5	3.4	2.5
GS-500-04	1.10	4.14	31.18	83.08	96.88	100.00	0.6	1.4	2	1.3
GS-500-05	2.58	10.18	43.48	89.33	99.55	100.00	0.25	1.15	1.8	1.1
GS-500-06	1.29	10.20	43.16	90.50	99.46	100.00	0.25	1.15	1.8	1.1
GS-501-01	0.57	2.15	10.70	39.22	83.43	100.00	1.25	2.25	3	2.2
GS-501-02	0.11	0.51	7.88	73.06	97.81	100.00	1.2	1.6	2.25	1.7
GS-502-03	0.13	0.21	0.41	0.64	1.67	100.00	3.2	3.55	3.8	3.5
GS-502-04	0.15	4.10	39.62	72.59	94.63	100.00	0.4	1.25	2.4	1.4
GS-502-05	2.23	10.84	51.27	94.16	99.58	100.00	0.2	0.95	1.7	1.0
MAX	12.30	46.04	83.64	98.98	99.99	100.00	3.2	3.6	3.8	3.5
MIN	0.04	0.12	0.30	0.64	1.67	100.00	-0.8	0.1	1.0	0.2
AVG	3.02	18.14	53.12	85.12	94.09	100.00	0.1	1.0	1.8	1.0
SD	2.92	12.27	23.85	23.54	19.40	0.00	0.9	0.8	0.7	0.7

APPENDIX C. ActLabs Report A1504158, July 2015

Provided as MS Excel data file to accompany this report