AGGREGATE RESOURCES

CRUSHED STONE POTENTIAL

Mille Lacs County, MN

Produced by the Aggregate Resource Mapping Program
Division of Lands and Minerals

Minnesota Department of Natural Resources

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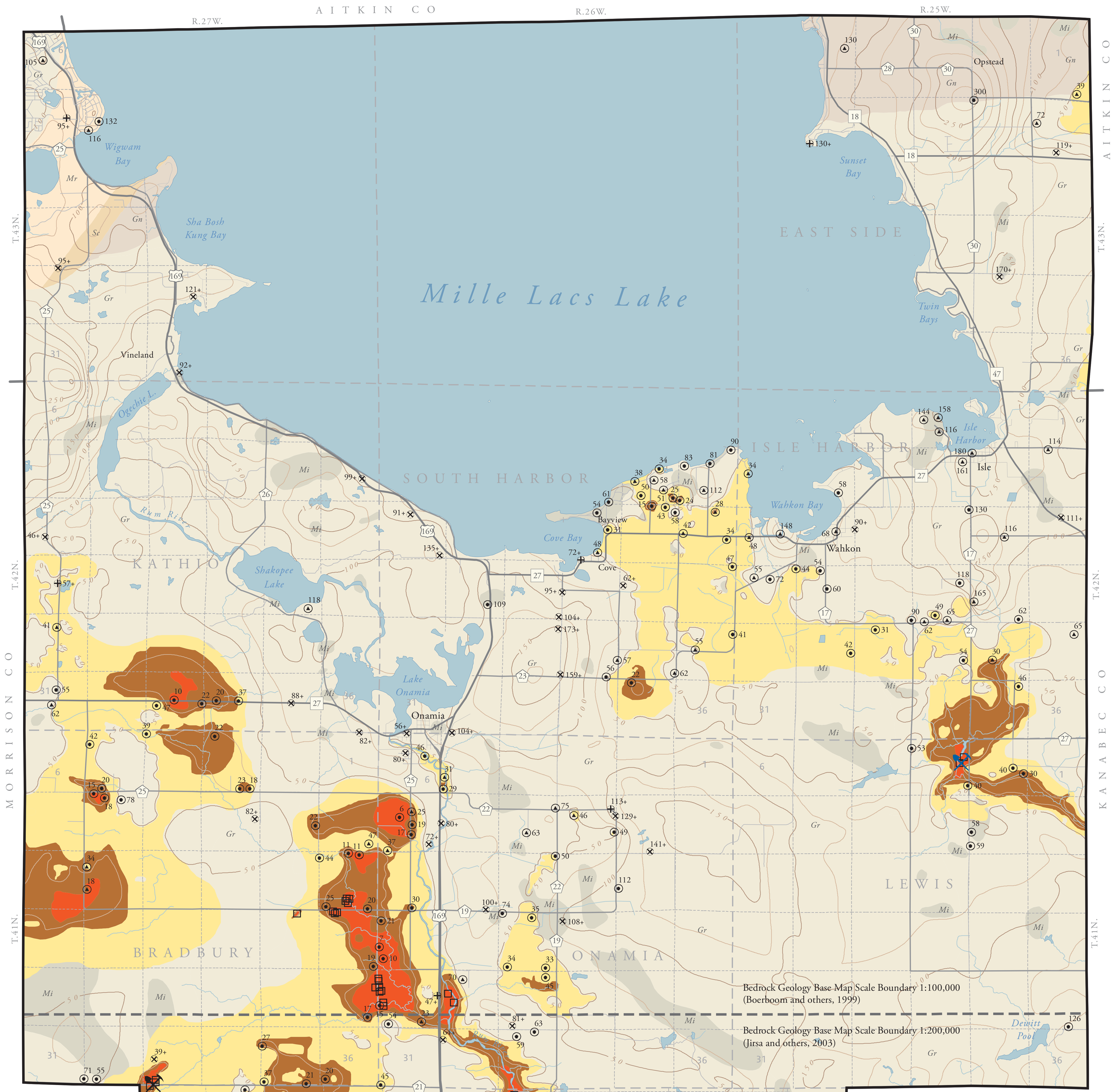
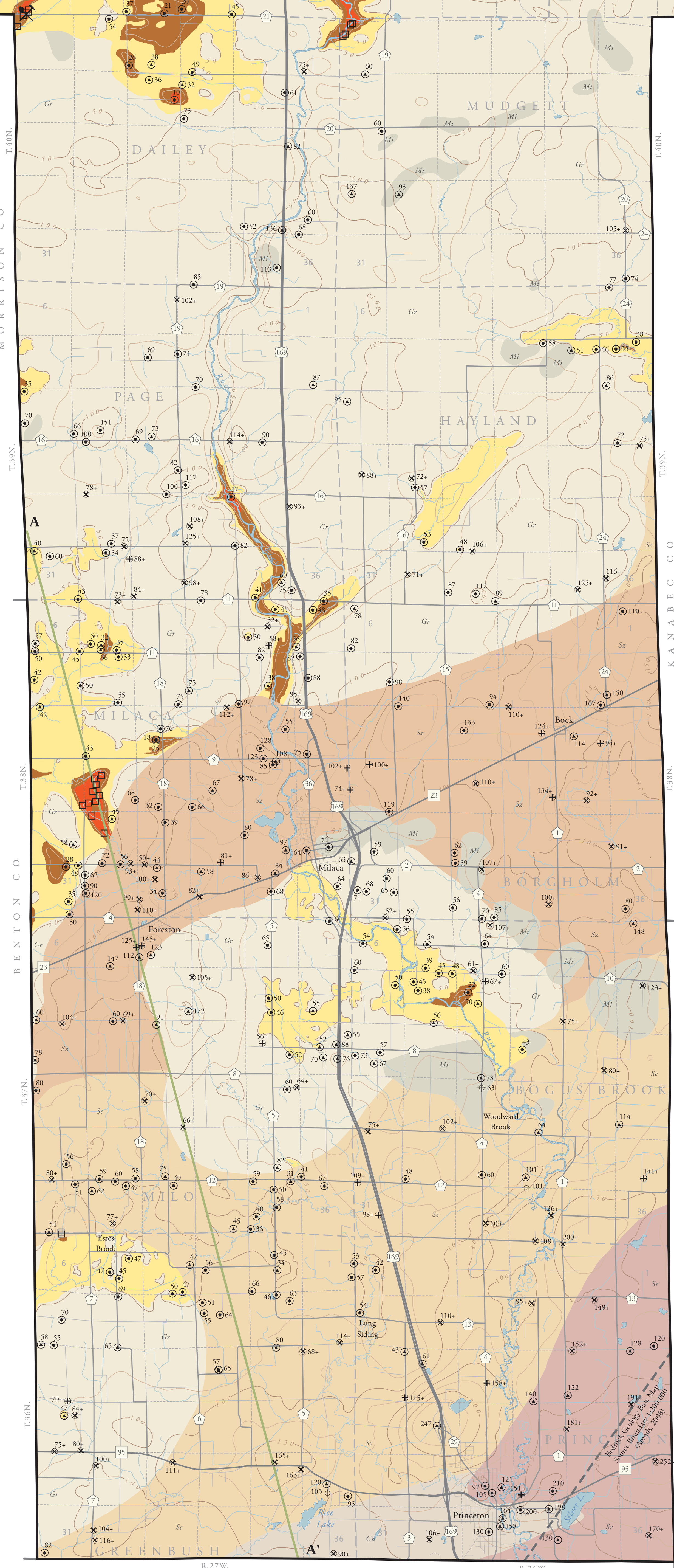
Aggregate Resource Mapping Webpage
http://www.dnr.state.mn.us/lands_minerals/aggregate_maps





POTENTIAL CRUSHED STONE RESOURCES: Granite and other crystalline bedrock formations (e.g., gneiss, monzonite, gabbro, and basalt) suitable for crushing. These units are inferred to be relatively thick (greater than 100 feet), with overburden thicknesses ranging from 0 to 50 feet. Quarries located within these units are classified as identified resources.

High Potential for Crushed Stone Resources: Granite and other crystalline bedrock formations exposed at the land surface or buried by less than 15 feet of overburden. Based on the rock types shown on existing bedrock geologic maps, these units have a moderate to high probability of providing material suitable for crushed stone aggregates.

Moderate Potential for Crushed Stone Resources: Granite and other crystalline bedrock buried beneath 15 to 30 feet of overburden. Based on the rock types shown on existing bedrock geologic maps, these units have a moderately low to high probability of providing material suitable for crushed stone aggregates.

Low Potential for Crushed Stone Resources: Granite and other crystalline bedrock buried beneath 30 to 50 feet of overburden. Based on the rock types shown on existing bedrock geologic maps, these units have a low to moderately low probability of providing material suitable for crushed stone aggregates.

BEDROCK GEOLOGY: Most of the bedrock geology shown on this plate is compiled and derived from two Minnesota Geological Survey (MGS) Miscellaneous Map Series published at 1:100,000 scale (Boerboom and others, 1999) and 1:200,000 scale (Jirsa and others, 2003). A small portion of the county not mapped by MGS was delineated for this evaluation using aeromagnetic and County Well Index (CWI) data. For the purposes of mapping crushed stone resources, these bedrock maps are merged and reinterpreted with respect to aggregate potential to produce a generalized bedrock map of the county displayed at a scale of 1:100,000. Therefore, it is important to note that the southern portion of the bedrock geology is displayed at an enlarged scale from the original dataset.

The bedrock units are summarized in terms of rock type, durability, general quality, and overall crushed stone potential. For more detailed geologic descriptions and delineations of bedrock units, refer to the original MGS bedrock maps.

Gr — **Granitic Rock:** Durable coarse-grained, crystalline rock. This bedrock unit combines several granitic, tonalitic, and granodioritic rock formations, which vary in color, composition, and physical properties. The quality is interpreted as high for crushed stone resources. Local occurrences of preferred orientation of larger minerals, large crystal size, shearing, foliation, and elongation of minerals may lower the quality and durability of this unit in some areas. Specific gravity typically ranges from 2.5 to 2.7. This unit combines MGS bedrock map units Pbm, Pfm, Pgr, Phm, Phmu, Piw, Piwu, and Pwi.

Gn — **Gneiss:** Durable medium to coarse-grained, crystalline, metamorphic rock. This bedrock is pinkish-gray that is variably sheared and foliated. However, the quality is broadly interpreted as high for crushed stone resources. Quality and durability are affected by the local extent and degree of metamorphism, which is observed by the orientation of larger mineral grains, shearing, foliation, and mineral elongation. Specific gravity typically ranges from 2.5 to 2.9. This unit combines MGS bedrock map units Apg, Amc, and Amcu.

Mi — **Mafic to Ultramafic Intrusive Rocks:** Contains a variety of minerals and rock types, typically serpentinized peridotite, pyroxenite, hornblendite, diorite, and gabbro with some granodiorite. This quality of this rock is variable depending on dominant lithology; however, quality is broadly interpreted be moderate. Quality and durability improve with larger intrusions, distance from contacts of other rock units, and degree of fracturing within rock. Specific gravity typically ranges from 2.6 to 3.0. This unit combines MGS bedrock map units Pmi, Pp, and Ppu.

Mr — **Metamorphosed Sedimentary Rocks:** Predominantly schist and interpreted to have limited crushed stone potential. Variability of composition and degree of metamorphism all contribute to non-durability and low quality of these rocks. This unit combines MGS bedrock map units Pps and Ppsu.

Sc — **Schist:** Predominantly consists of schist derived from volcanic and sedimentary rocks and is unsound and non-durable rock that is characterized by a high degree of metamorphism. The minerals in schist tend be elongated and easily fractured into flakes and slabs, which contribute to non-durability and low quality. This unit combines MGS bedrock map units Pdam, Psm, and Psv.

Sr — **Sedimentary Rocks:** Poorly lithified sedimentary rocks, which include sandstone, siltstone, and shale. These rocks are friable, contain high clay content, and cleave along bedding planes, which contribute to non-durability and low quality. This unit consists of MGS bedrock map unit C.

Sz — **Shear Zone:** Highly fractured and deformed granitic rock, cut by numerous northeast-trending mafic dikes. The aggregate potential of this unit is limited due to the extent of alteration and shearing. This unit consists of MGS bedrock map unit Psz.

IDENTIFIED CRUSHED STONE RESOURCES: Geographic areas where crushed stone resources have been or are currently being mined. The quarry locations were gathered from topographic maps, aerial photographs, and fieldwork. There were two quarries active in Mille Lacs County during the time of mapping. One quarry is currently mined for dimension stone, the other quarry is currently mined for aggregate. Both quarries are larger than 15 acres.

Crushed Stone Quarry — **Dimension Stone Quarry**

OVERBURDEN MODELING DATA SOURCES: Several data sets are used to model the thickness of overburden in Mille Lacs County: County Well Index (CWI), exploratory drilling, MGS bedrock outcrops from MGS datasets M-100 & M-132, MN DNR field observations of bedrock outcrops, & NRCS-USDA SSURGO bedrock outcrops soil survey data. Located CWI is a published dataset by the Department of Health where the location of the wells have been verified. **Unlocated* CWI is obtained by the DNR and approximately placed to a corresponding address. "Minima" are wells that do not hit bedrock, but help to identify areas where the bedrock is buried by thick overburden.

50 **CWI-Located:** Depth to Bedrock Label	50 **CWI-DNR Located*:** Depth to Bedrock Label
50+ **CWI-Located Minima:** Well Depth Label	50+ **CWI-DNR Located* Minima:** Well Depth Label
50 **Exploratory Drilling:** Depth to Bedrock Label	**Bedrock Outcrops**

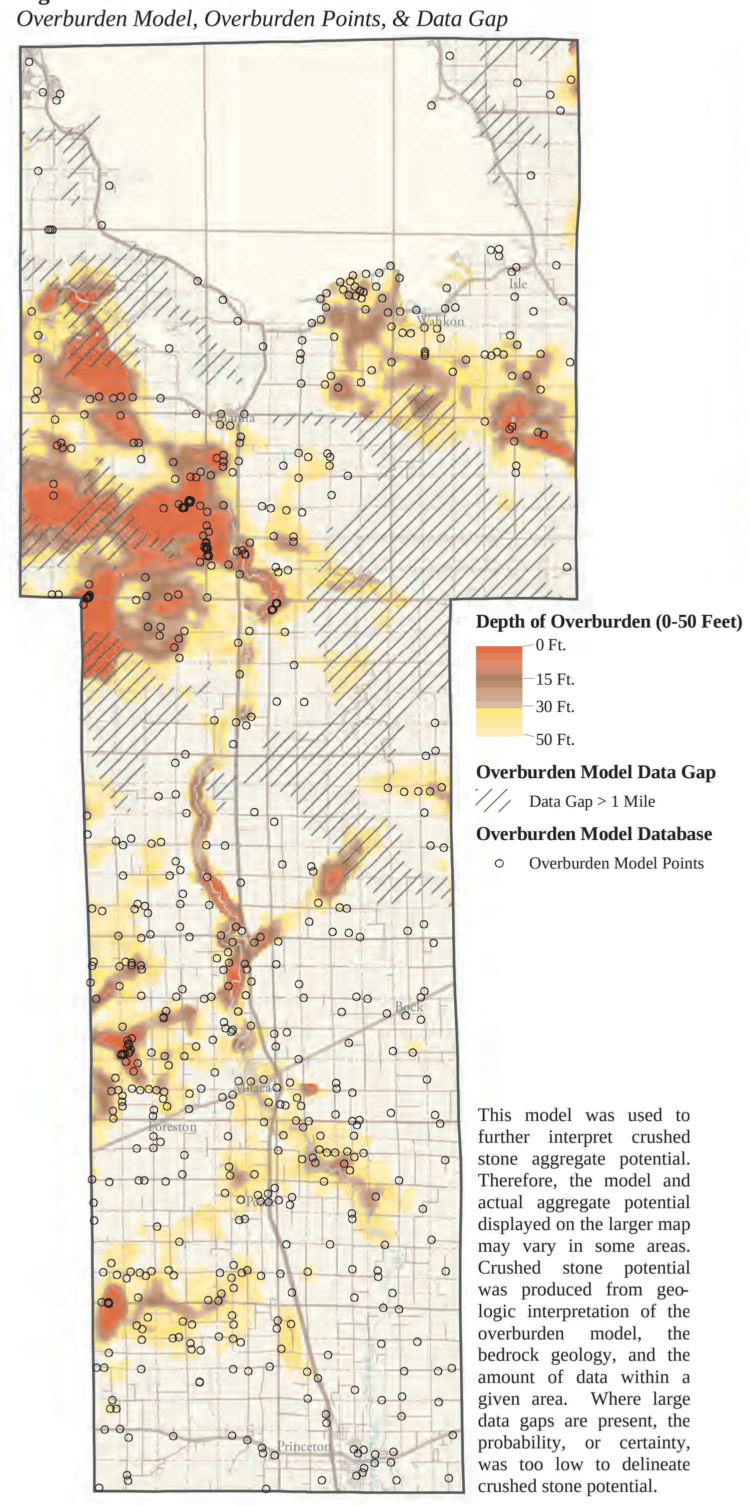
Overburden Data Source Labels are in Feet.

Scale 1:100,000
1 Inch = 1.6 Miles
0 1 2 3 Miles
0 1 2 3 4 5 Kilometers
1 Centimeter = 1 Kilometer

In the North, Crushed Stone Potential is Classified at 1:100,000
In the South, Crushed Stone Potential is Classified at 1:200,000

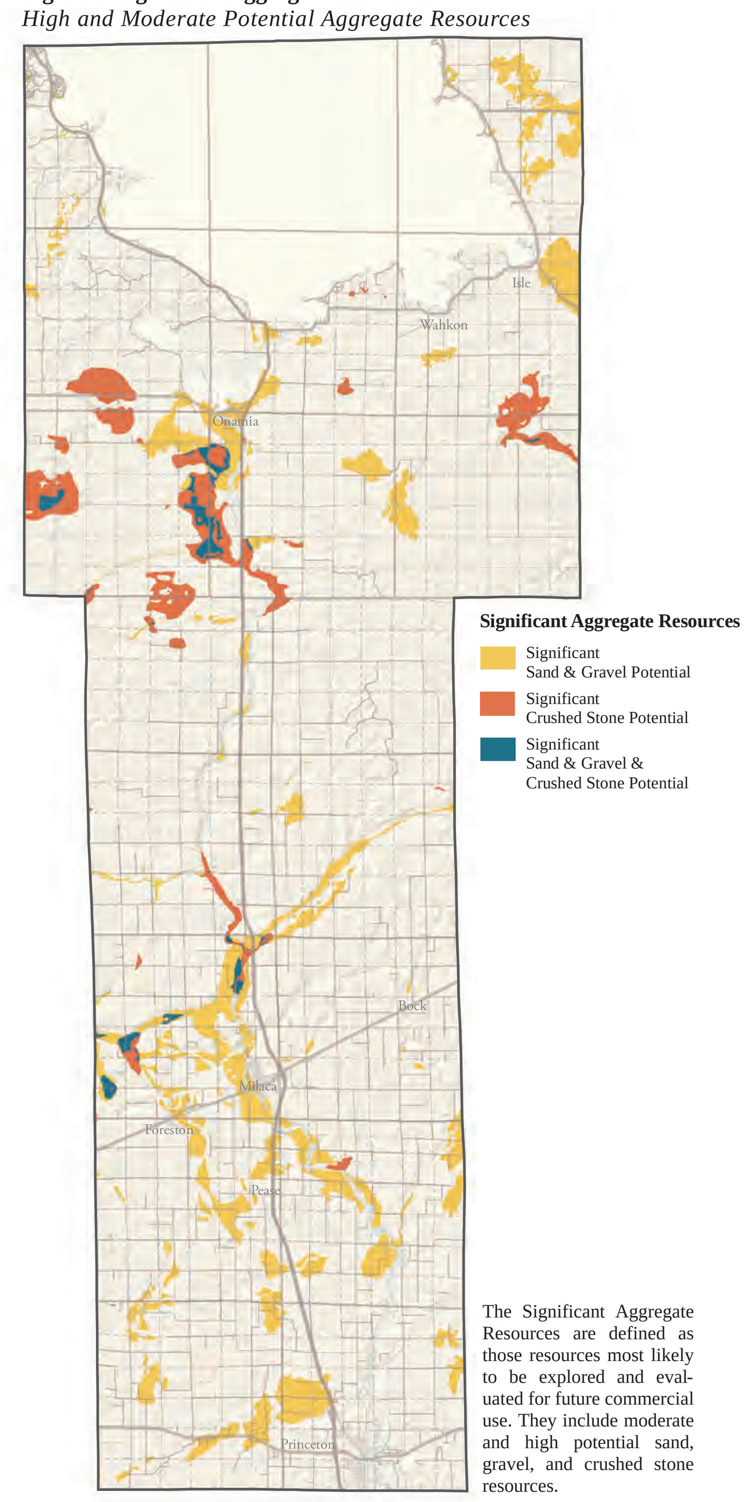
Other Map Symbols
- Lakes, Rivers, and Streams
- Depth to Bedrock/Overburden Contours (50 Ft. Intervals)
- Depth to Bedrock/Overburden Contours (25 Ft. Intervals)
- Cross-Section Line
- Bedrock Scale and Source Boundary
- U.S. Highway
- State Highway
- County Highway
- Other Roads
- Township Boundaries
- Section Boundaries

Figure 1. Overburden Model:
Overburden Model, Overburden Points, & Data Gap



This model was used to further interpret crushed stone aggregate potential. Therefore, the model and actual aggregate potential displayed on the larger map may vary in some areas. Crushed stone potential was produced from geologic interpretation of the overburden model, the bedrock geology, and the amount of data within a given area. Where large data gaps are present, the probability, or certainty, was too low to delineate crushed stone potential.

Figure 2. Significant Aggregate Resources:
High and Moderate Potential Aggregate Resources

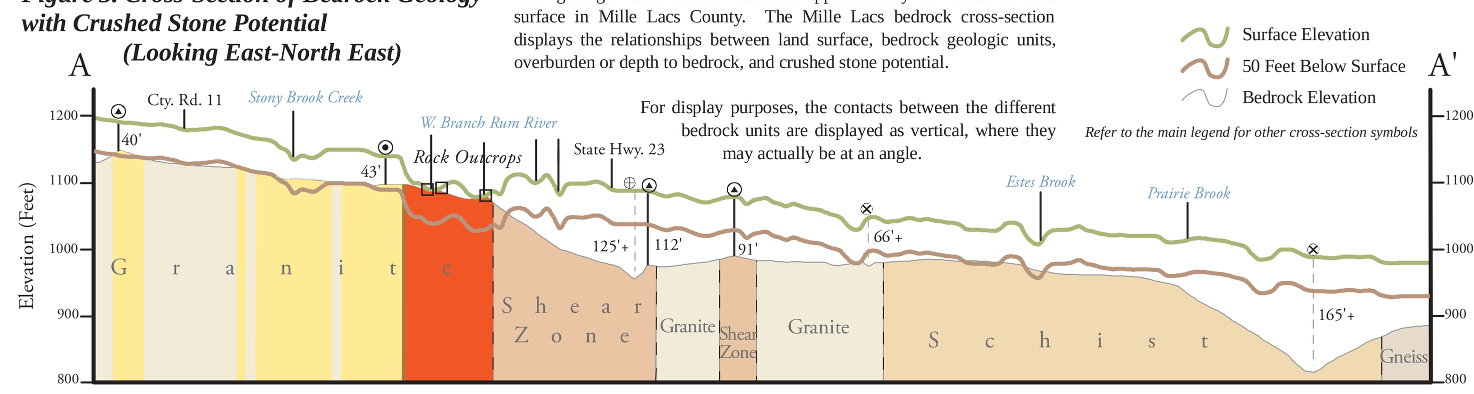


The Significant Aggregate Resources are defined as those resources most likely to be explored and evaluated for future commercial use. They include moderate and high potential sand, gravel, and crushed stone resources.

Figure 3. Cross-Section of Bedrock Geology with Crushed Stone Potential (Looking East-North East)

This geologic cross-section transects approximately 20 miles of land surface in Mille Lacs County. The Mille Lacs bedrock cross-section displays the relationships between land surface, bedrock geologic units, overburden or depth to bedrock, and crushed stone potential.

For display purposes, the contacts between the different bedrock units are displayed as vertical, where they may actually be at an angle.



INTRODUCTION: The purpose of this plate is to display crushed stone resource potential within 50 feet of surface of the earth and to describe this information in terms of crushed stone resource potential at a reconnaissance level. Crushed stone is produced by mechanically breaking down bedrock (granite, quartzite, limestone, etc.) into desired sized particles that have a consistent composition, angular shape, and can meet some of the most stringent specifications for aggregate used in building roads, bridges and airport runways.

Crushed stone resources are not evenly distributed across the state or within a single county. The availability of crushed stone resources depends on (1) the bedrock lithology (quality of the bedrock) and, (2) the overburden thickness. Bedrock lithology refers to the physical and compositional characteristics of different types of bedrock that determine the quality of a bedrock source. For example, granites have the potential to be a hard and durable aggregate source, while schist is soft, flaky, and not durable for an aggregate source. Overburden is a term used to generalize the sediment and rock on top of desired resources.

Reconnaissance-level geologic datasets and interpretations are used to delineate crushed stone potential. These datasets are gathered from a number of sources to determine the quality and depth to bedrock. Information sources range from exposed bedrock outcrops to subsurface water well data. Since this is a reconnaissance-level dataset, additional site-specific information is required to determine the suitability for economic development of a crushed stone quarry site. Site-specific factors to consider include land ownership, the owner's preference, environmental criteria, royalty rates, distance to the market, permitting requirements, and/or cultural and historical significance of the location. Furthermore, the potential within a map unit does not imply that aggregate resources exist everywhere within a given map unit. Crushed stone potential defines an area where geologic evidence exists and is interpreted using a simple analytical model.

METHODOLOGY: Because aggregate resources are mined from the earth, geologic evaluations can determine the location, distribution, and quality of a potential aggregate source. This section describes information sources and mapping techniques used to delineate crushed stone potential (general stages of geologic mapping and data sources are described in Plate A, Methodology Section).

A simple geologic model of evaluation is used to identify bedrock within 50 feet below the ground surface. The model combines compiling bedrock information from several data sources, computer-modeling the depth to bedrock, and interpreting crushed stone potential where durable, high-quality bedrock is located within 50 feet of the ground surface. Information sources include field observation points, County Well Index (CWI), exploratory drilling logs, National Resource Conservation Service (NRCS) bedrock data from soil surveys, Minnesota Geologic Survey (MGS) outcrop data and MGS bedrock geology maps.

CWI is an important data source and accounts for most of the subsurface information used to model depth to bedrock. CWI dataset (www.health.state.mn.us/divs/eh/cwi) is maintained by the Minnesota Department of Health and comes in two levels of data accuracy: *located* and *unlocated*. *Located* CWI data is assumed to be accurately located. *Unlocated* CWI data is used as a source only if the address information on the well log can be verified and located using a number of general information sources: parcel data from the county tax records, address information, and online address location web sites. The well locations are further refined using published county parcel maps, plat maps, air photographs, and road maps. Once the address and parcel location of a well is confirmed, the well is placed near a residential dwelling within the parcel. This method of locating wells is not as accurate as field checking locations using 7.5 Minute USGS Quadrangle maps and/or GPS (Global Positioning Systems). However, for the scope of mapping overburden thickness, the level of accuracy of this dataset is within an acceptable range for delineating crushed stone potential at a reconnaissance level.

To determine the overburden thickness, ArcGIS is used to develop an overburden model seen in figure 1. A total of 830 data points with depth to bedrock information are used in the model. The data points used in the overburden model were calculated using an ordinary kriging method with a spherical semivariagram to produce a 30-meter bedrock elevation grid. To calculate overburden thickness, the modeled bedrock elevation is subtracted from the surface elevation. This calculation captures topographic expressions like hills and valleys better than modeling only depth to bedrock. The model is smoothed using Neighborhood Statistics in Spatial Analyst (ArcGIS 9.2) and contoured in 50-foot intervals.

The model has limitations due to the distribution, number, and general nature of the data sets. Within the dataset, near surface bedrock is captured more frequently due to having outcrop data points and CWI that encounter shallow bedrock. Few wells encounter bedrock at depths greater than 100 feet because groundwater sources are usually discovered in sand and gravel lenses within the glacial overburden. As a result, bedrock peaks are more likely to be captured than the bedrock valleys. The model reflects the lack of data in areas of deeply buried bedrock. As a result, the model skews bedrock elevations higher where deep depth to bedrock information is sparse. To counterbalance this fact, 166 minima are used. Minima are deep wells that do not hit bedrock, but are useful because the depths of those wells extend below the modeled bedrock elevation. Therefore, minima points are integrated into the model to "sink" bedrock elevations where known discrepancies occur.

Accuracy of the model depends on the density of data points. The more data points, the greater the certainty that the model reflects the real world. In Mille Lacs County, large tracts of land contain no information about depth to bedrock. The land tracts tend to be large wetlands, lakes, or publicly owned land. The lack of information in these areas creates data gaps. To spatially define all data gaps, data points are buffered with a one-mile radius. The data gap layer displays where no data points exist within a minimum distance of one mile.

To determine the quality of bedrock in terms of crushed stone potential, a generalized bedrock map is compiled and based on bedrock information from two Minnesota Geological Survey miscellaneous map series: "Bedrock Geology of Mille Lacs 30 x 60 Minute Quadrangle (1:100,000, Boerboom and others, 1999)" and "Bedrock Geology and Superimposed Magnetic on Gravity Anomaly for East-Central Minnesota (1:200,000, Jirsa and others, 2003)." Bedrock units are recombined on the basis of general composition, foliation, and degree of shear and mineral alteration. The generalized bedrock map represents the spatial extent of combined bedrock map units. It is important to note that the bedrock base maps used to interpret quality of crushed stone resources are at two different scales. As a result, crushed stone potential is delineated and mapped at 1:100,000 in the north and 1:200,000 in the south (see Crushed Stone Data Source inset).

The final determination of crushed stone potential integrates all sources of information: the overburden thickness model, lithologic categorization of bedrock units, the location of data gaps, and geologic interpretations. In general, the model was conservatively reinterpreted and crushed stone potential was not delineated in data gap areas. Also, potential was characterized on degree of certainty.

The results of the aggregate mapping for crushed stone resources indicate potential for several near surface resources of high-quality bedrock lithologies located in Mille Lacs County. The potential of these areas are classified: high with 0 – 15 feet of overburden, moderate with 15 – 30 feet of overburden, low with 30 – 50 feet of overburden, and limited with greater than 50 feet of overburden. Significant Aggregate Resources are defined as those with high and moderate potential displayed in figure 2.

CLASSIFICATION OF CRUSHED STONE POTENTIAL

The crushed stone potential of Mille Lacs County were divided into four categories: 1) high potential for crushed stone resources, 2) moderate potential for crushed stone resources, 3) low potential for crushed stone resources, and 4) limited potential for crushed stone resources.

The crushed stone resources were divided into these categories based on the bedrock lithology (quality), depth to bedrock, and probability or certainty that the resource exists (See Table 1). The areas identified as limited potential for crushed stone resources, did not meet the above mentioned criteria.

Table 1: Classifcation Matrix of Crushed Stone Potential Used for Mille Lacs County

Characteristics	Potential Rating			
	High	Moderate	Low	Limited
Bedrock Lithology	Granite and other crystalline bedrock formations	Granite and other crystalline bedrock formations	Granite and other crystalline bedrock formations	Sedimentary rocks, metamorphic sedimentary rocks, schist, and shear zones
Depth to Bedrock	0 to 15 Feet	15 to 30 Feet	30 to 50 Feet	Greater than 50 Feet
Probability[1]	Moderate to high	Moderately low to high	Low to moderately low	Very low to moderately low

[1]*Probability* : The degree of certainty that aggregate exists within a mapping unit

General References
Boerboom, T.J., Severson, M.J., and Southwick, D.L., 1999, Bedrock geology of the Mille Lacs 30 x 60 minute quadrangle, east-central Minnesota, Minnesota Geological Survey, Report M-100 Plate 1 and 2, scale 1:100,000.
Ellingson, B.E., 2002, Aggregate Resources, Benton County, Minnesota Department of Natural Resources, Division of Lands and Minerals, Report 356, Plates I, II, III, and IV.
Jirsa, M.A., Chandler, V.W., Lively, R.S., and Boerboom, T.J., 2003. Maps of bedrock geology and superimposed magnetic on gravity (SMOG) anomaly for East-central Minnesota, Minnesota Geological Survey, Report M-132, scale 1:200,000.

Mapping and Cartographic Sources:
Bedrock geology and bedrock model interpretation, fieldwork, and delineation of mapping units by Heather Arends, 2006. Overburden modeling, bedrock geology geoprocessing, bedrock geology cross-section, and locating the County Well Index *unlocated* points by Kevin Hanson, 2006. Remote sensing sources were; 2003-2005 aerial photographs from NAPP (National Aerial Photography Program), 1991-1992, 9" x 9" color infrared photos at 1:40,000: DOQs (Digital Orthophoto Quadrangles) at 1:12,000. Other mapping sources include; DRGs (Digital Raster Graphics) at 1:24,000 from USGS; 7.5-minute USGS topographic quadrangles at 1:24,000 (dating from 1964-1992), USGS (United State Geological Survey) National Elevation Dataset's 1-arc second (30m) DEM, and where available 1/3-arc second (10m) DEM (Digital Elevation Model), and MGS Minnesota aeromagnetic grid (+/- 50 Meters horizontal accuracy) with micro-leveling (dating from 1961-1991).

Cartography by Kevin Hanson. GIS database design and processing by Kevin Hanson, Renee Johnson, and Heather Arends. Field and drilling assistance by Ricco Riihiluoma, Doug Rosnau and Pat Geiselman. Copy editing assistance by Nicholas Kroska.

Base Map Data Sources:
Contours compiled from processing the overburden model with a base surface layer from the USGS (United State Geological Survey) National Elevation Dataset's 1-arc second (30m) DEM, and where available 1/3-arc second (10m) DEM (Digital Elevation Model).
Lakes and rivers from National Wetland Inventory, U.S. Fish and Wildlife Service, compiled at 1:24,000 from aerial photography (1979-1988) and spot field checked.
Public Land Survey from PLS Project, 2001, Minnesota Department of Natural Resources, Division of Lands and Minerals.
Roads from MN/DOT BaseMap 2001- Roads, Minnesota Department of Transportation, BaseMap Development Group, Surveying and Mapping Section.
Civil Townships and Municipal Boundaries from MN/DOT Basemap 2001 - Civiltwp and Muni, Minnesota Department of Transportation, BaseMap Development Group, Surveying and Mapping Section.

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Mineral Diversification projects are determined by a committee composed of Governor-appointed members from the public and private sectors.

Products of this project include a CD/ROM of maps, data, and metadata in a digital format and the following plates:
Plate A, Report 366, Mille Lacs County Sand & Gravel Potential & *Plate B, Report 366, Mille Lacs County Crushed Stone Potential*