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Locating alternative sand sources for Michigan's foundry industry: A geographical approach

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A B S T R A C T

Numerous large coastal dune fields occur on the western coast of Lower Michigan. These dunes are an important ecological, geological, and recreational resource in the state. They also serve as a significant source of foundry sand for Michigan's automotive industry and thus have been mined intensively. Although Michigan contains extensive sand deposits besides those in coastal dunes, no studies have yet investigated alternative foundry sources from a distinct geographical perspective.

Acceptable alternative sand deposits must be sufficiently large and close to transportation networks to be economically viable. Using a GIS, water-well log stratigraphic data were employed to estimate sand thickness and rail line data were used to determine accessibility of deposits. Based on this information, 53 sites in 16 counties were selected, sampled, and tested for appropriate physical and chemical characteristics to determine their viability as inland sources of foundry sand. Results indicate that many cubic kilometers of inland sand suitable for foundry use are in close proximity to existing transportation networks. Three regions that show the most potential to be inland sand sources for the foundry industry are: 1) Wexford and southeastern Grand Traverse Counties, 2) northern Newaygo and southern Lake Counties, and 3) central Alger County. Sand in these areas will likely require preprocessing but should nonetheless be considered as a feasible and more ethically responsible alternative to mining coastal dunes.

Introduction

Extensive coastal sand dunes line much of the eastern shore of Lake Michigan and may represent the largest body of freshwater coastal dunes in the world (Peterson & Dersch, 1981; Fig. 1). Although these dunes are an important ecological and recreational landscape in the state (Michigan Legislature, 2001), they are mined heavily for foundry purposes in the region (Fig. 1). Coastal dune deposits are particularly well suited for industrial molds and cores, primarily for automobile manufacturing, because they have a small range of grain sizes, are particularly well-sorted, and contain very few chemical and physical impurities (Lewis, 1975; Michigan Legislature, 2001). The dunes' large size and proximity to both rail and barge transportation also make them ideal sources of foundry sand (Ayres, Lewis, Norris, and May, Inc. & Chapman, 1978; Kelly, 1971; Robert Marrone, 2005, pers. comm.).

Because of their broad appeal, Michigan's coastal dunes foster a collision of competing values. Their industrial value to sand mining companies is in direct conflict with the environmental and recreational value they provide to citizens. From an

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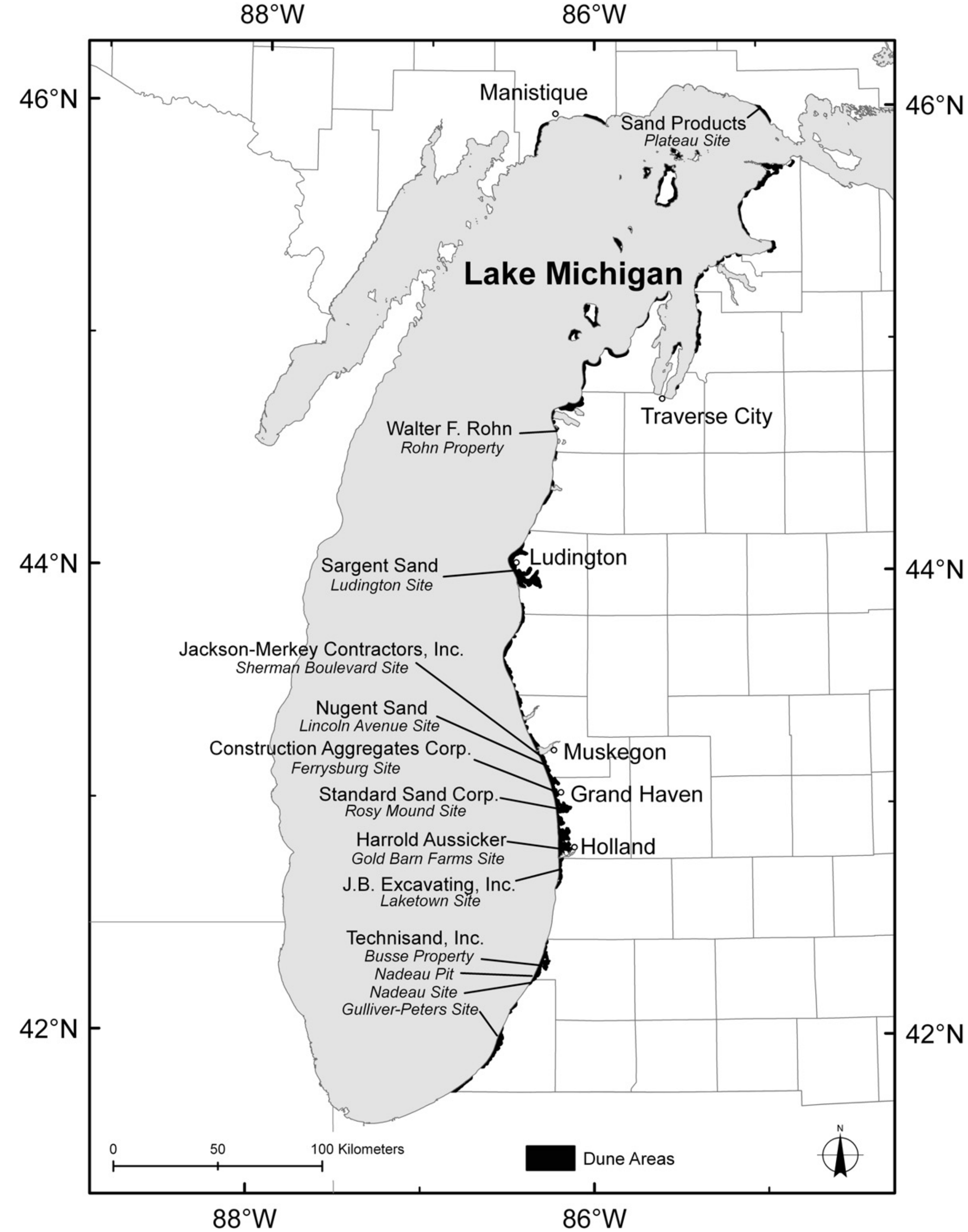

Fig. 1. Lake Michigan coastal dune areas in Michigan. The locations of active or potentially active coastal dune sand mining sites have been labeled.

ethical standpoint, Harman and Arbogast (2004) argued that dune preservation should supersede all other potential uses. In this context, environmental groups, representatives from industry, and Michigan's state government have all expressed a need to locate alternative sources for foundry sand in the state (Duane Johnson, 2005, pers. comm.; Lake Michigan Federation, 1999; Michigan Department of Natural Resources, 1984).

Previous studies suggest that Michigan's inland sand resources have the potential to be used in the foundry process (Brown, 1936; Ries & Rosen, 1908; Sundeen, 1978a, 1978b). Although these studies were informative, they were not explicit in approaching the issue from a geographical standpoint, by spatially interacting physical, chemical, and economic variables that are key factors in locating viable inland sand. This paper places the issue of alternative sand sources within its appropriate geographic context through a classic interdisciplinary study that integrates traditional field work, standard laboratory techniques, and digital technology (GIS) to assess the character *and* geography of inland sand sources.

This study is also significant because it is the first to bring representatives of industry (*Ford Motor Company*), environmental conservation (*The Alliance for the Great Lakes*) and academia (*Geography at Michigan State University*) together in a collaborative way to assess this issue. As a result, this paper is an excellent example of applied physical geography that will positively contribute to an important environmental issue in Michigan.

Foundry sand

Foundry sand is a subset of industrial sand that is used to create molds and cores from which metal can be cast (Fig. 2). This is the ultimate use of approximately 95% of the sand mined from Lake Michigan dunes (Lake Michigan Federation, 1999). Foundry sand has been mined and used in Michigan for over 100 years (Michigan Department of Environmental Quality, 2000), particularly to cast iron into engine blocks and other parts that are critical to Michigan's automobile industry. The criteria for foundry sand can vary considerably based on the type of casting performed, as well as the particular casting process employed by a given foundry (Brown, 1936). Because iron casting is a very important component of Michigan's automobile industry, sand used in that process is considered here.

Over the past century, a large body of literature has been published on important characteristics of foundry sand (American Foundry Society, 2004; American Foundrymen's Association, 1924; Ayres, Lewis, Norris, and May, Inc. & Chapman, 1978; Hofstetter, 1948; McLaws, 1971; Moldenke, 1930; Ries & Rosen, 1908). These characteristics include refractoriness, permeability, bond strength, grain fineness, and chemical reactivity. They are determined by important variables, including grain shape, grain size, clay content, pH, acid demand, chemical composition, and moisture content.

Grain shape

For foundry casting, the ideal grain shape represents a compromise between permeability, bonding ability, and smoothness of the finished surface of the casted part. Ideal foundry sand is generally subangular in shape although grain shape requirements can vary slightly depending on the user. A subangular shape allows individual grains to interlock sufficiently well to form a good mold or core while still providing necessary pore spaces for superheated gases to escape without breaking the mold during the casting process. A subangular shape also allows for a relatively smooth finished surface to the casted part.

Grain size

Grain size can affect the permeability of a mold or core and the finish of a casted part. A typical grain size distribution of foundry sand is centered on U.S. Standard Sieve 70 (212 microns), with very little sand being retained on sieve sizes lower than 30 (590 microns) or greater than 140 (105 microns). There is often a range of acceptable values for the percentage of sand retained on each sieve size (Table 1).

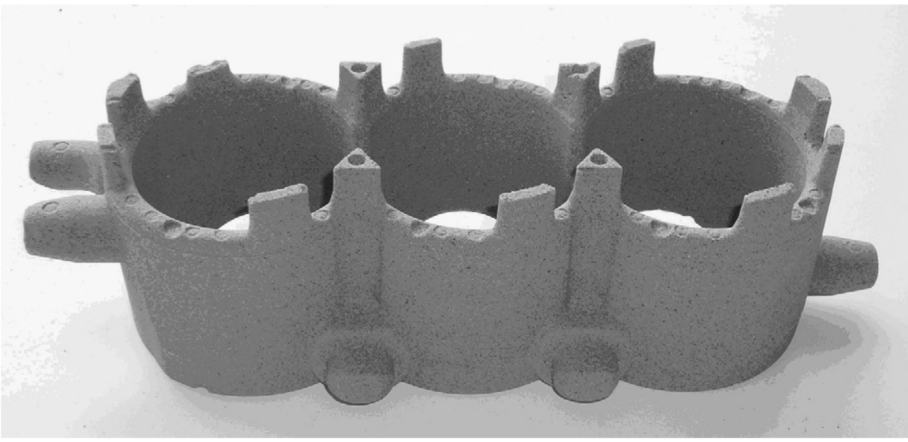

Fig. 2. Foundry sand core used for casting engine block components.

Table 1
General sieve ranges for foundry sand.[a]

Sieve #	Microns	Min %	Max %	Target %
20	840	0	0	0
30	590	0	2	1
40	420	4.5	13	10
50	300	25	35	32
70	212	30	40	36
100	149	10	20	16
140	105	2	6	4.5
200	74	–	–	0.4
270	53	–	–	0.1
Pan	<53	–	–	0
Through 70	<212	15	–	–
Through 200	<74	0	1	0.1

[a] Data from Ford Motor Co. (unpublished). Specific users' requirements can vary based on the casting technique used and the specifications of the finished product.

pH

The pH of a sample gives the water-soluble level of alkalinity or acidity of the sand. This determines its reactivity with resins used in the casting process. Sand with a pH that is close to neutral (7.0) is the least reactive and therefore best for casting.

Acid demand

An acid demand value measures the chemical reactivity of the sand with an acid. Low acid demand values indicate minimal reactivity when mixed with an acid, and are desired for foundry sand. In contrast, high values can alter reaction speeds and affect the function of chemical binders, and can lead to pinhole casting defects from the production of CO_2 gas. The acid demand test can detect carbonates and salts that can be deleterious in the casting process but may not be detected by pH testing alone.

25-Micron clay

Most foundry processes no longer use naturally occurring clay as a binder for molds and cores. For this reason, modern foundry sands ideally contain as little clay as possible. The foundry industry groups all particles smaller than 25 microns in diameter as '25-micron clay' (American Foundry Society, 2004).

Chemical composition

The chemical composition of sand affects its refractoriness and reactivity. Sands are identified by their primary mineral component (silica, zircon, olivine, etc.) but can contain other minerals as well (oxides of aluminum, titanium, etc.), which are usually considered undesirable impurities. Silica is the primary mineral of Michigan dune sand and inland sand.

Moisture

Moisture can affect bonding and reactivity of the mold or core. Since moisture can be adjusted after excavation, field moisture content can vary.

In addition to the physical and chemical variables described above, economic variables such as deposit volume and proximity to markets and transportation networks play an important role in determining the viability of sand for foundry use. Michigan's coastal sand dunes are excellent sources for foundry sand because, in addition to having most of the proper physical and chemical characteristics, they contain large quantities of sand and are easily accessible by barge and rail.

Sand mining in Michigan

Although Michigan has long been known for its copper and iron deposits, the state has also become a leader in the mining of sand and sandstone resources in the past century (Heinrich, 1979). In the early part of Michigan's industrial history, the preferred sources of foundry sand were 1) pockets in morainal drift, 2) glacial outwash deposits, 3) lake deposits, or 4) deposits bordering rivers that are either present-day flood deposits or reworked glacial material (Ries & Rosen, 1908). At this time foundry sand was bonded using the naturally occurring clay binders within these sediments, rather than synthetic substances. As a result, the physical and chemical purity of the host deposits was of less concern.

As industrial activity in the region expanded in the early 20th century, Brown (1936) recognized that naturally bonded molding sands were insufficiently abundant in Michigan to supply the needs of local foundries. He noted that coastal sand dunes were a potential source that were easily accessible, but they were an uncertain foundry supply because they contained very little (if any) silts and clays that could serve as bonding agents. After much testing, Brown (1936) concluded that these sands could be synthetically bonded to produce molds of comparable quality to naturally bonded sand. This finding vastly increased the amount of potential foundry sand that was available within Michigan and made the unbonded sands of the coastal dunes much more desirable. In addition, the study suggested that uniform and well-sized deposits of foundry sand in Michigan could also be expected in glacial outwash areas (Brown, 1936), but no effort was made to identify specific deposits.

Expansion of industrial sand mining in Michigan increased rapidly after World War I and was largely concentrated in coastal dune areas. By 1958, almost 1.8 million tons of industrial sand resources (sand and sandstone) were mined annually. By 1973, the amount of industrial sand resources mined in Michigan had risen to over 5.7 million tons (Lewis, 1975). In this context, research on sand in Michigan peaked in the mid to late 1970s. Over the course of that decade, the number of agencies, companies, and private groups requesting information on Michigan's mineral resources grew substantially (Lewis, 1975). This surge in interest was sparked by the emerging environmental movement and culminated in passage by the Michigan legislature of the Sand Dune Protection and Management Act (SDPMA) in 1976 (Michigan Legislature, Act No. 222, Public Acts of 1976). The purpose of this act was to protect, manage, and reclaim Michigan sand dune areas.

In support of this purpose, the Michigan Department of Natural Resources was required to conduct a comprehensive study and inventory of Michigan sand dunes. This task was broken into six parts: 1) an economic study of sand dune mining in Michigan, including where the sand is marketed, how the sand is used, and the quantity of sand in reserves, 2) a geologic study of non-dune sand and sandstone areas in Michigan that may be able to replace dune sand for industrial uses, 3) an assessment of dune areas that should be protected through purchase by the state or other means, 4) the identification and designation of barrier dunes along the shoreline, 5) a study of methods for recycling dune sand as well as alternatives to dune sand, and 6) recommendations for protecting dune areas from uses other than mining. Most of the required studies were completed during the decade following passage of the legislation. This research (Ayres, Lewis, Norris, and May, Inc. & Chapman, 1978; Buckler, 1979; Heinrich, 1979; Michigan Department of Natural Resources, 1984; Michigan Department of Natural Resources, 1985; Sundeen, 1978a, 1978b; Wyckoff, 1986) has been very important in the state's management of its sand resources. Certain studies (e.g. Michigan Department of Natural Resources, 1984) recommended the re-establishment of research programs that address the use of non-dune sand as a mineral resource in industrial processes. However, no such research programs have been restarted nor have any public studies on the use of non-dune sources of sand in industrial processes been published since these recommendations were made, despite an explicit recommendation to do so.

Following the passage of the SDPMA, a comprehensive study of Michigan dune sand users and markets was conducted (Ayres, Lewis, Norris, and May, Inc. & Chapman, 1978). In this study, 135 users of Michigan dune sand were identified in Michigan and surrounding states (and the province of Ontario). Of these users, over 90% of them used Michigan's dune sand for foundry purposes. At this time, over 80% of the dune sand mined in Michigan was destined either for Michigan or Ohio, with approximately equal amounts to each (Ayres, Lewis, Norris, and May, Inc. & Chapman, 1978). Recent statistics on Michigan's industrial sand production, suggest that approximately 55–70% of Michigan's industrial sand is used within the state (Dolley & Bolen, 2000).

Since the passage of the SDPMA (Michigan Legislature, Act No. 222, Public Acts of 1976) sand mining activities within designated dune areas have been regulated extensively by the State of Michigan. Therefore, the accuracy of sand mining statistics (from coastal dune areas) has increased greatly since 1978. Data indicate that the amount of coastal dune sand mined in Michigan (for all uses, foundry and non-foundry) peaked in 1979 at almost 3.5 million tons (Fig. 3). Since then it has fluctuated between 1.5 million and 3 million tons per year, with the most recent peak in mined sand being in 2000. This fluctuation in coastal sand dune mining in Michigan correlates closely with the number of motor vehicles produced in

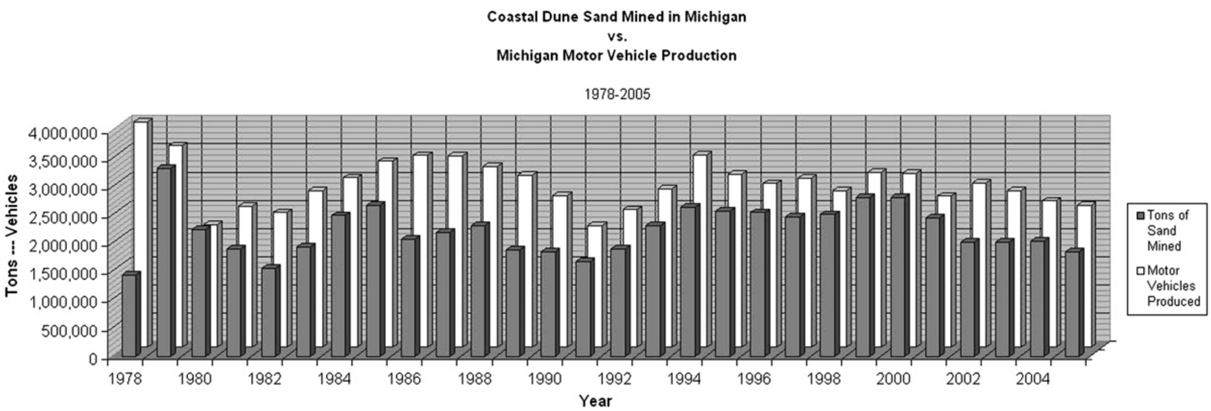

Fig. 3. Annual tonnage of coastal dune sand mined in Michigan versus Michigan motor vehicle production, 1978–2005 (data from Michigan Department of Environmental Quality, 2006 and Michigan Senate Fiscal Agency, 2007).

Michigan (Fig. 3). As vehicle production in the state goes up and down, so does the demand for foundry sand. This trend was especially strong in the 1990s, when an increase in motor vehicle production was matched by a similar increase in the amount of industrial sand that was mined. Years that do not reflect the overall trend (e.g. 1978, 1986, 1987) may reflect an increased use of sand from surrounding states.

In 1989, the SDPMA (Michigan Legislature, Act No. 222, Public Acts of 1976) was amended with Public Acts 146 and 147. The major change associated with these amendments was the creation of a new category of dunes known as Critical Dune Areas. Critical Dune Areas fall within designated sand dune areas and are less than 3.25 km (2 mi) from the lakeshore. These areas include the most fragile and unique areas of the dunes. Activities such as vegetation removal, earth removal, and construction require additional permitting inside Critical Dune Areas. These amendments to the original act also decreed that no sand mining may be permitted within Critical Dune Areas. Exceptions to this rule are 1) the area was being mined prior to passage of these amendments, or 2) the proposed mining area is on property contiguous to a currently permitted mining operation for which sand mining rights were owned prior to the passage of the amendments. Approximately 30% of designated sand dune areas are Critical Dune Areas.

Between 1995 and 2005 the average number of tons of dune sand mined in a given year was approximately 80% of the number of cars manufactured in Michigan during the previous year (Fig. 3). Future demand for industrial sand in Michigan will be directly tied to the health of the state's auto industry. While a decrease in vehicle production may keep the current coastal dune mines viable for a longer period of time, current legislation will over time force a move to non-dune resources.

At present, coastal dune sand for foundry use typically costs between $7 and $11 per ton at its source, while inland sand for this purpose (when available) can cost between $13 and $16, due to the extra processing required (Ford Motor Company, unpublished). These costs do not include transportation of the sand to a foundry, which can end up doubling the final cost. Tapping of inland deposits that more closely align with foundry industry needs may result in a lowering of price that would make it more competitive with coastal dune sand.

Study purpose

The purpose of this study is to determine whether Michigan's widespread inland sand resources have the potential to be used by the foundry industry and to place these findings within a systematic geographic context that can be used in the future. This research compares untapped inland sand deposits to the character of "ideal" foundry sands derived from coastal sand dunes. In addition, it compares these untapped resources to an existing inland sand mine that has been shown to be viable for foundry use. This comparison is based on economic, physical, and chemical criteria of the sand and sand deposits, including grain size, grain shape, clay content, pH, acid demand value, deposit volume, and deposit accessibility. These general characteristics are the most important in determining whether sand is viable for foundries.

As previously indicated, this research was borne out of collaboration between The Alliance for the Great Lakes, Michigan Department of Environmental Quality (MDEQ; Coastal Zone Management Division), Ford Motor Company, and Michigan State University (MSU; Geography). The Alliance is an environmental advocacy group that works to conserve and restore the world's largest freshwater resource through policy, education and local efforts. The project began when representatives of The Alliance approached Ford and the authors about the potential to collaborate on such a project in an effort to locate less controversial supplies of foundry sand. Once Ford and MSU agreed to the project, The Alliance used this unique collaboration to secure funds from MDEQ to support the project. Results of this project have been shared with each of these stakeholders.

Study area

The study area in this investigation consists of public lands in both Upper and Lower Michigan that occur in non-coastal settings in 16 counties (Fig. 4). The sediments contained within these areas consist almost entirely of glacial deposits deposited during the Wisconsin glaciation (Blewett & Winters, 1995; Derouin, Lowell, & Hajdas, 2007; Farrand & Eschman, 1974; Larson & Schaetzl, 2001; Rieck & Winters, 1993; Schaetzl & Weisenborn, 2004). These deposits are contained within a variety of glacial landforms, including kames, moraines, outwash plains, and pro-glacial lake plains. In addition to these deposits, some interior dune fields occur in various places (e.g. Arbogast, Wintle, & Packman, 2002) that are a potential source of foundry sand.

Methods

In order to best locate alternative sand sources of foundry sand, a combination of mapping, field sampling, and laboratory analysis was employed. These methods are summarized below.

Preliminary mapping

To facilitate effective field sampling, ESRI's ArcGIS 9, was utilized to spatially overlay a wide range of data, including surficial geology of Michigan (Farrand & Bell, 1982), USGS 7.5 min topographic quadrangles, railroad networks, public land data (from GAP Land Stewardship maps), Michigan Department of Environmental Quality drinking water-well spot locations, Great Lakes shorelines, and critical dune areas (Michigan Center for Geographic Information, 2005). Associated with the

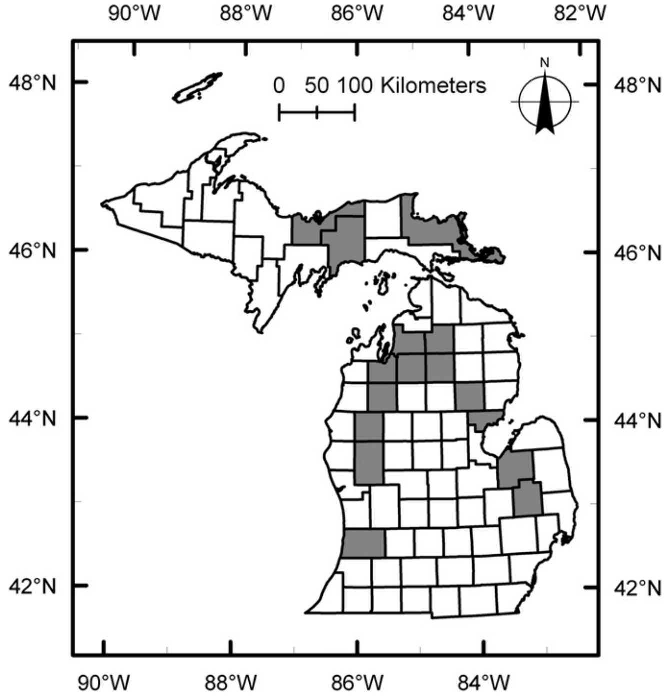

Fig. 4. Counties in which sand samples were collected for this study.

water-well spot locations were lithostratigraphic data logged for each well. These data included the primary lithology, depth, and thickness of each stratigraphic layer encountered during well-drilling. Common database techniques were used to isolate and sum the thickness of those continuous lithologic layers in the water-well logs that 1) were classified as sand or sand and gravel and 2) began within approximately 2 m of the surface. The geospatial interpolation method of inverse distance weighting was then used with k equal to two and using the six nearest neighbors, to create a preliminary estimate map of areas of deep sand deposits that could potentially be hand sampled from the surface.

The additional data layers (railroad corridors, public land, topographic quadrangles, shorelines, and critical dune areas) were added to this preliminary map in the GIS. By spatially intersecting these relevant data layers, suitability could be assessed for potential sample areas. Potentially suitable deposits (warranting a field visit) were chosen based on several criteria. First, they could not be located within places mapped as critical dune areas. Given the high volume of sand needed for a mine to be profitable, only deposits with an estimated sand thickness $>$50 ft were then chosen. Once these areas were identified, a further subdivision was made to include deposits that lay within 8 km (5 mi.) of an existing railroad line so they can be transported economically with the development of a short rail spur. In addition, the sites needed to lie within public lands, so they could be easily accessed during the sampling stage. The locations of sand and gravel pits (public and private, as marked on USGS 7.5 min topographic maps) were also digitized and added to the suitability map, as potential sample locations.

Field collection

Using the initial suitability maps, potential areas for collecting sand samples were identified for field checking. Map-selected locations were evaluated in the field as to their suitability as sample locations. If surficial geology, public status, proximity to a railroad, location outside a critical dune area, and accessibility were confirmed, and no additional prohibitive factors were identified, the site was selected as a sample location. In all, 53 locations were selected for sample collection, in both the Upper and Lower Peninsulas (Fig. 5).

Prior to the collection of samples from these 53 locations, comparison field samples were collected at Wexford Sand Company's Harrietta, Michigan, mine, which provides sand to Ford Motor Co. for foundry use. This sand mine is the only non-dune mine in the state currently providing foundry sand and has been operating since the mid-1970s. For this reason, it was decided that sand collected at this location could serve as a proxy indicator of viable inland sand. Samples collected at this location were used as a reference by which to compare other inland sand samples both physically and chemically. Reference samples were collected at four different locations within the active mining area, including three in situ samples in the pit wall and one sample from a talus apron. A fifth sample of processed sand was collected but is not included in the analysis.

A total of 167 samples were collected from the 53 locations sampled in this study. Most field sampling was conducted using a bucket auger, with samples collected at 1.5 m intervals to a depth of 6 m. At a typical sample site, samples were

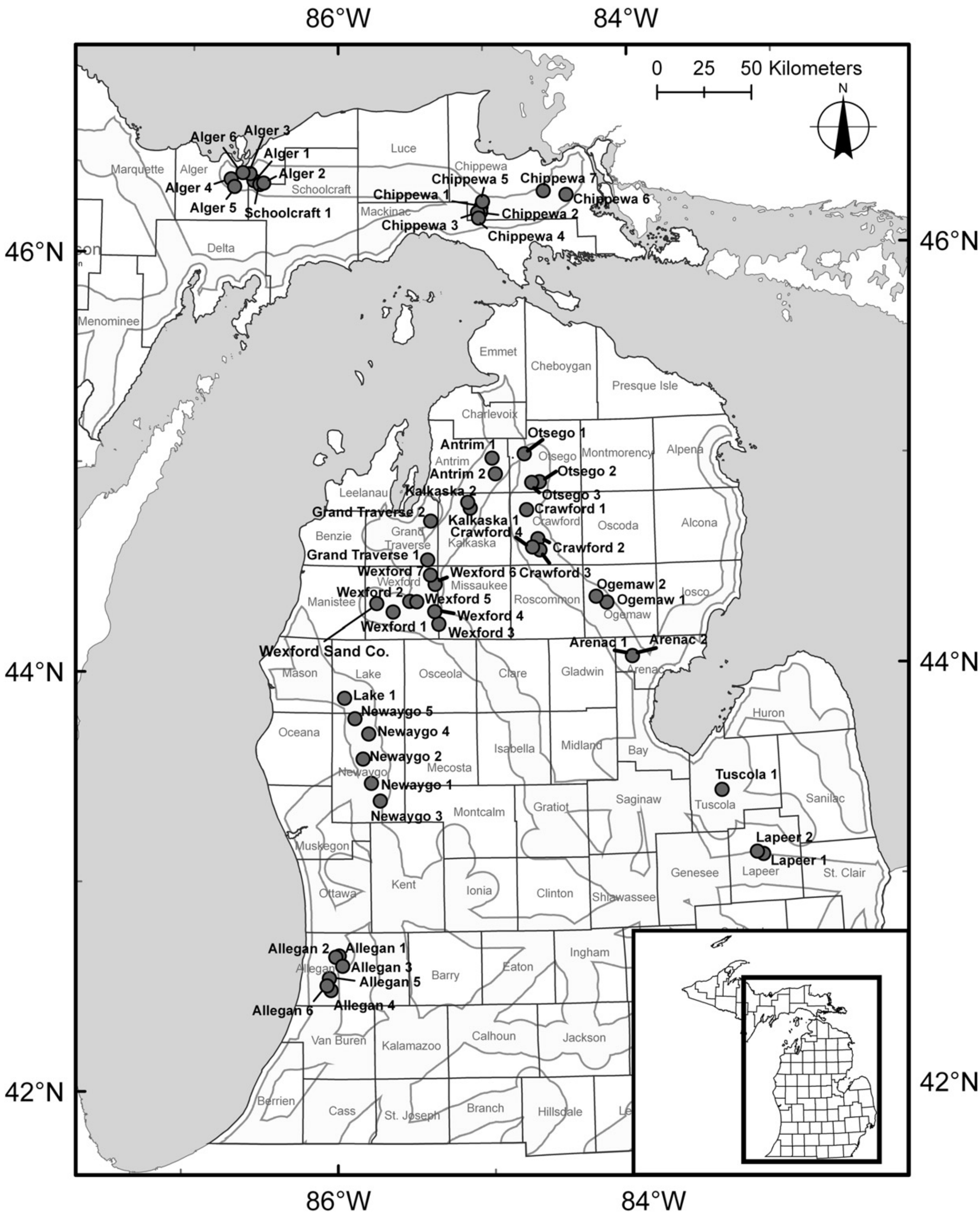

Fig. 5. Field sample locations. Railroad corridors have been shaded. Sample locations and counties have been labeled.

collected from depths of 1.5 m, 3.0 m, 4.5 m, and 6.0 m. It is believed that these samples provide an accurate representation of sands that lie beyond reach at deeper depths. If, for reasons such as stones, clay, or shallow water table, a depth of 6.0 m could not be reached, samples were taken as permitted at the aforementioned intervals with a final sample being collected at the maximum depth reached.

Several of the locations selected for sampling were pre-existing sand and gravel pits. At these locations sand was collected by hand at intervals determined by conditions at the sampling site. At some locations a combination of hand-sampling and bucket augering was used. By typically collecting samples from four different depths at a single location, variability within a deposit could be better described and results could be rendered more representative of the deposit as a whole.

Laboratory analysis

In order for sand-casted automobile parts to meet certain quality control specifications, sand used by the foundry industry must meet rigorous specifications in regards to numerous physical and chemical characteristics. Important characteristics for foundry sand are grain shape, grain size distribution, pH, acid demand, and 25-micron clay content. Chemical composition can also affect the finished sand product, but was beyond the scope of this project.

After collection, samples were air-dried for at least 48 h to remove all moisture. In order to better characterize the target range of grain sizes, gravel, cobbles, stones, and large pieces of organic material (greater than 2 mm) were removed from the sample. Each dried sand sample (approximately 1 kg) was then homogenized using a sample splitter. Laboratory procedures were performed on extracted subsets of these dried, homogenized sample materials.

American Foundry Society (AFS) procedure AFS 1105-00-S: Sieve Analysis (Particle Size Determination of Sand) (American Foundry Society, 2004) was used to determine the grain size distribution of each sand sample. Approximately 50 g of loose, dry sand was obtained from each sample and weighed to determine its exact weight to 0.01 g. The sample was passed through a stack of 11 sieves and the amount retained on each sieve was weighed and recorded. Results were compared against the general grain size requirements for foundry sand (Table 1).

Grain size results were used to calculate a grain fineness number (GFN) for each sample, using procedure "AFS 1106-00-S: Grain Fineness Number, AFS GFN, Calculation" (American Foundry Society, 2004). The GFN represents the U.S. Standard Sieve size through which the sample would just pass if all grains were the weighted average grain size of the entire sample. Results were compared against a typical foundry sand acceptable GFN range of 47–53.

Dominant grain shapes were classified according to procedure AFS 1107-00-S: Grain Shape Classification (American Foundry Society, 2004). AFS standard comparison grain shapes are split into four categories: rounded, subangular, angular, and compound (Fig. 6). Approximately 15 sand grains were centered in the microscope field of view and using the AFS categories a dominant grain shape was noted. Ideal grain shape for foundry sand is subangular.

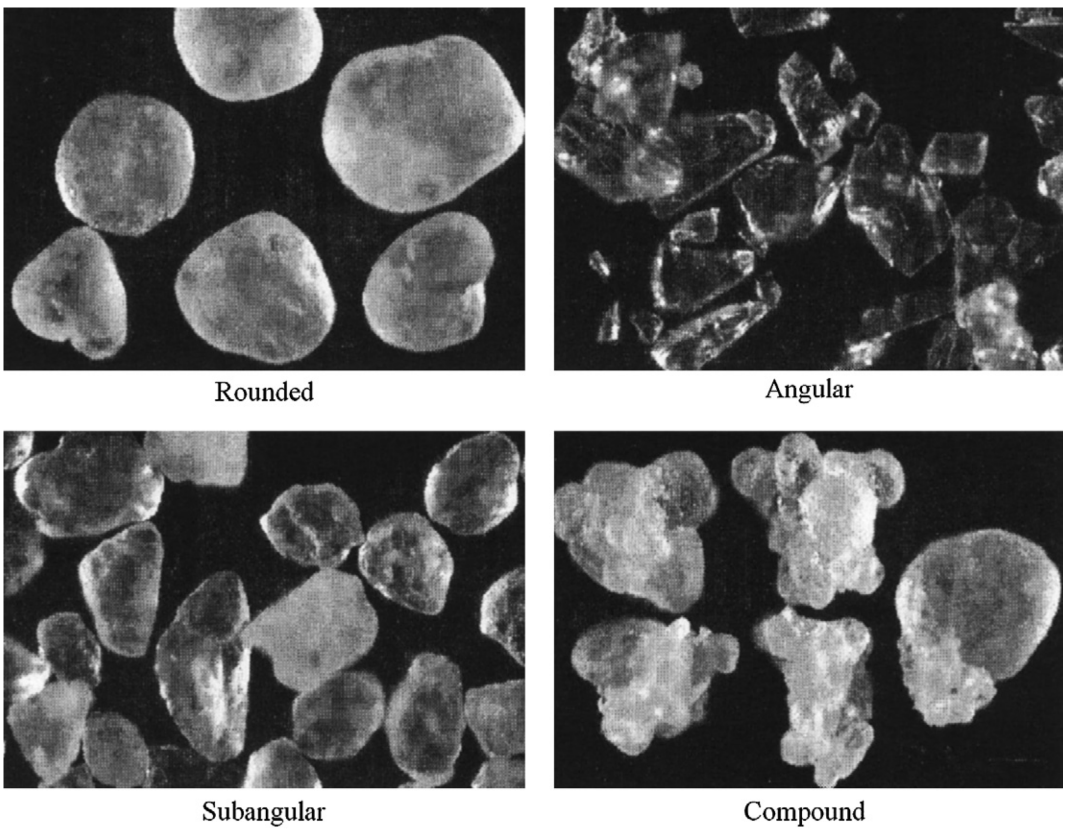

Fig. 6. AFS standard comparison grain shapes used in grain shape determination (modified from American Foundry Society, 2004).

Samples were pH-tested using an electronic pH meter immersed in previously-agitated 2:1 water to sediment solution. Given the propensity for carbonate leaching in Michigan's sandy sediments (Schaetzl & Weisenborn, 2004), only the deepest of all samples from each location was pH-tested, and only then if the sample was collected below 3.0 m. Acceptable pH for foundry sand should be close to neutral. A pH range of 6.5–7.8 was used for this research.

In addition to pH-testing, samples were also subjected to tests measuring acid demand. These tests were conducted on the same subset of samples that were pH-tested, since acid demand can also be affected by soil processes in a similar manner. Acid demand is determined by mixing 50 g of sand with 50 mL of distilled water and 50 mL of 0.1 N hydrochloric acid, then measuring the amount of sodium hydroxide needed to titrate the solution to a neutral pH. These tests were conducted according to American Foundry Society procedure AFS 1114-00-S (American Foundry Society, 2004). High acid demand values can alter reaction speeds and the strength of binders used in forming molds and cores from sand. A threshold value of 10.00 was used in this research.

Because particles smaller than 25 microns in diameter can have a significant effect on the permeability of a mold or core, and thus on the finished surface of casted products, all particles below this threshold level are described by the AFS as 25-micron clay (American Foundry Society, 2004). The 25-micron clay content of all collected samples was determined using a modified version of the AFS hydrometer method (American Foundry Society, 1978). Samples were dispersed for at least 10 h in a medium-speed agitator and then brought to standard temperature (20 °C). Using Stokes' law, the settling rate was determined for particles 25 microns in diameter. Suspended sediment measurements were taken in a 1-L graduated cylinder using an ASTM 152H hydrometer at approximately 5 min. Results are in 0.5 percent increments.

Estimating sand thickness

Sand thickness was estimated by using stratigraphic information in water-well logs (Michigan Center for Geographic Information, 2005). Data were initially compiled by the Michigan Department of Environmental Quality based on required submissions by well-drilling companies. The geostatistical technique of ordinary kriging (e.g. Venteris, 2007) was used to interpolate sand thickness between known points (i.e. water-well locations). Kriging, unlike inverse distance weighting, can account for spatially correlated distance or directional bias in the data and can provide a statistical measure of uncertainty in the results. Using Michigan Geological Survey water-well data, two sand thickness statistics were calculated for each well location: 1) the cumulative thickness of all "sand" stratigraphic layers between the surface and the bottom of the well ("sand" layers, in this context, are those layers in which sand was listed first in the stratigraphic layer name and silt and/or clay were not present, i.e. "sand," "sand & gravel," "sand & cobbles," "sand & stones," or "sand & boulders"); and 2) the thickness of sand within 23 m (75 ft) of the surface. Because water-well data are self-reported by well-drilling companies, data quality varies widely. Bad data points were identified by comparing the two sand thickness statistics to other well data, such as the depth of the well or the depth to bedrock. Wells with conflicting data were removed. It must be emphasized, however, that the water-

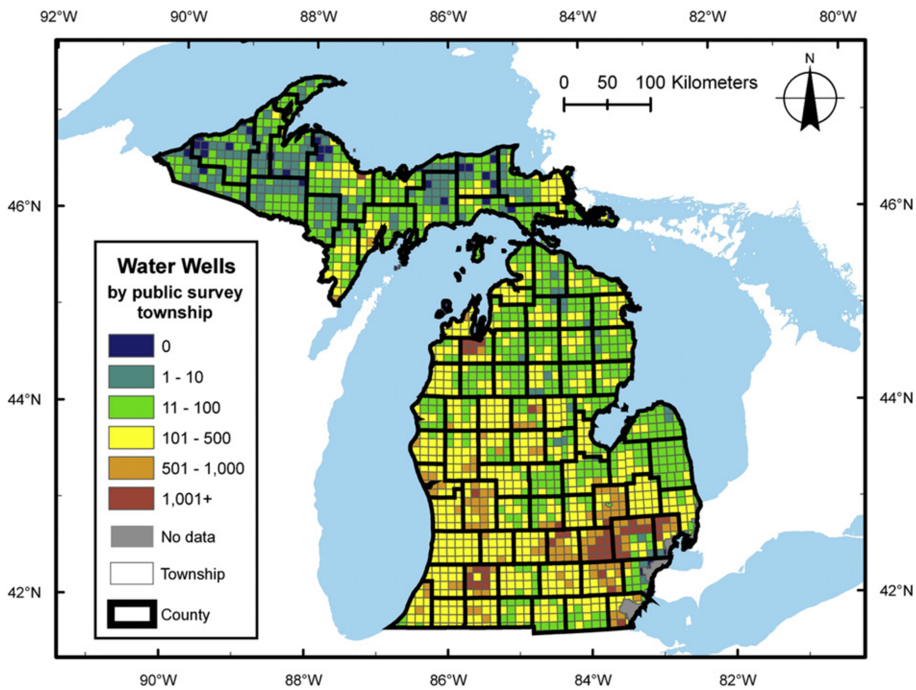

Fig. 7. Distribution of water wells used to estimate sand thickness.

well data retained and used has not been independently verified as to its accuracy by the authors. A total of approximately 318,000 data points were used in the final analysis (Fig. 7). Statistical uncertainty of the results, a function of well location and spatial dependence, is highest in areas where well density is low (e.g. the western Upper Peninsula) and lowest in areas where well density is high (e.g. southeast Michigan).

In order to minimize the effects of nonstationarity in the data, each county was kriged individually and results were mosaicked. For each county, kriging was performed using ArcGIS on all the water-well point locations within the county or within 10 km of its boundary. Spatial dependence was modeled on an individual county basis. For most counties, a spherical model was used for the semi-variogram with the nugget, sill, and range values being determined automatically by ArcGIS. Five neighbors were used in each of four sectors, divided on the diagonal around the location being interpolated (ESRI, 2005). If the data appeared to indicate anisotropy, new parameters taking this into account were generated automatically based on the data.

Results

Economic analysis

Two important economic characteristics of sand deposits considered by the foundry industry are 1) the size of the deposit, and 2) the accessibility of its location. Every potential site must contain a sufficient amount of sand to allow for operation for a long period of time, in order to recoup start-up costs. Accessibility is critical because of its direct impact on the cost of transporting sand from mine to market. Although this is a simplified view of the economic factors that are involved in sand mining, these two components are the most important in determining the economic viability of inland sand resources for the foundry industry (Robert Marrone, 2005, pers. comm.).

Transportation costs

Reducing transportation costs is one means of making inland sand deposits better suited to foundry and other industrial uses. Transporting industrial sand to a market can add significantly to its final cost. Depending on the distance it must travel, the cost per ton can more than double by the time sand reaches a foundry. The ideal method of moving large amounts of sand cheaply to market is barge transportation (Robert Marrone, 2005, pers. comm.), especially when transport distances are long. Cost of barge transportation usually ranges from 0.75 to 1 cent per ton mile (Kogel, Trivedi, Barker, & Krukowski, 2006). At $7 per ton as the base commodity price, barge transportation costs would surpass the base commodity price when transportation distances are greater than 700–900 mi. Although this transportation method works well on the Great Lakes, it is inappropriate for inland sand sources because no sufficiently navigable rivers occur in Michigan.

The next best method of transporting foundry sand to market is by rail (Robert Marrone, 2005, pers. comm.), especially for medium-range transport. Rail transportation costs for industrial minerals generally range from 2 to 4 cents per ton mile (Kogel et al., 2006). At $7 per ton, rail transport costs would surpass base commodity prices at distances greater than 175–350 mi. Michigan contains an extensive network of rail lines which could be used to transport sand from interior locations. Ideally, potential inland sand deposits would be located within 8 km (5 mi) of an existing rail line (Robert Marrone, 2005, pers. comm.). This geography would allow for quick and easy construction of a spur line to access the deposit, reducing significantly the need for costly investment in new rail networks or expensive truck transportation.

Truck transportation is the most expensive way to transport industrial sand. Such transportation usually ranges in cost between 10 and 25 cents per ton mile (Kogel et al., 2006). At $7 per ton, truck transport costs would surpass base commodity prices at distances of only 28–70 mi. While truck transport is the most flexible way to transport industrial sand, its high costs mean it would not likely be suitable for inland sand unless the sand was mined very close to the delivery market. Because inland sand is not suitable for barge transport and transportation distances would generally be greater than 100 mi, rail transport is the most economically feasible method for delivering inland sand to market. Barge transport could possibly be used seasonally to transport Upper Peninsula deposits.

Our analysis indicates that about 64,674 km^2 ($\sim$1/3 of the state) of the Michigan landscape lies within 8 km (5 mi.) of an existing rail line, but more than 3.25 km (2 mi.) from the lakeshore. Most of these rail corridors are in the southern half of the Lower Peninsula. Although the Upper Peninsula contains railroad lines, they do not cross the Straits of Mackinac. This geography means that sands cannot be transported by rail directly from the Upper to the Lower Peninsula but must be moved by barge at some point. Ice buildup and the closure of the Soo Locks prohibit barge transport on Lake Superior during the winter months of the year (U.S. Army Corps of Engineers, 2007). Such a route, however, could be used from spring through fall. Direct rail lines are in place between the Upper Peninsula and Wisconsin and Ontario.

Based on this simple analysis, sand in Michigan's Lower Peninsula, especially its southern half, would be easiest to access, and thus likely the cheapest to bring to market. Inland sand from Michigan's Upper Peninsula cannot be ruled out as an accessible source of sand for the foundry industry, because a combination of rail and barge transport could be used. A more in-depth study focusing solely on transportation costs would be necessary to obtain exact cost estimates for transporting sand from different regions of the state to different areas of Michigan or surrounding states. However, these results highlight those areas of the state in which inland sand mining could be undertaken without the need to make significant changes to the current transportation infrastructure.

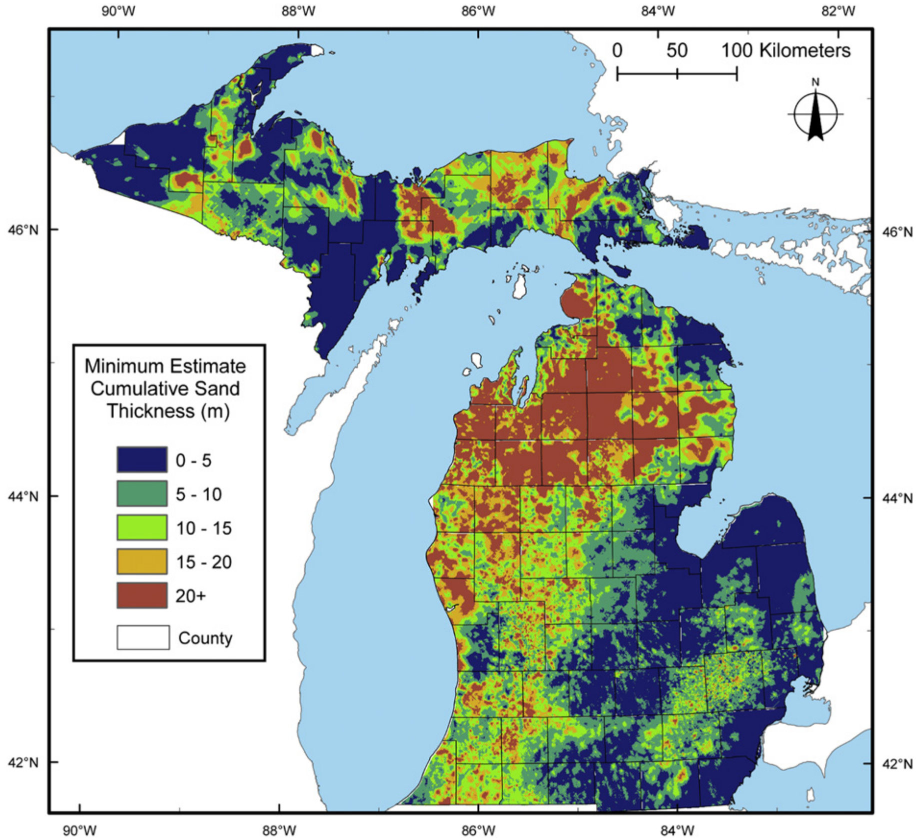

Fig. 8. Minimum estimated cumulative sand thickness between the surface and bedrock. Data are minimum estimates because not all water-wells used in the estimation process reach bedrock.

Sand thickness and volume

Water-wells clearly indicate that the thickest sand deposits in Michigan are in the northwest portion of the Lower Peninsula (Fig. 8). This conclusion is in agreement with Rieck and Winters (1993), who also estimated that the greatest total drift thickness is in this part of the state. The cumulative thickness of sand between the surface and bedrock in most of this region is estimated to be at least 20 m, with some areas likely having cumulative sand thicknesses over 75 m. The thickest deposits are largely located in the north-central interlobate area (Rieck & Winters, 1993). This area was between the retreating Michigan and Saginaw lobes of ice during the late Pleistocene and thus became a repository for large amounts of sandy glaciofluvial material (Blewett & Winters, 1995; Rieck & Winters, 1993). Other significant concentrations of sand occur in the southwest Michigan interlobate area and scattered across the length of the Upper Peninsula. Areas estimated to contain very little sand include much of the southeast quarter of the Lower Peninsula, the extreme northeastern portion of the Lower Peninsula, and areas of the Upper Peninsula where bedrock is very shallow or even at the surface (Fig. 8).

A more realistic look at potentially accessible sand deposits is possible by mapping sand thickness only within 23 m (75 ft) of the surface (from here on referred to as "near-surface sand"; Fig. 9). Sand detected deep beneath the surface during well-drilling increases the cumulative thickness of sand at that location but may not be feasible to mine. Areas with the most near-surface sand are largely located in the north-central portion of the Lower Peninsula (Fig. 9). Additional areas with large amounts of near-surface sand include Muskegon, Lake, and northern Newaygo Counties in the Lower Peninsula and Alger, Schoolcraft, and Luce Counties in the Upper Peninsula. In Emmett County, results suggest large amounts of total cumulative sand (Fig. 8), but much smaller amounts of near-surface sand (Fig. 9). Much of the sand in the deposit is likely located deep below the surface (at least below 23 m) and may be difficult to extract.

Results are dependent on many variables, including the accuracy of the water-well data used, the amount of spatial dependence exhibited by the data, and the scale at which the data are intended to be utilized. Because slight changes in water-well lithology (e.g. sand and gravel vs. sand, clay and gravel) can sometimes cause nearby wells to have significantly different sand thickness values, variance in the data was fairly high. Mean standard error by county for cumulative sand thickness was generally between 6 and 12 m. Mean standard error by county for near-surface sand thickness was generally between 4 and 8 m. These results are meant to show the general trend in sand deposit thickness (and therefore volume) across Michigan. It is inappropriate to use them for predicting the exact sand thickness (or volume) at any specific location. These results are

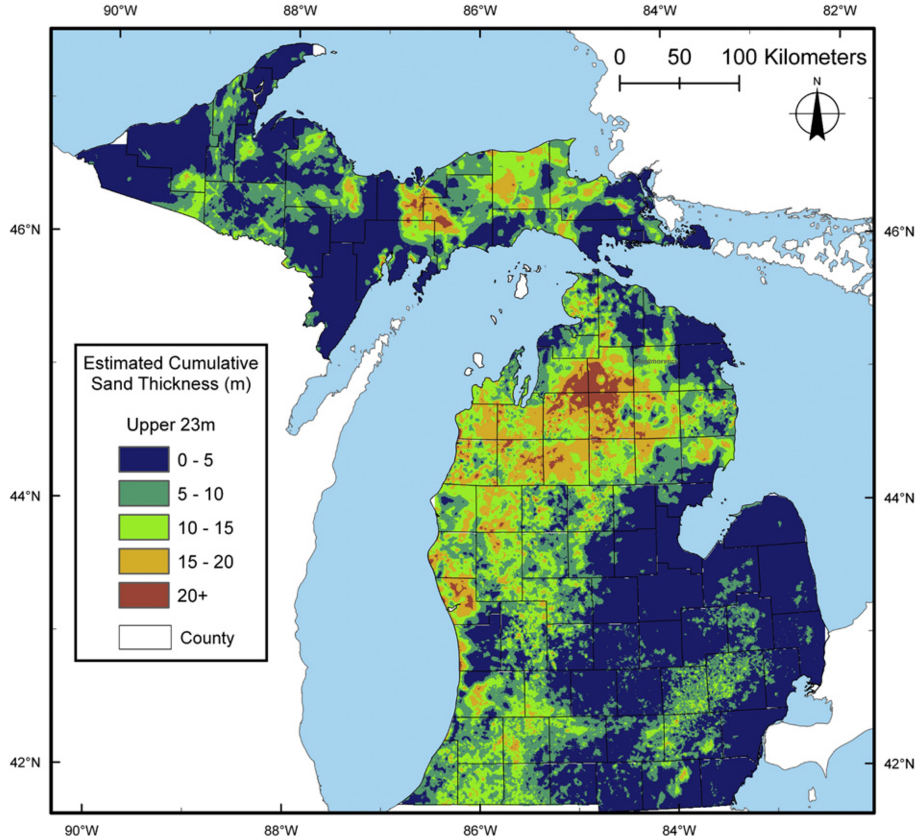

Fig. 9. Estimated cumulative thickness of sand between the surface and a depth of 23 m (75 ft).

considered a minimum estimate for sand thickness because many of the wells used in the analysis are drift wells (tapping an aquifer contained in glacial drift) and therefore do not reach bedrock.

Because kriging is a method of interpolating between known data points to estimate unknown values, the best results are in areas where well density is high (Fig. 7). In those areas with many closely spaced wells that show strong spatial dependence, estimates are likely more accurate than in those areas where there are few wells and/or where spatial dependence between them is low. The highest concentrations of water wells are in the southern half of Michigan's Lower Peninsula, giving higher confidence to the sand thickness estimates for this part of the state. The lowest concentrations of water wells are in rural areas of the Upper Peninsula and, accordingly, confidence in sand thickness estimates in these areas is lower (Fig. 7).

Other variables affecting sand thickness estimates include well type (drift vs. bedrock) and whether or not the well is completed in sand. In areas of the state where most wells are drift wells there is a high likelihood that sand thickness is greater than estimated. This includes much of the north-central Lower Peninsula and, to a lesser degree, the southwest corner of the Lower Peninsula. In areas in which bedrock wells are predominant, sand thickness estimates will be more accurate. Bedrock wells are predominant in southeast and south-central Lower Michigan, the Saginaw Bay region, the "Thumb" region (Huron Peninsula), and much of the Upper Peninsula. In these areas sand thickness estimates will be closer to their actual values. When a well is completed in sand, it is not unreasonable to assume that this lowest sand unit extends below the depth of the water well. When this is the case, sand thickness will be underestimated. Most water-wells in the northern half of the Lower Peninsula are drilled into a water-bearing unit of sand. Many wells in southwest Michigan and a smaller number in southeast Michigan also have sand as their lowest stratigraphic unit. Based on these two variables, those areas most likely to have the greatest amounts of sand (Figs. 8 and 9) are also the most likely to have been underestimated.

Physical analysis

Results of the grain shape, grain size distribution, and 25-micron clay analyses have been grouped by general geomorphic setting, either inland dunes or glacial outwash. Glacial outwash is widespread across Michigan but can adjoin or overlie texturally similar sandy lacustrine sediments or sandy till in some areas. A detailed differentiation of such deposits was not within the scope of this project. Thick deposits of sand identified in this project may be a mix of outwash sand, sandy till, and/or sandy lacustrine sediments. Because location selection was dependent on calculated sand thickness, focusing on areas of deeper sand, results are more likely to represent proximal outwash deposits than medial or distal depositional areas. In addition to being thicker, proximal deposits are also more likely to be less well-sorted, due to the change in fluvial dynamics moving away from the source area during deposition. Samples used in both the physical and chemical analyses were collected from the locations shown in Fig. 5.

Grain shape

Grain shapes varied little across all locations. Using the AFS 4-group categorization matrix (rounded, subangular, angular, or compound; Fig. 6) approximately 96% of all samples had a subangular grain shape. Only 2 samples had compound grains, while 3 samples had angular grains.

Glacial outwash locations. Approximately 96% of all outwash locations had grain shapes that were subangular. Examination revealed that the smallest grain sizes (<100 μm) tend toward being angular in shape, while in many cases grain sizes larger than approximately 400 microns were more rounded. Since the majority of sand grains were between 100 and 400 microns in size the dominant grain shape was almost always subangular. Vertical consistency of grain shape within a sample location was very high.

Sand currently being extracted from the Wexford Sand Co. mine was also analyzed for grain shape. This sand is derived from glacial outwash and was predominantly subangular in shape. The grain shape of samples from this location appeared very similar to most samples collected from other inland locations.

Few glacial outwash sites had samples that failed to meet AFS grain shape criteria for foundry usage. Two locations, Wexford 4 and Wexford 1, exhibited compound grains, which are unacceptable for use by foundries. At Chippewa 6 angular grain shapes were dominant.

Inland dune locations. Inland dune samples showed little difference from glacial outwash samples with regard to grain shape. Grain size tended to be a better predictor of grain shape than geomorphic setting. Approximately 96% of inland dune samples had subangular grain shapes. This is consistent with glacial outwash results. Similar to outwash samples, inland dune samples also showed increased rounding with larger grain sizes.

All inland dune samples, except for one, met the necessary grain shape criteria for foundry use. Chippewa 3 had angular grains at a depth of 4.5 m. All other locations had all subangular grain shapes. Inland dune locations, like glacial outwash locations, also showed strong vertical consistency of grain shape.

Grain size distribution

GFNs measured in this study ranged from a low of 32.2 at Wexford 6 to a high of 171.5 at Chippewa 6. The median GFN of all samples was 48.8 and the mean GFN was 53.8. A total of 38 samples (37 outwash and 1 inland dune) had grain fineness numbers that fell within the target range of 47–53 (Table 2). These 38 samples were collected from 24 different sample locations, an indication of the high amount of variability in GFN results. Areas in which few samples fell within the target range included Lapeer and Tuscola Counties, eastern Wexford County, Otsego County, and Chippewa County.

Glacial outwash locations. Both the median GFN (48.2) and the mean GFN (52.5) of glacial outwash samples fell within the target range. However, the overall range of GFN for glacial outwash (32.2–171.5) was large. Grain size distribution is a much

Table 2
Location and depth of samples having GFNs within the target range (47–53).

Location	Depth (m)	GFN	Location (cont.)	Depth (m)	GFN
Alger 1	1.50	49.4	Grand Traverse 2	5.35	49.2
Alger 1	3.00	52.6	Kalkaska 2	3.00	50.2
Alger 5	3.00	52.4	Newaygo 1	3.00	47.1
Alger 5	4.50	51.2	Newaygo 2	3.00	48.7
Alger 6	1.70	51.7	Newaygo 2	6.00	51.2
Allegan 1	2.70	48.4	Newaygo 3	0.85	47.6
Allegan 1	4.40	51.8	Newaygo 4	1.50	52.0
Allegan 2	6.00	47.4	Newaygo 5	1.50	52.2
Allegan 3	4.50	50.7	Ogemaw 1	1.70	47.6
Allegan 5	1.50	50.6	Ogemaw 1	3.40	52.2
Antrim 2	1.50	48.2	Ogemaw 1	6.80	52.7
Antrim 2	3.00	48.5	Ogemaw 2	0.77	47.8
Chippewa 1	3.00	47.1	Otsego 3	1.50	48.6
Crawford 1	4.50	48.3	Otsego 3	3.00	48.2
Crawford 2	1.50	48.9	Wexford 1	1.50	52.3
Crawford 2	4.50	49.8	Wexford 1	3.00	51.2
Crawford 3	4.50	50.6	Wexford 1	4.50	48.7
Grand Traverse 1	3.00	51.3	Wexford 1	6.00	52.0
Grand Traverse 2	4.50	47.8	Wexford 5	3.00	52.5

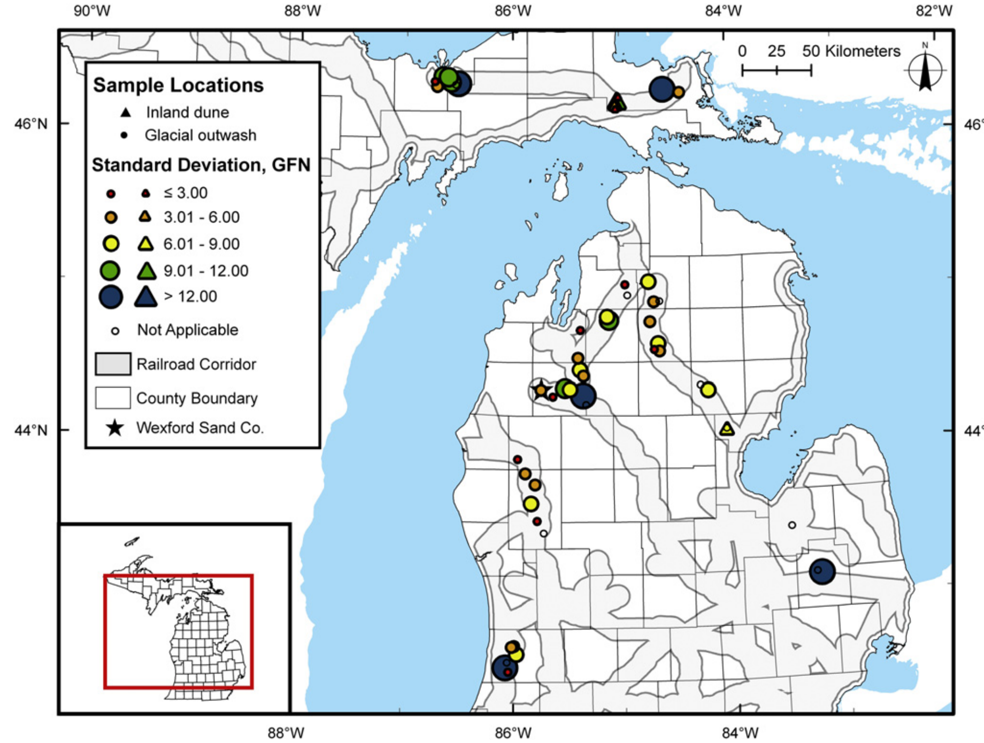

Fig. 10. Variability in grain size distribution, based on the standard deviation of GFN for sites with samples from multiple depths. Low standard deviations are desired, as they signify more consistency of GFN at a given location.

more variable characteristic in glacial outwash sand than is grain shape. Thirty-seven glacial outwash samples met the target GFN criteria (between 47 and 53) and were from 23 different locations (Fig. 10). Only at Wexford 1 did all samples from a location fall within the target range. Many locations only had one or two samples that were within the target range. Samples taken from Wexford Sand Company's inland sand mine showed similar GFN variability. This variability in grain size distribution is not surprising given the fluvial origin of these deposits. Fluvial deposits are typically well stratified, with fining upwards sequences and various degrees of sorting in the sediments.

Using standard deviation it is possible to make comparisons between the Wexford mining location and other sample locations on the basis of grain size variability. The four samples collected from Wexford Sand Company's mine had GFNs ranging from 41.4 to 49.4 with a standard deviation of 3.83. Standard deviation of GFNs for glacial outwash sand ranged from 1.20 to 41.01 (Fig. 10). The median standard deviation was 5.85 and the mean standard deviation was 8.47. On average, sampled locations express slightly more variability than might be expected at Wexford Sand Company's mine. However, 12 glacial outwash sample locations exhibited less variability in grain size than the sampled deposits at the Wexford Sand Company. Three glacial outwash locations (Grand Traverse 2, Newaygo 2, and Wexford 1) had both less variability in grain size than Wexford Sand Company and at least one sample with a GFN within the target range. These results suggest that in terms of grain size the location of the Wexford Sand Company is not anomalous and sand deposits with similar grain size distributions and similar levels of variability can be found in other inland areas of the state.

For each sample, the percentage of sand retained on each of 9 different size sieves (or groups of sieves) was compared to the appropriate acceptable range (Table 1). The total number of sieves or sieve groups on which the percentage retained fell within the acceptable range was totaled for each sample, with a possible range of 0–9.

Actual tallies from all of the samples collected ranged from 0 to 8. No glacial outwash samples were acceptable on all sieves, including sand from Wexford Sand Company. Samples from Wexford Sand Company had scores between 2 and 7. Fourteen glacial outwash samples (10%; not including those from Wexford Sand Co.) were within the acceptable range in at least 7 of the 9 categories. Thirty-nine outwash samples (28%) were within the acceptable range on at least 5 of the 9 sieves.

Inland dune locations. The median GFN (64.1) and the mean GFN (63.5) of inland dune samples were both above the target range. The GFN range of 38.1–83.1 for inland dune samples was narrower than the GFN range for glacial outwash samples. As with the outwash samples, the grain size distributions of inland dune sands were highly variable. At no inland dune locations did all samples fall within the target range for GFN. Only one inland dune sample (Chippewa 1, 3.0 m depth) was within the GFN target range. The non-parametric Mann–Whitney test was used to test whether a significant difference existed between median GFN for outwash locations and dune locations. While GFN results were approximately normal in distribution, other data exhibited non-normal characteristics. To maintain consistency, a non-parametric test was used for this and all statistical comparisons. Using this test, the difference in median GFN between glacial outwash samples (52.2) and inland dune samples (64.1) was shown to be significant at the 0.05 level ($U = 2326$, $p = 0.00$). The results suggest a slightly finer texture for inland dune sand, which concurs with the findings of Sundeen (1978a).

Standard deviations of GFNs for inland dune sand range from 1.47 to 10.69 (Fig. 10). The median standard deviation of GFN for inland dune samples was 5.61 and the mean was 5.67. Two inland dune locations (Chippewa 4 and 5) exhibited less variability in grain size than the Wexford Sand Company sand mine. Sieve totals for inland dune samples ranged from 1 to 8. One of 20 inland dune samples (5%) was within the acceptable range in at least 7 of the 9 categories. Nine samples (45%) were within the acceptable range on at least 5 of the 9 categories.

25-Micron clay

Glacial outwash locations. Clay content in glacial outwash samples was minimal in most cases. Sixty-two glacial outwash samples (45%) from 27 locations contained less than 1.0% clay. At 7 locations, all samples had less than 1.0% clay: Alger 1, 3, and 5, Allegan 1, Crawford 4, Grand Traverse 1, and Lake 1. The median clay content for glacial outwash samples was 1.0% and the mean was 2.0%. Eight of nine outwash locations in Michigan's Upper Peninsula (all except Chippewa 6) had at least one sample with less than 1.0% clay.

Inland dune locations. Seventeen inland dune samples collected from 6 locations contained less than 1.0% 25-micron clay. Median clay content was 0.0% and the mean was 0.3%. All 5 inland dune locations in the Upper Peninsula had at least 1 sample with less than 1.0% 25-micron clay. At three inland dune locations (Chippewa 2, 3, and 5) all samples had less than 1.0% 25-micron clay. The Mann–Whitney test was used to test for significant difference of median clay content between glacial outwash samples and inland dune samples. Test results show that median clay content is lower for inland dune samples and that this difference is significant at the 0.05 level ($U = 620.5$, $p = 0.00$).

This difference in mean clay content is expected given the different processes of fluvial and eolian deposition. When clay particles are eroded by wind they are carried in suspension and often deposited large distances from their source area. Sand grains, however, are usually transported by saltation and creep and thus are carried only relatively short distances before a sufficient decrease in wind velocity allows them to be deposited (Goldsmith, 1985). Fluvial erosion often results in both sand and clay being carried in suspension. The deposition that occurs as water velocity decreases is usually a sequence of fining upwards. The end result becomes stratified layers that often include a wider range of grain sizes, from cobbles and gravel through sand to silts and clays.

Chemical analysis

Important chemical factors that determine whether sand deposits can be viably used in the foundry process include pH and Acid Demand Value (ADV). These two variables affect the chemical reactivity of the sand, which must be subjected to multiple chemicals during the casting process, such as acid catalysts and binding resins.

pH

Glacial outwash locations. Thirty-one glacial outwash locations were tested for pH. In addition, 4 samples from Wexford Sand Co. were tested for comparative purposes. The range of pH from outwash locations was 5.81–8.56 (Fig. 11). Median pH for glacial outwash locations was 7.51 and mean pH was 7.28. Thirteen of 31 glacial outwash samples (42%) fell within the foundry sand pH target range of 6.5–7.8. Only one of the samples meeting the target criteria was located in the Upper Peninsula. All other Upper Peninsula outwash samples had pH values below the target range. Given the relative lack of carbonate-rich bedrock in the Upper Peninsula compared to the Lower Peninsula (Dorr & Eschman, 1970) it is not surprising that pH values of sand from the former region are generally below the target range. Results from the Wexford Sand Co. mine ranged from 7.85 to 8.01, slightly above the target range for foundry sand.

Inland dune locations. Five inland dune locations were tested for pH. The pH range for inland dune samples was 5.12–7.95 (Fig. 11). Median pH for inland dune locations was 6.14 and mean pH was 6.41. One of 5 inland dune locations (20%) was within the pH target range.

The Mann–Whitney test was used to test for a significant difference in pH based on geomorphic setting. The test found that the difference in pH between glacial outwash and inland dunes is not significant at the 0.05 level ($U = 46.0$, $p = 0.15$). However, a significant difference was detected when samples were grouped by location (Upper Peninsula vs. Lower Peninsula) as opposed to geomorphic setting ($U = 236.0$, $p = 0.00$).

Acid demand value

Acid demand results from this research ranged from 0.00 to 47.01 (Fig. 12). The distribution of values was bimodal with one peak between 0 and 5 and a second peak between 35 and 40. Only one sample had an acid demand value between 10 and 30. Median acid demand value is 6.03, evidence of the relatively large number of samples with low ADV.

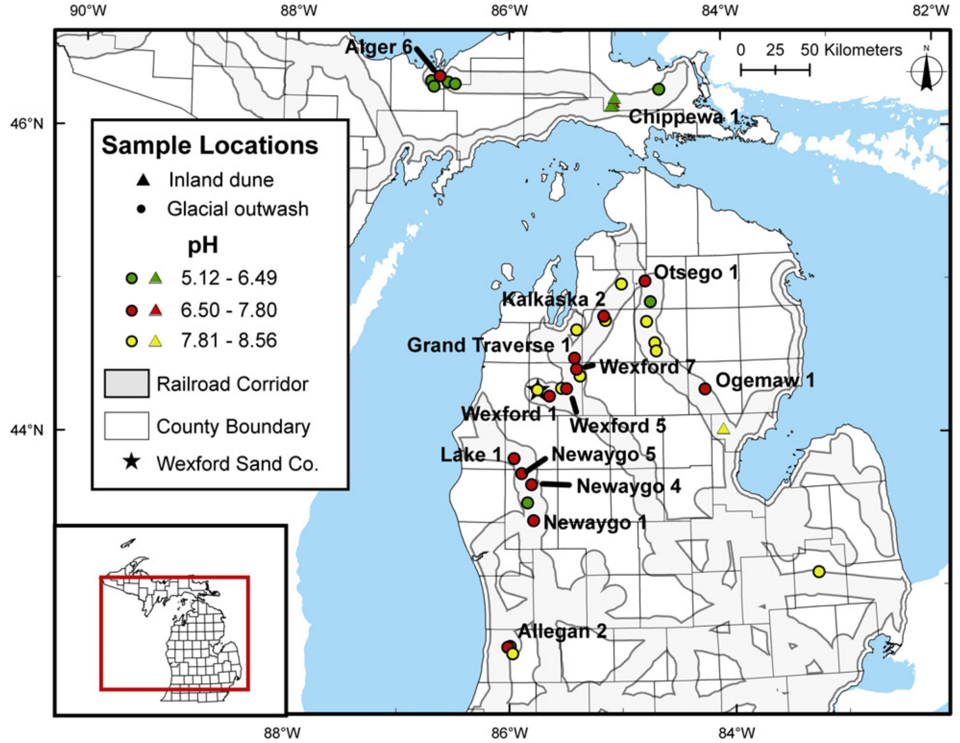

Fig. 11. pH of the deepest sample taken at each location (if below 3.0 m). Labeled locations are within the target range.

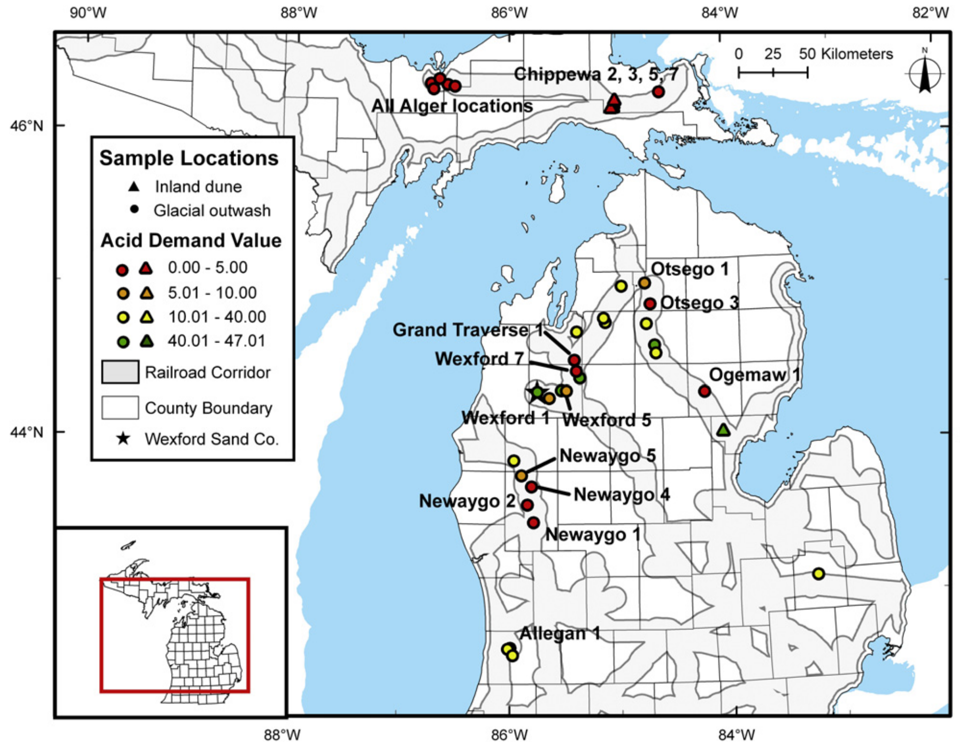

Fig. 12. Acid demand value (ADV) for all tested locations. Locations with values less than 10.00 are best suited for foundry sand and have been labeled.

Results suggest a moderate correlation between pH and ADV. Samples with acidic pH tended to have low ADV values and samples with basic pH largely had high ADV values. If pH was near neutral, ADV varied from low to high. The reason for a general lack of mid-range values is unknown, but it may relate to the presence or absence of natural carbonates or salts in the sample. Alkaline materials such as limestone, shell, dolomite, or lime in the parent material can increase the acid demand value of a sand.

Glacial outwash locations. Acid demand value (ADV) of glacial outwash samples ranged from 0.00 to 45.69, with a median of 6.61. Eighteen of thirty-one glacial outwash locations (58%) met the foundry sand criteria for ADV. Six of these locations were from the Upper Peninsula whereas twelve were from the Lower Peninsula (Fig. 12).

Sand currently mined from Wexford Sand Company's inland site was also tested for ADV. Unprocessed sand collected from multiple locations at the site had acid demand values that ranged from 33.33 to 43.39. This sand must be processed after mining to lower the ADV to levels acceptable for foundry use. Nineteen glacial outwash locations in this study have lower acid demand values than all samples taken at Wexford Sand Company's inland site, while 30 locations have acid demand values that are lower than at least one of the samples collected from this sand quarry.

Inland dune locations. Acid demand value at inland dune locations ranged from 0.00 to 47.01 (Fig. 12), with a median of 0.00. Three of five inland dune locations analyzed (60%) had acid demand values of less than 10.00, meeting foundry sand criteria. Results suggest that for acid demand value, like pH, location (Upper Peninsula vs. Lower Peninsula), and not geomorphic setting, plays a more significant determining role.

Discussion

By combining the results of all 7 physical and chemical tests it is possible to rank sample locations based on overall suitability. No locations, including the sand mine operated by Wexford Sand Co., were completely suitable for all 7 tests. The results of each test were scored on a scale of 0–4 for each location, with a score of 4 meaning that the location met all foundry parameters for that test. A combined score of 28 would signify a location at which all variables tested were found suitable for all samples.

Of the locations at which all 7 variables were measured, the best results were in northern Lower Michigan (Table 3, Fig. 13). Three locations in Wexford County (Wexford 1, 5, and 7), one in Grand Traverse County (Grand Traverse 1) and four in Newaygo County (Newaygo 1, 2, 4, and 5) scored very high and are in areas estimated to have thick and extensive near-surface sand deposits. Upper Peninsula locations with high suitability are mostly in Alger County (Table 3, Fig. 14). Due to the depth restriction imposed on testing pH and ADV and the need for multiple samples from the same location to calculate standard deviation of GFN, not all locations were tested for all 7 variables. Suitability results based on the 4 variables tested at most locations (grain shape, GFN, sieve percentages, and 25-micron clay) are listed in the "Subtotal" column of Table 3.

Overall, the most likely candidates for replacing coastal dune sand are in three distinct zones: Wexford and southeast Grand Traverse Counties, central Alger County, and northern Newaygo and southern Lake Counties (Figs. 13 and 14). Not all targets were met with all samples tested but combined results suggest the amount of processing necessary to prepare sand from these zones for foundry use (in regards to those characteristics tested) would be lowest among deposits that were sampled in this study.

Each of the three primary zones listed tested well for most variables but weaker for some. Highly suitable locations in Alger County generally had high rankings for grain shape, grain size, and clay content, but pH was below the ideal range. In addition, delivery may require a combination of rail and barge transportation, depending on destination, which would increase shipping costs above the other two locations. In Wexford County, some locations scored very well, while others scored quite low, suggesting sand deposits in this area may be quite variable and further testing would be prudent. Highly suitable locations in Newaygo and Lake Counties generally scored well for pH and ADV but lower for clay content and GFN.

All things considered, these three zones would likely require the least amount of processing to be used by the foundry industry and may have sand that is just as good as or better than sand currently being mined from the Wexford Sand Co. mine. Each foundry places slightly different importance on the characteristics tested here, based on their own individual needs. By listing the many benefits and few less suitable characteristics of each of the primary zones, individual foundries can better focus on the area that best meets their needs.

Secondary areas that may be suitable but would likely need additional testing include the Trout Lake area of Chippewa County (Chippewa 1 through 5; Fig. 14) as well as a larger area covering portions of northern Grand Traverse, Antrim, Kalkaska, Otsego, and Crawford Counties (Fig. 13). The latter group of five counties did not score as well as the primary zones described above, however, sand volume in this region is immense and further testing may reveal subsections that rival or exceed the primary zones in suitability.

The Trout Lake area of Chippewa County (Fig. 14; Table 3) shows moderate suitability but is somewhat confined in extent. Further study would be needed to refine sand volume estimates in this area and to determine whether the inland dunes here could support a full-scale sand mine. Estimated sand thickness in this area probably includes lacustrine and/or outwash sands underlying the dunes, which would likely have characteristics that differ from the eolian sand above. Suitability may also be high around the location of Ogemaw 1, but given the limited number of samples in this area any recommendation should be tempered.

Table 3
Suitability rankings for all locations. A maximum score of 28 would indicate all variables are within foundry parameters. The subtotal column is the sum of values for grain shape, GFN, sieves, and 25-micron clay.

Location	Type	Grain shape	GFN	GFN standard deviation	Sieves	25-micron clay	pH	ADV	*Subtotal*	*Total*
Alger 1	outwash	4	3	1	2	3	0	4	*12*	*17*
Alger 2	outwash	4	0	0	1	2	0	4	*7*	*11*
Alger 3	outwash	4	0	1	2	3	–	–	*9*	–
Alger 4	outwash	4	0	4	1	3	0	4	*8*	*16*
Alger 5	outwash	4	3	3	2	3	0	4	*12*	*19*
Alger 6	outwash	4	1	1	1	3	4	4	*9*	*18*
Allegan 1	outwash	4	3	3	2	3	0	4	*12*	*19*
Allegan 2	outwash	4	1	3	1	1	4	0	*7*	*14*
Allegan 3	outwash	4	1	2	2	0	0	0	*7*	*9*
Allegan 4	outwash	4	0	4	2	3	–	–	*9*	–
Allegan 5	outwash	4	4	0	2	3	–	–	*13*	–
Allegan 6	outwash	2	0	0	2	3	–	–	*7*	–
Antrim 1	outwash	4	0	0	0	0	–	–	*4*	–
Antrim 2	outwash	4	3	4	2	3	0	0	*12*	*16*
Arenac 1	outwash	4	0	0	2	3	–	–	*9*	–
Arenac 2	dunes	4	0	2	2	3	0	0	*9*	*11*
Chippewa 1	dunes	4	1	1	2	3	4	0	*10*	*15*
Chippewa 2	dunes	4	0	0	2	4	0	4	*10*	*14*
Chippewa 3	dunes	3	0	3	2	3	0	4	*8*	*15*
Chippewa 4	dunes	4	0	4	2	3	–	–	*9*	–
Chippewa 5	dunes	4	0	4	2	3	0	4	*9*	*17*
Chippewa 6	outwash	0	0	3	1	1	–	–	*2*	–
Chippewa 7	outwash	4	0	0	2	2	0	4	*8*	*12*
Crawford 1	outwash	4	1	3	1	3	0	0	*9*	*12*
Crawford 2	outwash	4	3	2	1	1	0	0	*9*	*11*
Crawford 3	outwash	4	1	3	1	3	0	0	*9*	*12*
Crawford 4	outwash	4	0	4	1	4	–	–	*9*	–
Grand Traverse 1	outwash	4	1	3	2	3	4	4	*10*	*21*
Grand Traverse 2	outwash	4	3	4	2	2	0	0	*11*	*15*
Kalkaska 1	outwash	4	0	1	1	3	0	0	*8*	*9*
Kalkaska 2	outwash	4	1	2	2	3	4	0	*10*	*16*
Lake 1	outwash	4	0	4	1	3	4	0	*8*	*16*
Lapeer 1	outwash	4	0	0	1	1	0	0	*6*	*6*
Lapeer 2	outwash	4	0	0	1	0	–	–	*5*	–
Newaygo 1	outwash	4	1	4	1	2	4	4	*8*	*20*
Newaygo 2	outwash	4	3	2	2	3	0	4	*12*	*18*
Newaygo 3	outwash	4	4	0	0	2	–	–	*10*	–
Newaygo 4	outwash	4	1	3	2	2	4	4	*9*	*20*
Newaygo 5	outwash	4	1	3	2	3	4	4	*10*	*21*
Ogemaw 1	outwash	4	3	2	2	2	4	4	*11*	*21*
Ogemaw 2	outwash	4	4	0	2	1	–	–	*11*	–
Otsego 1	outwash	4	0	2	1	2	4	4	*7*	*17*
Otsego 2	outwash	4	0	0	1	1	–	–	*6*	–
Otsego 3	outwash	4	3	3	1	2	0	4	*10*	*17*
Schoolcraft 1	outwash	4	0	0	1	3	–	–	*8*	–
Tuscola 1	outwash	0	0	0	0	0	–	–	*0*	–
Wexford 1	outwash	3	4	4	3	2	4	4	*12*	*24*
Wexford 2	outwash	2	0	1	2	0	0	0	*4*	*5*
Wexford 3	outwash	4	2	0	2	0	–	–	*8*	–
Wexford 4	outwash	2	0	0	1	0	–	–	*3*	–
Wexford 5	outwash	4	1	2	2	3	4	4	*10*	*20*
Wexford 6	outwash	4	0	3	1	0	0	0	*5*	*8*
Wexford 7	outwash	4	0	2	2	3	4	4	*9*	*19*
Wexford Sand Co.	outwash	4	3	3	2	3	0	0	*12*	*15*

Overall physical and chemical results were variable for both glacial outwash locations and inland dune locations, however, the best locations tended to be from outwash locations. In addition, the volume of sand contained in inland dunes is dwarfed by that of outwash deposits. Because of this, few inland dune locations were initially selected as sampling locations. Estimated sand thickness at these inland dune locations probably reflects underlying outwash or lacustrine sands, since the inland dunes themselves are generally quite small, especially compared to their coastal counterparts. Inland dunes are also generally scattered across the landscape and not continuous like outwash deposits. Economically, glacial outwash deposits are far more suitable for foundry sand use than inland dunes because of these differences.

Within the primary zones of suitability, extensive sand deposits have been found that can be used to replace coastal sand dunes for foundry purposes. A variety of tests have confirmed the presence of sand that is low in clay, has a suitable or near-suitable range in grain size, has the desired subangular grain shape, and has pH and acid demand values that are

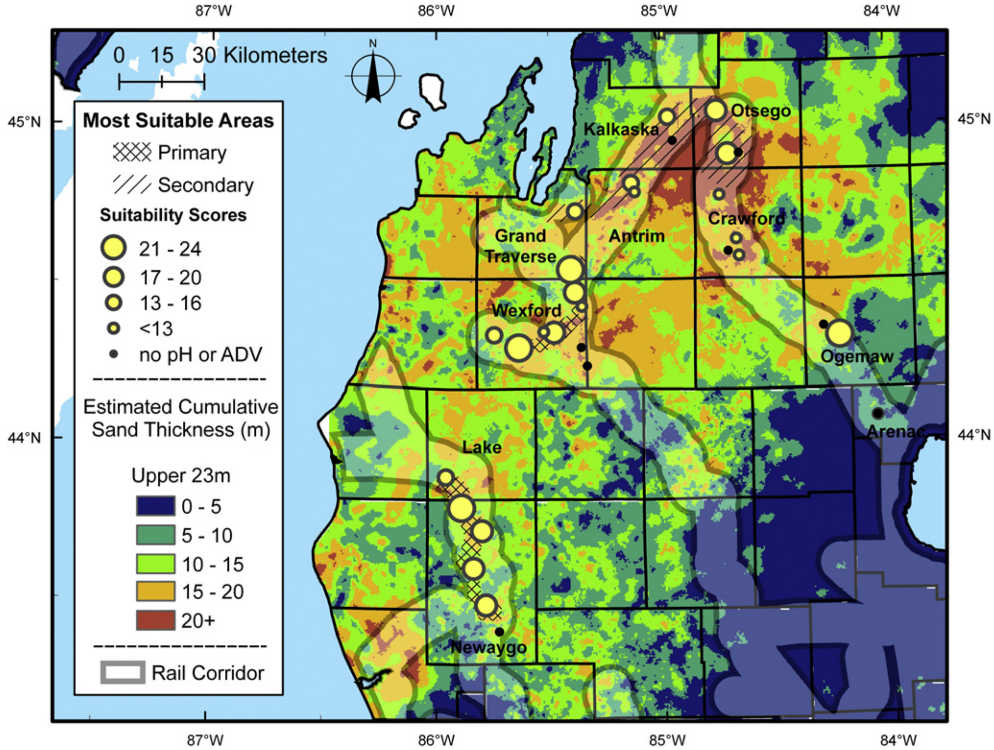

Fig. 13. Primary and secondary suitability zones in northwest Lower Michigan. Boundaries are generalized based on railroad corridors and estimated sand thickness. Counties with sample locations have been labeled.

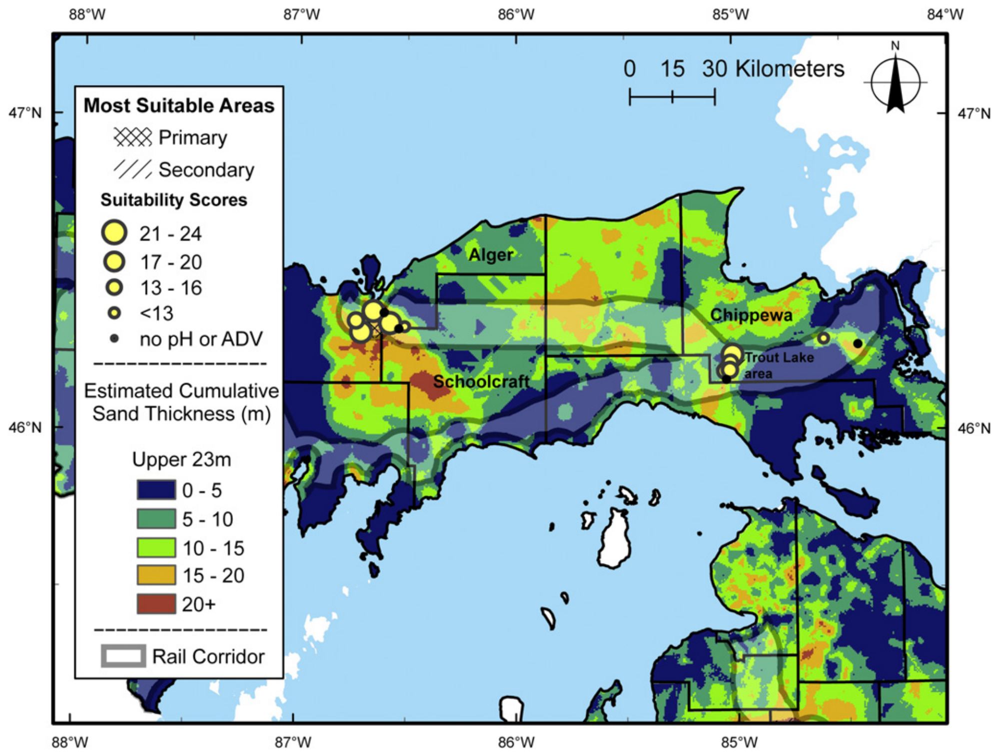

Fig. 14. Primary and secondary suitability zones in the Upper Peninsula. Boundaries are generalized based on railroad corridors and estimated sand thickness. Counties with sample locations have been labeled.

close to industry targets. A well-sited inland sand mine in one of these regions could potentially have enough sand resources to provide for decades of operation. Combined results of the economic, physical, and chemical tests have shown that areas of both northern Lower Michigan and the Upper Peninsula have the potential to replace current coastal dune sand mines.

Conclusion

This study assesses the physical, chemical, and economic characteristics of inland sand deposits in Michigan, all within a spatial (geographic) framework, to determine their potential to replace coastal dune sand in foundries. It represents a unique collaboration between industrial sand users (Ford), environmental conservationists (Alliance for the Great Lakes), and university researchers (Michigan State University Geography) to solve a pressing and important issue in the state of Michigan. It is also the first study on this topic to employ a distinctly geographical approach. Therefore, it was possible to efficiently and systematically assess the nature of a wide range of inland sand deposits in the state. These results can be used by advocacy groups such as The Alliance to make the general public and mining companies aware that alternative sources of foundry sand indeed exist and should be targeted in the future when new operations are required.

When ranked by combined test results 3 regions show the most potential to be inland sand sources for the foundry industry: 1) Wexford and southeastern Grand Traverse Counties, 2) northern Newaygo and southern Lake Counties, and 3) central Alger County. These areas tested highly in both physical and chemical sand characteristics. They are within 8 km (5 mi) of existing rail lines and are estimated to have large volumes of near-surface sand.

Secondary inland areas that also may have the potential to replace coastal dune sand include: 1) eastern Antrim and western Otsego Counties (and into northern Grand Traverse, Kalkaska, and Crawford Counties), and 2) the Trout Lake area of southwest Chippewa County. These areas are also located close to existing transportation networks and generally have very thick sand deposits. However, they tend to be either more limited in extent (the Trout Lake area) or less amenable physically and chemically (Antrim, Otsego, and surrounding counties) than the primary regions. Foundry sand from these areas would likely require more preprocessing than sand from the primary regions listed above.

The conclusions of this research have considerable implications for foundry sand mining in Michigan. Large amounts of potential foundry sand are located in accessible inland areas. Given the political, environmental, and ethical controversy surrounding the mining of coastal dunes, a move to inland sources is clearly possible. Such a move would not be free from its own controversy, but should be explored as a better means of balancing the economic, environmental, and recreational value of Michigan's natural resources.

Current environmental regulations magnify the benefits of inland sand relative to coastal dune sand. While inland sand deposits are also a component of ecological systems, these systems are generally not regarded as being at the same level of risk as Michigan's coastal dune environments. As such, regulations are less restrictive in inland areas. This has the potential to offset any decrease in the physical and chemical quality of inland sand relative to coastal dune deposits.

Foundry sand users and sand mine operators may wish to apply these new data to their specific requirements. Because mold- and core-making processes are not identical at every foundry, physical and chemical sand specifications can vary to a limited degree. Individual users may find inland sand somewhat more or less amenable to their own specific needs. In addition, non-foundry uses of the vast inland sand resources can be explored. Because many non-foundry sand users have less stringent physical and chemical requirements than foundries, the potential available amount of inland sand is even greater.

This study also highlights the need for continued investigation of Michigan's inland sand resources. Over the past 30 years there has been a dearth of published studies on Michigan's industrial sand resources, even though such studies have been both needed and explicitly requested. Future studies should address the following important areas:

1) Detailed investigation of the primary inland sand areas identified by this research, including their extent and the variability within them.

2) The feasibility of processing sand in secondary areas for foundry use.

3) The economic variables, beyond distance and mode of transportation, that effect market access to sand resources.

4) Non-foundry uses for which sand with these physical and chemical specifications would be appropriate.

5) The potential of sand from adjacent states to replace Michigan coastal dune sand in foundries.

Based on the results of this research, a move to inland sand sources and away from coastal dune mining is feasible. Such a move has the potential to benefit the interests of many vested parties, including sand mine operators, recreational dune users, and all those who place intangible value on coastal dune ecosystems. Further study can refine these results and lead to even more specific recommendations and direction toward inland sand resources.

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