GIS application in mineral resource analysis—A case study of offshore marine placer gold at Nome, Alaska

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Abstract

Geographic information system (GIS) technology has been applied to analyze the offshore marine placer gold deposits at Nome, Alaska. Two geodatabases, namely Integrated Geodatabase (IG) and Regularized 2.5D Geodatabase (R2.5DG), were created to store and integrate digital data sets in heterogeneous formats. The IG served as a data warehouse and used to manage various geological data, such as borehole, bedrock geology, surficial geology, and geochemical data. The R2.5DG was generated based on the IG and could be used for gold resource estimate at any given spatial domain. Information on placer gold deposits can be updated, queried, visualized, and analyzed by making use of these geodatabases. Ore body boundaries, gold distribution, and the resource estimation at various cutoff grades can be calculated in a timely manner. Based on the enhanced GIS architecture, a web-based GIS (http://uaf-db.uaf.edu/website/) was developed to facilitate remote users to access the offshore marine placer gold data. Users can integrate local data sources with remote data sources for query, visualization and analysis via a web browser. The GIS architecture developed in this project can be readily adapted to mineral resource management in other areas of the state.

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1. Introduction

Miners, geologists, and engineers have been dealing with problems related to the analysis and manipulation of geo-referenced information (i.e. spatial data) for many decades. Conventionally, analog maps are used to store and display such information. A major component of many geological surveys consists of mapping the composition and structure of bedrock and surficial geology using traditional field methods as well as geochemical, geophysical and remote-sensing techniques. Integration of field survey data, maps, and other pertinent information for the purpose of mineral resource exploration and resource estimation is a very time-consuming task. However, geographic information systems (GIS) can accomplish such a task in a time-efficient and cost-effective manner. A GIS is a computer system capable of assembling, storing, manipulating, and displaying geographically referenced information, i.e. data identified according to their locations (USGS web site). Practitioners also regard the total GIS as including operating personnel and the data that go into the system. With the

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increasing popularity and functional development of GIS in recent years, many mining companies started using GIS as the preferred tool for mine planning, analysis, and management. Moreover, the state and federal agencies involved in the mine permitting process are adopting the GIS format as the standard for communicating spatial data.

Abundant beach and offshore resources of heavy refractory minerals occur along the coast of Alaska. Nome, for example, is one of the most recently active areas of marine and beach placer mining in the State of Alaska (Koschmann and Bergendahl, 1968; Garnett, 2000). From as early as 1897–1962, the Nome area produced about 5 million ounces of gold (Koschmann and Bergendahl, 1968). Because of the huge amount of data in variety of forms accumulated from placer gold exploration and production over the past century, the analysis and management of these data for future development of the Nome offshore gold resource is an enormous task. GIS technology is a tool well suited to meet this challenge. First, GIS technology facilitates building and maintaining geodatabases for the project. A geodatabase is an object-oriented data model that represents geographic features and attributes as objects and the relationships between objects but is hosted inside a relational database management system. A geodatabase can store objects, such as feature classes, feature data sets, non-spatial tables, and relationship classes (ESRI, 2004a). Data queries, analysis, and visualization can be then carried out based on these geodatabases (Bonham-Carter, 1994). Such an approach to data management provides an in-depth understanding of the Nome offshore gold deposit, which, in turn, will greatly assist the development of the offshore gold resource.

In the Nome Offshore Marine Mineral Resources Project, two relational geodatabases for storing various maps integrated with digital data sets have been created. A relational geodatabase is a method of structuring data as collections of tables that are logically associated with each other by shared attributes. Any data element can be found in a relation by knowing the name of the table, the attribute (column) name, and the value of the primary key (ESRI, 2004a). One geodatabase is known as the Integrated Geodatabase (IG). It serves as a data warehouse and stores all the relevant data that could possibly be collected in the Nome area, such as borehole data, bedrock geology, surficial geology, and geochemical data. Another geodatabase, known as the Regularized 2.5D Geodatabase (R2.5DG), has been generated based on the IG. The R2.5DG is used to define orebody boundaries, perform grade interpolation, and estimate the resource at any given spatial domain. In addition, specialized GIS models can be developed from these geodatabases to meet the various needs of a project.

The GIS procedure developed in this project can be readily adapted for the analysis of offshore marine mineral data in other areas. This procedure also enables web-based GIS, which can be used by authorized users from remote computers.

2. Data collection

Data collected in this study has been gathered from private records held by mining and exploration companies, published professional literature, reports from engineering firms, maps and open file reports from government agencies, documents from recording offices, and information through the Internet. One large set of data, including databases and documents, is from government agencies, such as USBM (United States Bureau of Mines), ADNR (Alaska Department of Natural Resources), USGS (United States Geological Survey), and NOAA (National Oceanic and Atmosphere Administration). Another large set of data is from WestGold Exploration Mining Company, Limited Partnership (WestGold). WestGold operated the bucketline dredge from 1985 to 1990 (Howkins, 1992). During the summers of 1986 and 1987, WestGold carried out 3400 line km of high-resolution seismic surveys of the lease area. Seismic data were interpreted to provide facies interfaces and thicknesses, allowing faulting to be identified and profiles to be drawn. Simultaneous side scan sonar surveys, with a 3-mm penetration, were used to map sediment type on the seafloor. From 1987 to 1989, WestGold completed 2530 holes and collected 57 bulk samples. Each hole was drilled in 1-m increments. The sediment from each 1-m interval was collected and stored, a brief sediment description was recorded and the gold content was assayed (Bronston, 1989).

Data files from 3468 drill holes in the offshore area at Nome were reformatted and complied. These file types are the principal sources of information for this project (Huang et al., 2001). Most drill hole logs record lithology, gold concentration value, and penetration blow count. Blow count data, the number of blows needed to drive each barrel through a sample length of 30 cm,
provides sediment hardness information. A geologic key describes lithologic types intercepted. Gold concentration values are tabulated in oz/m³ and oz/yd³, along with “normalized” and “intensity” values. The normalized value is the relative gold concentration as compared with a reference gold concentration. The intensity value shows normalized gold values (from 0 to 45) as 9 even intervals with intensity 9 signifying highest gold concentration.

The authors then re-compiled and integrated the information to better understand the geologic characteristics, geochemical and geophysical signatures, borehole data, economic considerations, oceanographic factors, submarine topography, and potential environmental impacts.

2.1. Geology of Nome area

Because of the extent and richness of the Nome gold resources, the area was studied extensively, and geological, geophysical, and geochemical characteristics of offshore gold deposits were well documented in the published literature. Various aspects of geology of the Nome placer deposits onshore and offshore have been described by Nelson and Hopkins (1972), and Bronston (1990).

There are 22 metasedimentary, metavolcanic, and metaplutonic bedrock units in the area. The Nome Group is a series of four lithostratigraphic units that are locally deformed by low-angle thrust faults. The Nome Group consists of the following four subunits (Bundtzen et al., 1994):

1. a basal, complexly deformed quartz-rich pelitic schist,
2. a unit of mafic and pelitic schists and marble,
3. a mafic-dominated schist assemblage, and
4. a dirty marble (Bundtzen et al., 1994).

The bedrock topography (Pleistocene–Pliocene contact) was interpreted from high-resolution seismic survey (Bronston, 1990).

Extensive faulting in the Precambrian basement rock displaced the Pliocene sediments, producing an asymmetrical, concave trough synform, which plunges to the south. The east–west trending fault, which is named the “basin boundary fault” (Bronston, 1990), delineates the northern extent of the synform. Numerous smaller faults strike northeast and northwest at various angles to the basin boundary fault.

2.2. Offshore geology

Nome, Alaska is located on the southern coastline of the Seward Peninsula, on the northern coast of Norton Sound, which is a part of the northeastern Bering Sea (Fig. 1). Gold is abundant offshore (Koschmann and Bergendahl, 1968; Garnett, 2000) at Nome because fluvial and glacial processes transported gold from gold-enriched bedrock in the uplands into the marine environment where it was further concentrated by wave and current action. The USGS and USBM have summarized much of the geology of the area (Nelson and Hopkins, 1972; Tagg and Greene 1973).

2.3. Offshore sediment lithology

The lithologies of offshore sediments in the Nome area include arenites and gravels composed of red granite and quartz monzonite (Howkins, 1992). Fine-grained marine sediments deeply bury offshore bedrock east of Nome. Offshore bedrock is just below the sea bottom to the west. Fig. 2 shows a lithologic map of the offshore sediments.

2.4. Glaciation Events

Moraine deposits from glacier activity covers most of the area (Fig. 3), the most extensive of which is a surface drift sheet deposited during the Nome River glaciation period of the middle Pleistocene (Bundtzen et al., 1994). Subsequent periods (Stewart River, Salmon Lake, and Mount Osborn glaciations) were less extensive and restricted to higher elevations and mountain valleys (Howkins, 1992).

According to Nelson and Hopkins (1972) glaciers have advanced past the present Nome coast at least twice (the early Pleistocene, and Illinoian glaciations). These glacial activities resulted in the emergent beach deposits in the Nome area being a major source of placer gold by eroding and concentrating gold from bedrock.

2.4.1. Economic geology

Gold in the Nome area was sourced originally from gold–polymetallic–quartz–carbonate veins, stratiform, massive sulfide–barite deposits associated with felsic metavolcanic schist and metafelsite centers, massive sulfide–iron deposits hosted in carbonate-dominated terranes of uncertain origin,
Fig. 1. Location of Nome, Alaska (modified from http://maps.yahoo.com/).

Fig. 2. Lithologic map of the ocean floor off the coast of Nome (surficial geology digitized from Howkins, 1992).
and heavy mineral placer deposits (Boyle, 1979). These materials were transported via streams and glaciers to a coastal environment, and subsequently concentrated in the marine and near-marine environments.

The formation of offshore gold deposits at Nome might be divided in three stages. During the first stages, lean gold gravels were deposited along the margins of the Bering Sea as stream deltas and fans. The next stage involved the coastal uplift. After uplift, the new beach was subjected to erosion by ocean wave, and gold-rich gravels became more concentrated. The final stage deals with the concept that glaciation could lead to concentration of gold, as is seen in Nome. As glaciers moved, gold segregated from the sediments carried by glaciers due to its high density. According to the concentration processes in these three stages, other placers in areas of heavy glaciation, especially valleys covered in glacial sediment may prove to be worthwhile exploration targets (Boyle, 1979).

3. Development of geodatabases

A considerable amount of data in map, image and tabular formats were collected, complied, and integrated. These data were further processed and structured into an IG. Database is strictly defined as
one or more structured sets of persistent data, managed and stored as a unit and generally associated with software to update and query the data (Litton, 1987; Navathe and Elmasri, 2002; Date, 2003). A geodatabase in GIS includes data about the spatial locations and shapes of geographic features recorded as points, lines, areas, pixels, grid cells, or TINs, as well as their attributes. A geodatabase is a collection of geographic data sets for use by ArcGIS (ESRI, 2004a).

The IG in this project stores all data that are related to the placer gold deposits that possibly could be collected in the Nome area, such as borehole, bedrock geology, surficial geology, and geochemical data. The IG is good for data management and information query. In order to facilitate resource estimation of the placer gold in the Nome area, another geodatabase known as R2.5DG was created. The two geodatabases are relational databases in which each item and its attributes are linked and related (cross-referenced) to every other item and its attributes. The flowchart in Fig. 4 shows the conceptual GIS model of this project. Detailed discussions are given in the following sections. Building database is the primary task of the project.

### 3.1. Building the integrated geodatabase

Geodatabase is a container for storing spatial and attribute data as well as the relationships among them (ESRI, 2004a). It manages the same types of geographic information in a relational database management system (RDBMS) using programs, such as DB2, Informix, Oracle, SQL Server, or MS Access database. MS Access was used to create the geodatabases in this project. However, MS Access only supports a simplified geodatabase that cannot store raster data. Therefore, most of the spatial data layers and non-spatial tables collected are stored in the geodatabase known as IG. Table 1 lists the feature classes stored in the IG. A geodatabase feature class stores text or graphics that provide additional information about features or general areas of a map (ESRI, 2004b).

The IG was created using the functions in Microsoft (MS) Access, ArcMap, and ArcCatalog. The following four tasks were performed using MS Access:

1. The borehole location data was imported into MS Access and integrated to form a borehole location information table.
2. The borehole layered lithologies and gold value logs were imported and integrated to form

<table>
<thead>
<tr>
<th>Feature class</th>
<th>Feature type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DH_location</td>
<td>Table</td>
<td>Drill hole location info</td>
</tr>
<tr>
<td>DH_segmentinfo</td>
<td>Table</td>
<td>Borehole segment attributes</td>
</tr>
<tr>
<td>DH_sliceinfo</td>
<td>Table</td>
<td>Layered orebody information</td>
</tr>
<tr>
<td>GeoDH_sliceinfo</td>
<td>Point</td>
<td>Layered orebody information</td>
</tr>
<tr>
<td>Lith_slice_Poly</td>
<td>Polygon</td>
<td>Layered lithology</td>
</tr>
<tr>
<td>OnshoreGeo</td>
<td>Polygon</td>
<td>Onshore geology</td>
</tr>
<tr>
<td>OffshoreGeo</td>
<td>Polygon</td>
<td>Ocean floor geology</td>
</tr>
<tr>
<td>Structure</td>
<td>Polygon</td>
<td>Offshore sediment structure elements</td>
</tr>
<tr>
<td>Permitblk</td>
<td>Polygon</td>
<td>Exploration permit blocks</td>
</tr>
<tr>
<td>Rivers</td>
<td>Polygon</td>
<td>Rivers, town and roads of Nome</td>
</tr>
<tr>
<td>Study area</td>
<td>Polygon</td>
<td>Study area boundary</td>
</tr>
</tbody>
</table>

Fig. 4. Conceptual GIS architecture of the project.
a borehole segment attributes table. Both metric and imperial systems were used for gold content for the convenience of the database users.

3. The calculation of average gold grades for a single borehole based on various criteria is a crucial task in this study. Since orebody boundaries are different at various specified planes and cutoff grades, their associated thickness and average grade also are different. The specified planes in this study are either parallel to the sea level ($C_0_{18}$, $C_0_{20}$, $C_0_{22}$, $C_0_{24}$, $C_0_{26}$, $C_0_{28}$, $C_0_{30}$, $C_0_{42}$ m) or to the sea floor ($C_0_{1}$, $C_0_{2}$, $C_0_{4}$, $C_0_{6}$, $C_0_{8}$, $C_0_{10}$, $C_0_{12}$, $C_0_{14}$, $C_0_{27}$ m). The selection of the above intervals was based on the consideration of average sea floor depth and average borehole depth in the study area, as well as the balance between precision and computer capacity. The calculations are performed repetitively in MS Access using SQL language, based on segment records stored in the borehole segment information table (DH_segmentinfo) in the IG. The calculated average grades and thickness at various layers form the layered orebody information table (DH_sliceinfo). Detailed information on the procedure of average grade calculations can be found in Table 2.

4. The above two tables are linked by a related field, i.e. borehole ID in this case, to create the relationships in the IG.

The two tables created in the steps 2 and 3 contain no spatial data sets, i.e. there are no spatial attributes, such $X$, $Y$ coordinates or longitude and latitude. A new spatial feature layer could be created in a shape file format based on the coordinate information stored in the drill hole location table using ArcMap, and then the new spatial data set could be converted into a geodatabase file. A shape file in ArcGIS is a vector data storage format for storing the location, shape, and attributes of geographic features (ESRI, 2004b). To achieve this, the following three tasks were performed using ArcMap:

(1) A borehole distribution map (i.e. a drill hole layer in ArcMap) was created based on the borehole location information table.

(2) The layered orebody information table was related to the drill hole layer by related field of borehole ID.

(3) The above layer was exported to a geodatabase (Nome_ori_GDB.mdb) in the form of feature class named GeoDH_sliceinfo.

This GeoDH_sliceinfo geodatabase feature class file is compatible with both ArcGIS and MS Access. The attributes of GeoDH_sliceinfo table include all of those attributes in both tables—the borehole location information table and the layered orebody information table.

In addition, existing ArcInfo shape files and coverage files (onshore geology, and permit block) were converted into the IG (Nome_ori_GDB.mdb) using the Import tool in ArcCatalog. Coverages are data models for storing geographic features (ESRI, 2004b). Several new feature classes (offshore geology, structure element, rivers and study area) were also created using ArcCatalog and edited using ArcMap. ArcScan, another application program of

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### Table 2

Partial listing of field attributes of DH_sliceinfo

<table>
<thead>
<tr>
<th>Field name</th>
<th>Data type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHID</td>
<td>Number</td>
<td>Serial number of drillhole ID</td>
</tr>
<tr>
<td>Seafloor_depth</td>
<td>Number</td>
<td>Depth of sea floor from sea level</td>
</tr>
<tr>
<td>Ore_begin</td>
<td>Number</td>
<td>Starting depth of orebody $(g &gt; 1 \text{ mg/m}^3)$</td>
</tr>
<tr>
<td>Ore_end</td>
<td>Number</td>
<td>Ending depth of orebody $(g &gt; 1 \text{ mg/m}^3)$</td>
</tr>
<tr>
<td>Ore_Thickn</td>
<td>Number</td>
<td>$\Sigma(\text{content} \times \text{thickness})/(\text{Ore_Thickn})(\text{mg/m}^3)$</td>
</tr>
<tr>
<td>Ave_OZCM</td>
<td>Number</td>
<td>Orebody parameter above $-18 \text{ m sea level}$</td>
</tr>
<tr>
<td>Ore_begin18</td>
<td>Number</td>
<td>Orebody parameter above $18 \text{ m sea level}$</td>
</tr>
<tr>
<td>Ore_Thickn18</td>
<td>Number</td>
<td>$\Sigma(\text{content} \times \text{thickness})$ At above $-18 \text{ m sea level}$</td>
</tr>
<tr>
<td>Ave_18</td>
<td>Number</td>
<td>Orebody above $-20 \text{ m sea level}$</td>
</tr>
<tr>
<td>Ore_begin20</td>
<td>Number</td>
<td>Orebody above $20 \text{ m sea level}$</td>
</tr>
<tr>
<td>Ore_end20</td>
<td>Number</td>
<td>Orebody above $-20 \text{ m sea level}$</td>
</tr>
<tr>
<td>Ore_Thickn20</td>
<td>Number</td>
<td>Orebody above $20 \text{ m sea level}$</td>
</tr>
<tr>
<td>GH18</td>
<td>Number</td>
<td>Gold concentration on the plane $2 \text{ m under sea floor}$</td>
</tr>
<tr>
<td>Undersea_floor2m_g</td>
<td>Number</td>
<td>Gold concentration on the plane $4 \text{ m under sea floor}$</td>
</tr>
<tr>
<td>Lith8m</td>
<td>Text</td>
<td>Lithology on the plane $8 \text{ m under sea level}$</td>
</tr>
<tr>
<td>Lith12m</td>
<td>Text</td>
<td>Lithology on the plane $12 \text{ m under sea level}$</td>
</tr>
</tbody>
</table>

Field counts = 84; Records counts = 3468
ArcGIS, was used to vectorize the scanned image of paper maps.

3.2. Building a Regularized 2.5D Geodatabase

The IG is capable of performing GIS analyses using a number of ArcGIS extensions, such as 3D Analyst, Geostatistics Analyst, and Spatial Analyst. 3D Analyst is a 3D visualization and analysis extension of ArcGIS (ESRI, 2004c). 3D Analyst allows one to perform surface creation and analysis tasks. It, however, does not have the capability for solid 3D analyses and cannot yield information on volume calculation and resource estimation. In order to be able to perform resource estimation, a quasi-3D geodatabase, namely a Regularized 2.5D Geodatabase (R2.5DG), was developed by subdividing the study area into cells. The R2.5G is able to define orebody boundaries, perform grade extrapolation, and estimate the resource at any given spatial domain.

Within approximately 40.43 km² of the entire study area, a total of 3468 drill holes spaced from 50 to 120 m apart, are distributed irregularly. To develop the regularized geodatabase, the area was divided into 10 × 10 m grids, forming 404 319 spatial records with one record for each cell. Obviously, the finer the grid is and the more precise the result is. On the other hand, however, it would need more storage on the computer and take longer time to perform ore resource estimation. For the purpose of this project, a 10 × 10 m grid is sufficient for the precision and yet time efficient to perform ore resource estimation.

Orebody attribute data in the GeoDH_slicesinfo feature class was utilized to build surface models. For each cross section, three surfaces are generated: orebody upper boundary, orebody lower boundary, and a hypothetical gold concentration surfaces (Fig. 5). The orebody boundary surfaces are generated by interpolation using Natural Neighbor method, and the gold concentration surfaces are generated by the Inverse Distance Weighted (IDW) interpolation method. The choice of interpolation method was based on the comparative analysis of interpolation methods, which will be discussed in the Resource Estimation section.

These surfaces were converted into 10 m × 10 m cell size grid files, and then saved as personal geodatabase layers in the R2.5DG. A personal geodatabase is a geodatabase that stores data in a single-user relational database management system. A personal geodatabase can be read simultaneously by several users, but only one user at a time can write data into it (ESRI, 2004a). The R2.5DG was formed by integrating all personal geodatabase layers together based on spatial locations in ArcMap.

4. Case study—Nome offshore gold resource analysis

There is much potential in GIS technology for marine mineral resource analysis. Some useful and powerful functions in the ArcGIS have been utilized to query, analyze, and visualize the data, and to provide useful information for mining industry.

Fig. 5. 3D drill holes and ore body boundaries.
4.1. Relational database query

The geodatabases constructed supports the storage and analysis of geo-referenced data. The relational database management system (RDBMS) allows flexible data extraction, called a “query”, with a single criterion or multiple criteria, based on Structured Query Language (SQL). The geodatabase, however, is more than RDBMS. It can store and manage the geographic data, as well as implement logic operations, for example, building relationships between data types, such as topologies and geometric networks, validating data, and controlling access.

The two geodatabases built around this project are relational. Since a relationship was constructed so that each item and its attributes are linked and related (cross-referenced) to every other item and its attributes (Davis, 1996), significant advantages exist in a simple data table. Simple and complex queries can be linked to spatial objects. Various queries, such as drill hole information query and multi-variable query of gold resource, can be performed through these geodatabases. With a single click on the drill hole distribution map, a pop-up window will list all the information about that borehole in tabular format. Multi-variable query can be conducted by drawing a polygon with a mouse. A pop-up window of the polygon area will show information on selected drill holes, resource estimation, as well as statistical characteristics of the selected area (Fig. 6).

4.2. Data visualization

Visualization is the presentation of data in graphic format. Graphics provide the most intuitive representation of the data, while a detailed numerical table is useful for in-depth analysis.

The 3D drill hole plots with orebody boundaries (Fig. 5) can be created using ArcScene, an application program of ArcGIS. Vertical cross-sectional orebody profiles can be created by using 3D Analyst (Fig. 7) along any defined polyline for each grid layer, based on parameters, such as gold grade, gold deposit thickness, sea floor elevation and others. Such profiles provide useful information for mining operation design. For example, it is often necessary to compare the distribution of an orebody with the distribution and characteristics of bedrock and sediments along vertical cross-sectional profiles.

4.3. Sediment data analysis

The sediment type of each sample segment of drill hole was examined in the laboratory and recorded in original drill hole log. Nine sediment types were classified. Table 3 lists the criteria for sediment classification and code assignments.

Based on the depositional environment, Howkins (1992) divided the sediment facies of Nome offshore into five major facies groups—diamict, gravel, sand, mud and peculiar facies. To determine the horizontal and vertical distribution of sediments, layered lithology Thiessen polygon feature classes (Lith_slice_Poly) were created from layered lithology point feature classes (DH_sliceinfo) using ArcInfo and stored into the IG. A series of layered sediment distribution maps were then created using ArcGIS at various levels parallel to sea surface level (−8, −12, −16, −20, −24, −28 m) and parallel to sea floor level (−1, −4, −8, −12 m) to illustrate the changes in the sediment with depth. The distribution

![Fig. 6. Procedure of information query on gold resource within a selected polygon area.](image-url)
of sediments is closely related to surfical geology when, comparing the ocean floor lithologic map (Fig. 2) with sediment distribution map at 1 m below the sea floor (Fig. 8) generated from drill hole data in this study.

4.4. Gold distribution analysis

4.4.1. Gold distribution with sediment type

The proportions of gold mineralization of each sediment type vary from 5% to 70%. Over 70% of bedrock samples are mineralized. The high percentage mineralization of bedrock is in part due to the fact that the sample locations are at the interface of bedrock and diamict, where the particulates of gold have a higher chance to deposit immediately during transport. For other eight sediment types besides bedrock, from finer sediments (MUD, SAN) to coarser sediments (DIA, WAD), the percentages of mineralization decreases from 37.5% to 5%. This indicates that marine transgression and the erosion of gold-bearing glacial debris are reasons for gold dissemination.

The average gold contents of each sediment type are calculated with non-mineralized samples included. The results can be divided to two groups: The coarser grain sediments, i.e. SAG, CRD, DIA, SWD, WAD, have higher gold contents ranging from 220 to 309 mg/m³, and the finer grain sediments, i.e. MUD, SAM and SAN, have lower gold contents ranging from 119 to 154 mg/m³. 

<table>
<thead>
<tr>
<th>Number code</th>
<th>Text code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MUD</td>
<td>Mud; silt and clay any mixture, may contain a trace of sand but no more than 5%</td>
</tr>
<tr>
<td>2</td>
<td>SAM</td>
<td>Sandy mud; silt/clay coating sand grains, may be cohesive</td>
</tr>
<tr>
<td>3</td>
<td>SAN</td>
<td>Sand; clean sand may have a trace of silt/clay, not enough to coat the grains, no more than 5%</td>
</tr>
<tr>
<td>4</td>
<td>SAG</td>
<td>Sand and gravel; mixture of sand and gravel, may have a trace of silt/clay in the water but not enough to coat the grains, friable</td>
</tr>
<tr>
<td>5</td>
<td>SWD</td>
<td>Slightly washed diamict; silt/clay, sand and gravel. Silt/clay enough to coat the grains. The mixture is moderately cohesive but will crumble (forms a crumbly ball)</td>
</tr>
<tr>
<td>6</td>
<td>DIA</td>
<td>Diamict; silt/clay, sand and gravel. Enough silt/clay to form a cohesive matrix (for a firm ball)</td>
</tr>
<tr>
<td>7</td>
<td>CRD</td>
<td>Clay-rich diamict; silt/clay with 10–20% sand and pebbles. Appears to be a mud with rock fragments within its matrix (sticky and cohesive)</td>
</tr>
<tr>
<td>8</td>
<td>WAD</td>
<td>Washed diamict; sand, gravel, silt and clay, silt/clay enough to coat the grains, but does not give it cohesion (cannot form a ball)</td>
</tr>
<tr>
<td>9</td>
<td>BER</td>
<td>Bedrock; angular fresh rock chips of one rock type, associated with high blow counts and little penetration</td>
</tr>
</tbody>
</table>

Fig. 7. Vertical cross-sectional profiles of ore body boundaries.
higher average gold content in diamict facies and gravel facies indicates that glacial sediments are origin of the gold.

Gravel facies, composed of SAG, which is an indicator of fluvial channel including outwash plains, beach, marine surface lag, and other high-energy sedimentary environments, logically have the highest average gold content (309 mg/m³), and also have a relatively higher proportion of mineralization (15.5%) among the coarse sediment group. Gravel facies sediments account for approximately 44% of the total gold resource in the sediment.

4.4.2. Spatial gold distribution

Based on the gold grade attribute in layered orebody feature class (GeoDH_sliceinfo) stored in IG, using the interpolation tools of Geostatistics Analyst or 3D Analyst extension in ArcGIS, a series of layered gold distribution maps (raster and contour) are generated at various planes parallel to sea surface level (−18, −20, −22, −24, −26, −28, −30, and −42 m) and parallel to sea floor (−2, −4, −6, −8, −10, −12, and −14 m). Inverse Distance Weighted (IDW) interpolation method was used for generating the gold concentration surfaces. An influence neighborhood radius of 600 m and an inverse power of 2 were used in the IDW method.

Fig. 9 shows the gold distribution contour map of the plane of 2 m below sea floor. In this example, the gold distribution contour ranges from 200 to 8400 mg/m³.

Inverse distance weighted (IDW) is one of the many methods to perform interpolation of scattered spatial data. A neighborhood about the point to be interpolated is selected and a weighted average is calculated of the observed values within this neighborhood. The weighting factors of observed points are a function of the distance between the observed points to the interpolated point, the closer the distance the bigger the weights. The interpolating function is constructed as a linear combination of the observed values $v_i$ at point $x$ multiplied with weight functions $w_i$ (Fisher et al., 1987):

$$f(x) = \sum_{i=1}^{n} v_i w_i(x),$$

where the weight factors $w_i$ ($i = 1, 2, \ldots, n$) are constructed by normalizing each inverse distance:

$$w_i(x) = \frac{d_i^{-\lambda_i}(x)}{\sum_{j=1}^{n} d_j^{-\lambda_j}(x)},$$

where $d_i(x)$ is the Euclidean distance from point $x$ to node $x_i$, and $\lambda_i$ is the exponential power of weight. Each weight function $w_i$ is inversely proportional to
the distance from the point $x_i$ where the value $v_i$ is prescribed. The sum of the proportional factors $w_i (i = 1, 2, \ldots, n)$ should equal to one.

The offshore area of anomalous gold mineralization is oriented more or less parallel to the coast over an east–west distance of about 25 km. Gold mineralization occurs at each block throughout the study area at the 200 mg/m$^3$ cutoff grade. Based on the gold distribution, the study area is divided into 27 sub-areas (Fig. 10) at the 200 mg/m$^3$ cutoff grade. Six out of the 27 orebodies, i.e. Red1, King1, Silver2, Humpy2, Tomc2 and Coho1, exceed 3 tons of gold resource, comprising more than 70% of the total resource. With an increased cutoff grade, the areas of anomalous gold mineralization shrink sharply. At the 600 mg/m$^3$ cutoff grade, only 4 specific zones are particularly anomalous, i.e. Red1, King1, Tomc2 and Coho1.

4.5. Resource estimation

Resource estimation is an important component of the mineral resource management. All gold resource calculation problems must deal with estimating two inter-related items: the grade and the associated volume. This grade could be the economic cutoff grade or the average grade within a pre-specified volume. The volume of ore can be estimated based on orebody boundary. The total resource is then estimated based on the volume. Table 4 lists the total resource estimation at different cutoff grades within the entire study area.

The first step for resource calculation is to determine orebody thickness and average gold grade for every borehole. Calculation of average gold grade for each borehole based on various cutoff grades is a time-consuming task. Since orebody boundaries are different at various cutoff grades, their associated thickness and average grade are also different. The calculations are performed repetitively in MS Access using SQL language, based on segment records stored in the borehole segment information table in the IG. The calculated average grades and thicknesses of various layers form the layered orebody information table.

The second step is to create a point layer and grid coverage and add them to the R2.5DG. The point layer is used to store the layered orebody grades and thicknesses. In this layer, the entire study area is divided into 10 m $\times$ 10 m grids, and each point feature object in the center of a cell represents this cell and all of the grades and thickness are stored in this point object. The entire study area is approximately 40.4319 km$^2$. The R2.5DG contains 404319 spatial point records, each point record representing one 10 m $\times$ 10 m-grid cell.
The third step is to determine the thickness for each cell created during the second step. The attribute data in GeoDH_sliceinfo layer is utilized to build orebody boundaries. To determine the orebody thickness of each regularized cell, two orebody boundaries are generated based on the levels of the orebody’s beginning depth and the ending depth, respectively. The orebody boundaries are interpolated using the Natural Neighbor method, which is an interpolation method that estimates the value of a cell using weighted values of the input data points that are their natural neighbors, determined by creating a triangulation of the input points. The Natural Neighbor tool in ArcGIS can efficiently handle large numbers of input points. Other interpolators may have difficulty with large point data sets (ESRI, 2004d).

The next step is to interpolate the gold content for each regularized cell. Five interpolation methods are investigated and compared. IDW was selected for interpolating the gold concentration contour maps. The following paragraph will briefly describe the selection procedure, for detailed discussion can be found in Li et al. (2005).

Based on statistical analysis, the gold concentration data collected from the Nome offshore deposit are of characteristics such that: (1) near lognormal distribution of data, (2) high positive skewed distribution, (3) a small number of extreme values dominating the resource estimation, and (4) apparent anisotropy of the variogram. Five geostatistical methods namely Inverse Distance Weighted (IDW), Ordinary Kriging (OK), Ordinary Kriging with lognormal transformation (OK-log), Simple Kriging (SK) and Indicator Kriging (IK) were selected initially for the development of an interpolation model (ESRI, 2004e). The results by the five methods were evaluated and compared with each other. It was
determined that the OK and SK algorithms were not suitable for the Nome data set because of their difficulty of fitting the semivariogram model despite their lower root-mean-square error (RMSE) and the higher root-mean-square standardized (RMSS). The OK-log algorithm does not provide satisfactory interpolation for the Nome data set either, because it placed too much weight on the role of outliers resulting in overestimation and extremely high RMSE. Resource estimation was conducted using each of the interpolation methods and compared with the resource calculated using the conventional polygon method. The IWD and IK algorithm seemed to provide estimations more agreeable with the conventional polygon method (Li et al., 2005).

The last step is to estimate the gold resource within the study area. After the thickness ($T$) and average grade ($G$) for each cell are obtained, one new column ($G_T$) can be created to store $G_i \times T_i$. For any selected polygon area, $\Sigma(G_i \times T_i)$ and $\Sigma T_i$ can be obtained by using the “statistics” tool in ArcMap.

The gold resource within a selected polygon area is estimated by the following equation:

$$R = \sum (G_i \times T_i) \times 10 \times 10,$$

where $G_i$ is grade value of each cell above cutoff grade and $T_i$ is thickness of each cell.

The average grade ($G_{ave}$) within a polygon area is given by

$$G_{ave} = \frac{1}{\sum T_i} \sum (G_i \times T_i).$$

### 4.6. Customized resource estimation system

A customized resource estimation system was created around the project using Visual Basic for Applications (VBA). VBA is the customization environment that comes with ArcGIS. Many different programming languages can be used to expand the ArcGIS functionality. Visual Basic and Visual C++ are the two programming languages used in the Nome Project. Fig. 11 shows the steps and techniques used in creating the customized resource estimation system. With customization, resource estimation can be done by users without GIS knowledge. The procedure of performing resource estimation at any selected area is as follows:

1. Press the Estimation button from tool bar.
2. Select a polygon area interested.
3. Type in query parameters in the Estimation dialog box (e.g. cutoff grade).
4. Display the estimation table.

This customized tool allows users to query the resource information at any portion of the study area with a defined cutoff grade and defined reference plane, such as sea floor or sea level. Fig. 12 shows the resource estimation window in ArcGIS.

### 4.7. Web GIS

In order to facilitate remote users to access the two geodatabases (IG and R2.5DG) built for the

![Fig. 11. Procedure of building a customized resource estimation tool.](image-url)
Nome project, a web-based GIS (http://uaf-db.uaf.edu/website/) was developed for this project using ArcIMS, an application program of ArcGIS. A detailed description about the web GIS of the project can be found in Luo et al. (2005). The Web GIS structure developed in this project can be readily adapted to mineral resource analysis in other areas of the state.

5. Conclusions

GIS technology was applied for analyzing the data of the offshore placer gold resources near Nome, Alaska. Two relational databases were developed during this research, namely the Integrated Geodatabase (IG) and the Regularized 2.5D Geodatabase (R2.5DG). The IG contains most of the data collected, complied, and integrated. It serves as a data warehouse, and was designed to store, display, and disseminate offshore placer gold resource information in Nome area. Three surfaces, namely the orebody upper boundary surface, the orebody lower boundary surface and a hypothetical gold concentration surface were defined based on data stored in the IG. There are various methods available in ArcGIS for development of the interpolation model. In this study, the Natural Neighbor method was used for interpolation of the orebody boundaries, and the IDW interpolation method was used to generate gold concentration contours. The R2.5DG facilitates data management, retrieval, and integration. It can be used to perform more advanced tasks, such as advanced query, geostatistical and numerical modeling with a user-friendly graphic user interface (GUI). Most importantly, the R2.5DG is capable of handling volume calculation, and resource estimation, which is a frequently performed task for mineral resource management. A customized resource estimation tool was built around this project, which can be used to estimate...
gold resources at different cutoff grades and different spatial domains in a time-efficient way. The total placer gold resource near Nome is estimated from 113,767 oz (with a cutoff grade of 1000 mg/m³) to 2,309,664 oz (with a cutoff grade of 0 mg/m³). The average grade ranges from 0.233 g/m³ (with a cutoff grade of 0 mg/m³) to 1.929 g/m³ (with a cutoff grade of 1000 mg/m³).

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References