# A REVIEW OF FAVORABLE OFFSHORE AND COASTAL DEPOSITIONAL SITES FOR PLATINUM-GROUP METALS IN THE GOODNEWS BAY MINING DISTRICT, ALASKA

by Brian R. Zelenka
Alaska Field Operations Center, Anchorage, Alaska

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Donald P. Hodel, Secretary

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T S Ary, Director

CONTENTS



ILLUSTRATIONS

## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | |
|---|---|
| cm | centimeter |
| cm/yr | centimeter per year |
| $g/m^3$ | gram per cubic meter |
| gr | gram |
| kg | kilogram |
| km | kilometer |
| m | meter |
| $m^3$ | cubic meter |
| ppb | part per billion |
| ppm | part per million |
| pct | percent |
| sp gr | specific gravity |
| um | micron |
| $yd^3$ | cubic yard |
| yr | year |

# A REVIEW OF FAVORABLE OFFSHORE AND COASTAL DEPOSITIONAL SITES FOR PLATINUM-GROUP METALS IN THE GOODNEWS BAY MINING DISTRICT, ALASKA

By Brian R. Zelenka[1]

## ABSTRACT

The Bureau of Mines (Bureau) reviewed all available information regarding geologic and depositional processes contributing to potential coastal and offshore platinum group metal (PGM) placer deposits around the Goodnews Bay Mining District. The Bureau found that favorable environments for PGM along with gold and chromite enrichment include: (1) buried paleofluvial channels; (2) recent paleofluvial channels with little marine sediment overburden, (3) beach deposits, particularly in the upper swash zone and near back beach environments; (4) paleostrand lines; (5) shoal lag deposits inside the mouths of Goodnews and Chagvan bays; and (6) bases of far offshore tidal ridges which may represent reworked glacial deposits.

Limited geologic and compositional (assay) data prevent determination of deposit size and grade of PGM mineralization for each deposit class. Future geologic sampling requirements for demonstration of identifiable offshore and beach PGM-bearing placers are discussed. Beach and offshore sampling programs conducted by the Bureau in 1986 will contribute additional information providing verification of specific deposit classes.

## INTRODUCTION

The Bureau is currently investigating known and potential nearshore and offshore placer deposits in Alaska. The offshore region adjacent to the Goodnews Bay Mining District is recognized as having a high potential for PGM, gold, and chromium placers. Reliable quantitative analyses of beach and offshore sands around the Goodnews Bay Mining District are limited and the potential for economically extracting marine placers remains largely unknown. This study was undertaken as an attempt to compile available literature and evaluate the offshore and coastal placer potential near the Goodnews Bay Mining District. Specific depositional environments with possible economic concentrations of PGM, gold, and chromium are hypothesized.

Fluvial PGM placers were discovered in a small region south of Goodnews Bay, southwestern Alaska, during 1926 (23-25)[2]. From 1927 to 1934, the placers were worked by small-scale hand mining methods. Dragline excavators were employed in 1935, and in 1937 the Goodnews Bay Mining Company built a bucket-line dredge which was seasonally used until 1975. The dredge has been used intermittently since then.

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1/Mining Engineer, Alaska Field Operations Center (AFOC), Anchorage, Alaska (deceased).

2/ Underlined numbers in parentheses refer to items in the list of references at the end of this report.

Although PGM extraction has been restricted to gravels in the creeks which drain Red Mountain, the ultramafic source for the PGM (25, 35,), numerous researchers have reported trace to possibly economic concentrations of platinum in beach and offshore sands around Goodnews Bay, Chagvan Bay, and the adjacent coastal waters of Kuskokwim Bay (5, 7, 11, 28, 42). The presence of PGM-bearing sediments offshore was verified by the Bureau in 1985.

Significant concentrations of chromite, with lesser amounts of gold, are locally associated with the PGM placers and may represent economically recoverable co-products or by-products of PGM production. During the summer of 1986, the Bureau's Mineral Land Assessment (MLA) section and the Critical and Strategic Minerals sampling program continued to systematically collect bulk samples for PGM and heavy mineral analysis in the offshore and intertidal regions between Goodnews and Chagvan Bay.

This paper, which integrates the work of previous researchers, summarizes those characteristics which together suggest favorable marine placer environments in the Goodnews Bay Mining District. These include: (1) coastal and offshore geology; (2) Holocene geomorphology and its relationship to placer depositional environments; (3) Quaternary geology; (4) primary PGM sources; (5) secondary depositional environments; (6) PGM transport models; and (7) the results of marine sediment analyses. Depositional environments with possible PGM resources are identified using available data. Analysis of samples collected by the Bureau in 1985 and 1986 is incomplete, nor have assay data suggesting specific PGM placers in various offshore depositional environments been completely evaluated. However, limited compositional data from beach samples collected during 1986 by the Bureau's MLA program is presented.

## ACKNOWLEDGMENTS

Peter Barnes, Geologist for the U.S. Geological Survey, is gratefully acknowledged for providing invaluable unpublished data from his offshore investigations in 1969 of the Goodnews Bay district. The author also wishes to acknowledge his colleagues at the Bureau of Mines, Alaska Field Operations Center, who provided both data and interpretive reviews.

## STRATEGIC IMPORTANCE

Approximately 92% of the PGM consumed by the United States is imported from South Africa and the U.S.S.R., and is therefore considered strategic and critical for the U.S. (10, 27). Platinum is used for two principal functions; (1) as a catalyst in automotive, petroleum refining, and other industries, and (2) as a corrosion-resistant material for industries such as chemical, electrical, and dental-medical (21). The Goodnews Bay Mining District is the only district in the U.S. which has produced PGM as a primary commodity. Significant resources and limited reserves of this commodity exist in the Salmon River valley, adjacent tributaries, and nearby coastal zones in the Goodnews Bay Mining District; however, the reserve base has been only partially evaluated (13, 29).

## LOCATION

The Goodnews Bay Mining District is located north of Bristol Bay in southwestern Alaska (fig. 1). The district encompasses approximately 1.1 million acres, and is bounded by the Indian River on the north, Cape Newenham on the south, and Ungluayagat Mountain to the east (fig. 2, 31). This study investigates the nearshore and offshore region between the north spit at Goodnews Bay and the southern side of Chagvan Bay along the Bering Sea coast.

## PRODUCTION AND RESERVE BASE

Total production of PGM from the entire Goodnews Bay District between 1927-81 is approximately 20,031 kg (2). The bucket-line dredge at Goodnews Bay, operated by the Goodnews Bay Mining Company from 1937-75, produced at least 16,949 kg of PGM (13). Presently, the platinum dredge, owned by the R. A. Hanson Company, is being operated on a limited basis, hence current PGM production from Goodnews Bay is negligible (12).

Measured recoverable reserves for PGM contained onshore in fluvial placers near Goodnews Bay are in excess of 9,330 kg (12). Hypothetical resources of subeconomic grade include 40,430 kg recoverable from lode occurrences at Red Mountain, 15,550 kg from beach deposits, and 155,500 kg from offshore placers according to Page and others (29). The U.S. Geological Survey (USGS) estimate of 171,050 kg of PGM for coastal placers should be recognized as an estimate of order of magnitude precision only (29), because they rely heavily on analyses of a limited number of grab samples (5, 11). Data obtained by the Bureau during 1986 suggests that a significantly smaller resource base is present on the beaches and probably offshore.

## REGIONAL GEOLOGY

The geology of the Goodnews Bay Mining District has been studied by numerous investigators. The most significant contributions are discussed below. Reed (32, 33), in 1931 and 1933, described the early placer mining at Goodnews Bay and the ultramafic rocks comprising Red Mountain. In 1940, Mertie (23) reported on the regional geology and the character of the placers which included detailed petrographic investigations of the PGM. Mertie (24-25) went on, in 1969 and 1976, to summarize the mining history and composition of the PGM placers and also described the regional geology, Quaternary depositional environment, and economic significance. The heavy mineral potential of beach deposits along the coast of Bristol Bay was first reported by Berryhill (5) in 1963. Porter (30) described the Quaternary glacial history of the Chagvan Bay area in 1967. A comprehensive investigation of the Goodnews Bay District was released in 1978 by the USGS as part of the Alaska Mineral Resource Appraisal Project (AMRAP) (11, 16, 18-19). Bond (7) and Ulrich (42) reported on the distribution and processes involving the formation of beach placers in the Goodnews Bay district in 1982 and 1984 respectively. Wakeland (37), Welkie (40), and Walish (39) investigated the sedimentological processes active in Goodnews Bay, Chagvan Bay, and in nearshore environments in 1973, 1976, and 1977 respectively. The most recent

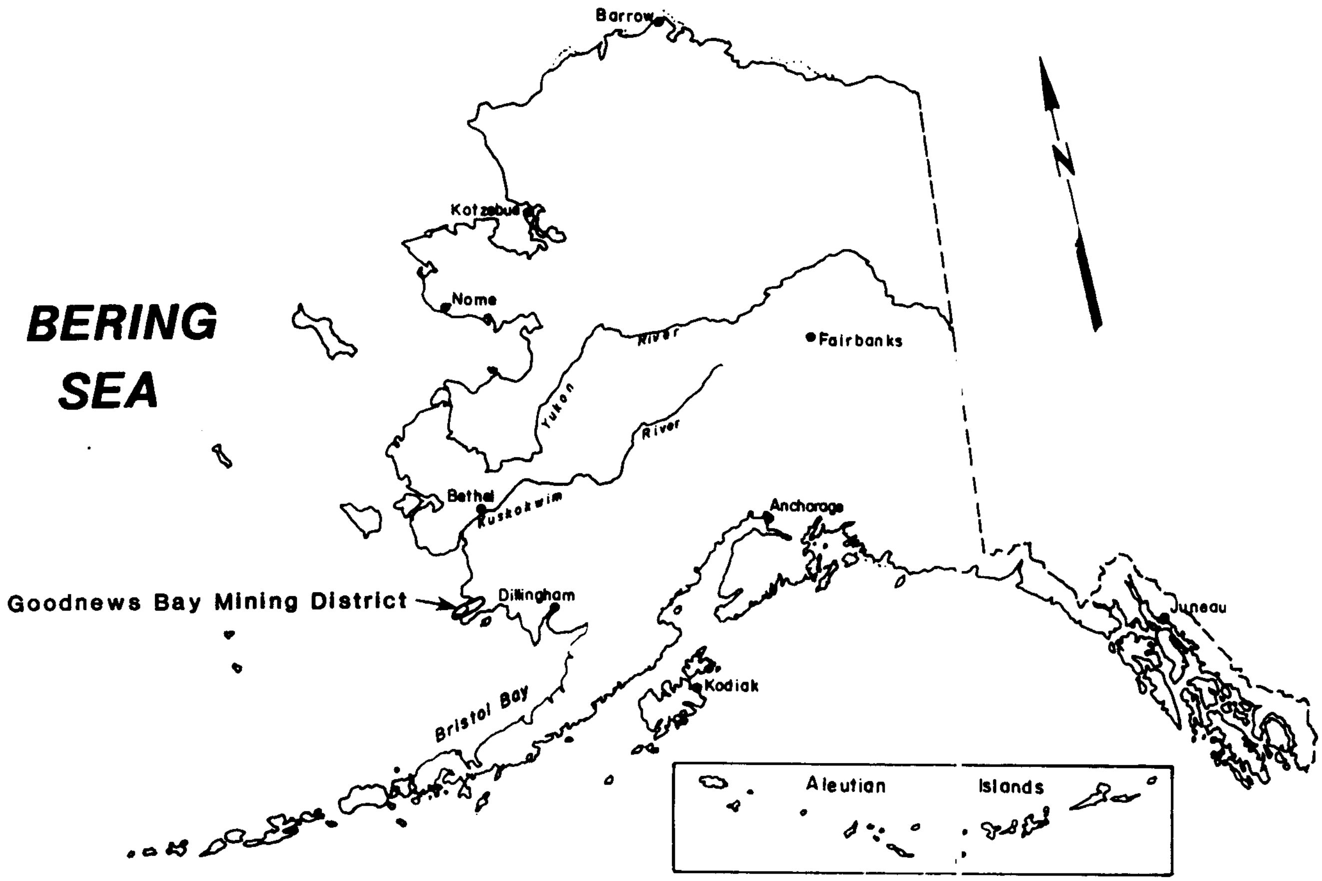
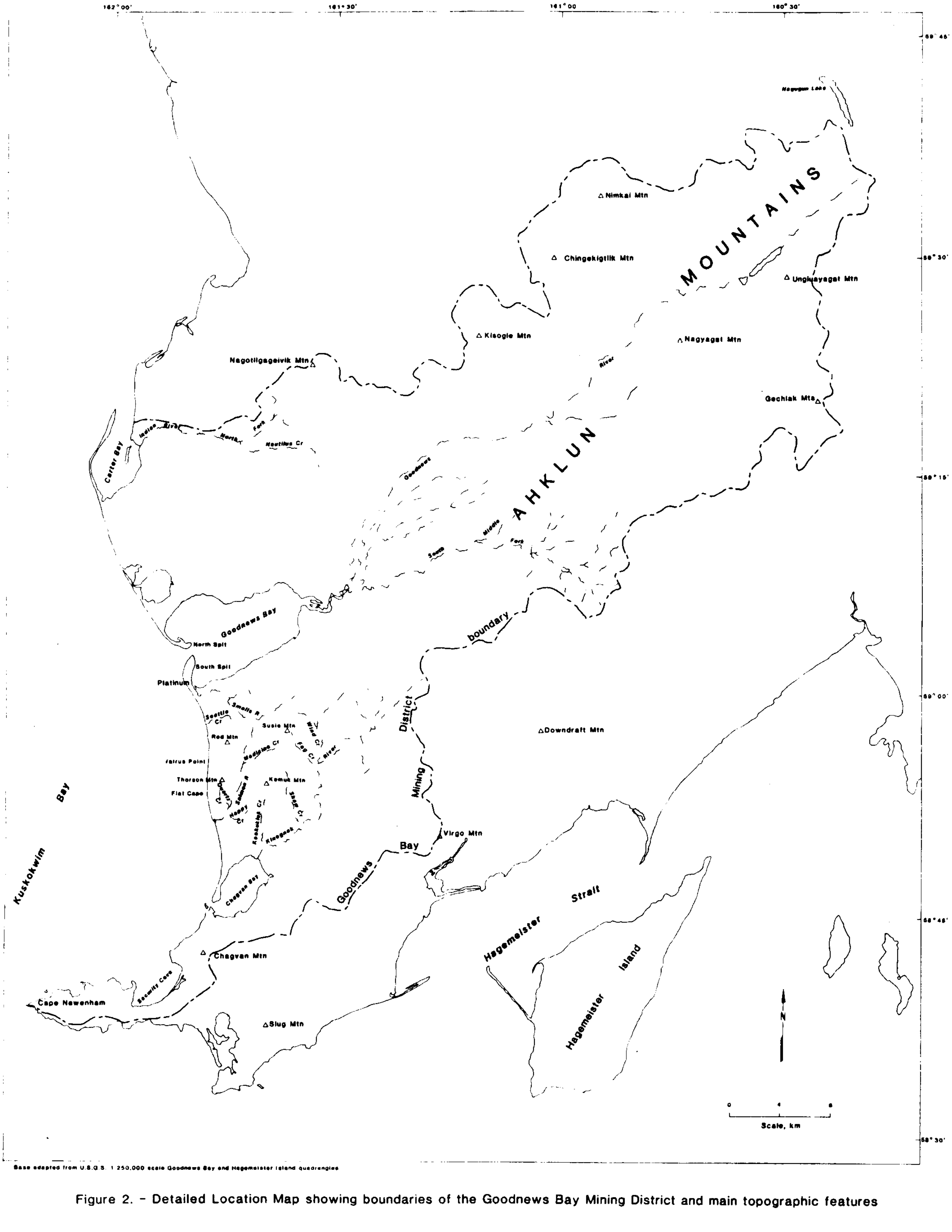



FIGURE 1. Location map of the Goodnews Bay Mining District, Alaska.




Base adapted from U.S.G.S. 1:250,000 scale Goodnews Bay and Hagemeister Island quadrangles

Figure 2. - Detailed Location Map showing boundaries of the Goodnews Bay Mining District and main topographic features

geologic map of the Goodnews Bay area was compiled by Hoare and Coonrad (19) for the Goodnews-Hagemeister Island quadrangles region in 1978. The tectonic setting of southwestern Alaska was recently investigated by Box (8-9), in 1982 and 1985, for the USGS. Southworth and Foley (36), and Southworth (35) published detailed descriptions of the ultramafic source rocks for PGM mineralization at Red Mountain. In 1982 and 1984, Box (8-9) subdivided the Goodnews Bay district into terranes which are overlain by unconsolidated glaciofluvial Quaternary deposits.

The tectonic setting of the Goodnews Bay complex is best described using the tectonostratigraphic terrane framework developed by Jones and others (20) and Box (8). The Goodnews Bay region consists of the Goodnews and Togiak Terranes. The following discussion is adapted from Box (8-9).

## TOGIAK TERRANE

The Togiak Terrane consists of Mesozoic volcanic and volcaniclastic sedimentary rocks which may be subdivided into the Hagemeister and Kulukak subterranes (fig. 3). The Hagemeister subterrane is a northeast striking belt which includes Chagvan Bay and Chagvan Mountain. The Hagemeister subterrane is comprised of Upper Triassic through Lower Cretaceous mafic igneous rocks, shallow marine volcaniclastic sedimentary rocks, and intercalated cherts. The subterrane may be further divided into three units with unconformable contacts.

The Kulukak subterrane consists of Jurassic volcaniclastic turbidites, and is exposed as a northeast trending belt south of the Goodnews Bay District (fig. 3). A northeast striking linear fault separates the Hagemeister and Platinum subterranes from the Nukluk subterrane to the northwest.

## GOODNEWS TERRANE

The Goodnews terrane is subdivided into the lithologically distinct Nukluk, Platinum, and Cape Peirce subterranes (fig. 3). The Nukluk subterrane strikes northeast with its western margin extending from Goodnews Bay to Carter Bay (fig. 3). The Nukluk subterrane consists of Triassic limestone and volcaniclastic sedimentary rocks, radiolarian cherts, and polymictic clastic rocks in a matrix-poor melange package. Locally, the subterrane is overprinted by greenschist to blueschist facies metamorphism along the northwestern margin. The Nukluk subterrane is separated from the Platinum and Hagemeister subterranes by a northeast trending linear fault. The Platinum subterrane is exposed around Goodnews Bay and the Upper Goodnews River, and consists of an unfoliated package of basalts, limestones, and volcanic conglomerates of Permian age. The Cape Peirce subterrane outcrops between Goodnews Bay and Chagvan Bay, around Security Cove, and on the northern shore of Hagemeister Strait (fig. 3). The Cape Peirce subterrane consists of foliated greenschist to blueschist facies metamorphic rocks of late Triassic or early Jurassic age, which have been thrust over the Platinum subterrane to the northwest. The Cape Peirce subterrane is exposed through a window under a low-angle fault overlain by the Hagemeister subterrane.

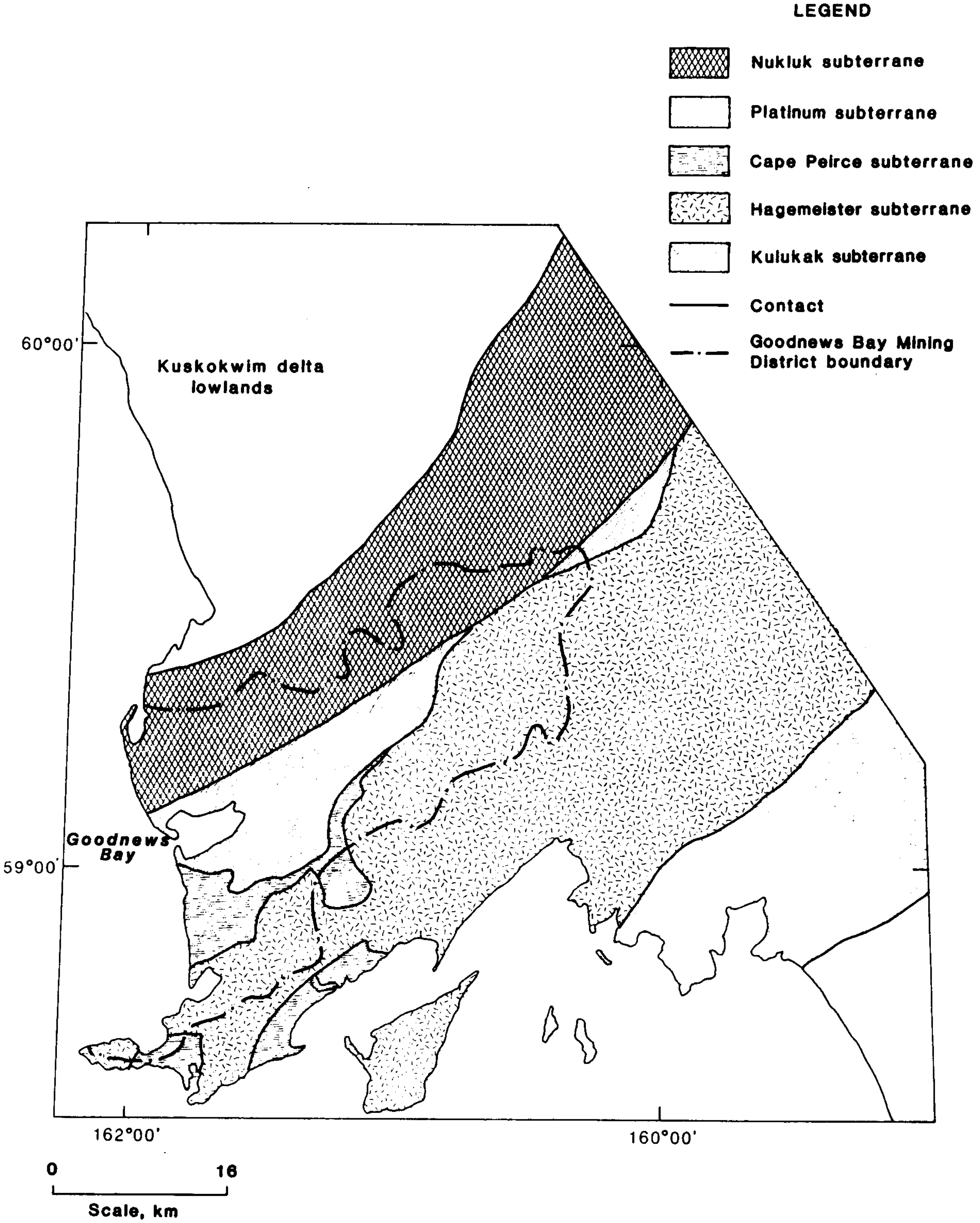



FIGURE 3. Teconostratigraphic terrane map of the Goodnews Bay Mining District

## ULTRAMAFIC ROCKS

Red Mountain and Suzie Mountain are two exposures of ultramafic rock within the Goodnews Bay Mining District and probably represent the same complex (35, 36). The ultramafic intrusives consist of dunite, pyroxenite, hornblendite, and gabbro which form a discontinuous belt of sill-like bodies which intruded the Cape Peirce subterrane during Late Cretaceous to Early Tertiary time (35). These intrusives represent the source of PGM, chromite, and minor gold (25, 35). Hoare and Coonrad (19) report potassium-argon ages of 176.4 $\pm$ 5.3 and 186.9 $\pm$ 5.6 million years for secondary amphibole located along the Red Mountain contact zone.

## QUATERNARY GEOLOGY AND DEPOSITS

Unconsolidated Quaternary deposits in the Goodnews Bay Mining District are derived from glacial, fluvial, and marine origins. A discussion of each is presented below.

## GLACIAL HISTORY AND DEPOSITS

Porter's (30) description of the glacial history of the Chagvan area may be applied to the Goodnews Bay area. Mertie (25) summarized many of Porter's conclusions and provided additional interpretations based on his observations of the placer mining operations.

Glaciers originating in the Ahklun Mountains, northeast of the Goodnews Bay Mining District, spread over the coastal lowlands at least four times as broad piedmont lobes. From oldest to youngest, the four ice sheets have been named Kemuk, Clara Creek, Chagvan, and Unaluk, which correspond to the Nebraskan, Kansan, Illinoian, and Wisconsinian Glaciations, respectively (25). The Kemuk drift sheet is deeply buried beneath younger drift and is indicated only from a single drill hole located half a mile north of Happy Creek. The sediments are characterized as strongly weathered and oxidized and directly overlie weathered bedrock. The Kemuk Glaciation did not erode bedrock at lower elevations in the Salmon River Valley, as evidenced by preservation of the bench placer on the east wall of the valley which was buried by the earliest ice advance. This early advance may have covered the entire upland as suggested by the distribution of placer gold presumably carried in by ice sheets from source rocks to the east.

The Clara Creek (Kansan) Glaciation was the most extensive of the four ice advances and produced massive morainal material which has been remobilized by erosion and mass-wasting. The preglacial course (bench placer) of the Salmon River was probably abandoned during the Kemuk or Clara Creek Glaciation because the younger, valley-bottom placer was truncated by ice advancing into the lower Salmon Valley from Chagvan Bay during the third glaciation.

The third ice advance, represented by the Chagvan (Illinoian) Glaciation, has been radiocarbon dated to have occurred at least 45,000 years before present (30, p. 13). The deeper (Clara Creek) bench placer was not eroded by this ice advance. This glaciation did, however, destroy PGM placers that presumably existed on the northeastern side of Red Mountain, as evidenced by erratic boulders found at elevations as high as 267 m (25, p. 13). The Chagvan Glaciation produced a less modified constructional topography than previous glaciations. Kettle lakes and arcuate ridges are the most characteristic features. Porter (30) mapped moraines of the three youngest glaciations on the north and west flanks of Red Mountain. Extensive drilling programs have found no significant placers there. However, the same source rocks (i.e. Red Mountain) provided glacial debris which were later reworked by fluvial processes to provide important paystreaks east and south of Red Mountain. Most of the unconsolidated deposits removed from the northern and western flanks of Red Mountain prior to glacial deposition were probably transported offshore as morainal and outwash material during marine regressions associated with continental glacial advances. Porter (30, p. 238) and Ulrich (42) estimate that glacial material was deposited at least 1.5 km offshore from the present coast. Reevaluation of data provided by Ulrich (42), however, suggests morainal material may have been deposited up to 5 km offshore.

The Unakluk Drift has been dated to be at least 8,910 ± 110 years old, representing the last glacial event near Goodnews Bay. The moraines of the Unaluk Glaciation have been altered little by erosion or mass-wasting. Terminal moraines are found four miles east of Chagvan Bay, and hence had little effect on the Goodnews Bay District except for glaciofluvial deposition from runoff.

Poorly sorted glacial deposits do not contain economic placers according the Mertie (25). Fluvial or marine reworking of the unsorted deposits is a necessary requisite in order to hydraulically concentrate the PGM and other heavy minerals.

## FLUVIAL DEPOSITS

Unconsolidated fluvial gravel deposits have yielded nearly all of the PGM recovered from the Goodnews Bay Mining District. The Salmon River is the only major PGM-bearing drainage in the district. Placer deposits of the Salmon River and its paleochannels (bench placers) range from 5 m to approximately 80 m in depth, with the highest grades directly above bedrock (25, 30). Two PGM-bearing paystreaks are recognized. The most recent deposit, located in the Salmon River valley, is shallow and approximately follows the modern drainage (24-25). The older, deep bench placer on the east wall of the valley was abandoned by the Salmon River and buried with glacial debris during the Clara Creek Glaciation (30). Extensive drilling programs have failed to locate additional PGM-bearing paleochannels. Most PGM recovered from these placers occurs within structural traps in the upper meter of bedrock, if unweathered, or as much as 1.3 m into broken or highly altered bedrock (25).

Smaller drainages and tributary streams contain shallow fluvial deposits overlain by 2 to 7 m of overburden. Although these shallow deposits proved to be easily accessible by hand and dragline placer mining techniques, their limited minable volume, and difficult accessibility has restricted dredge recovery except where the drainages feed into the Salmon River Valley.

Tributaries draining from the north and west side of Red Mountain lack economically significant concentrations of PGM, gold and chromite (23-25). The Chagvan glacial advance scoured the northwestern flanks of Red Mountain presumably removing the richer placer accumulations of these metals (30). Tributaries have had insufficient time to rework the glacial deposits and reconcentrate the heavy minerals in this area. In the lower Salmon River Valley, south of Red Mountain, glacial erosion removed most of the placer deposits present in stream channels. PGM and gold deposits recovered from the lower Salmon River are the result of glaciofluvial reconcentration from highly disseminated heavy mineral-bearing glacial deposits.

## MARINE DEPOSITS

Marine deposits occurring in Kuskokwim Bay are derived from: detritus transported offshore during ice advances; the coastal erosion of alluvial (mostly morainal) bluffs along the western side of Red Mountain; direct weathering of ultramafic bedrock exposed at Walrus Point which probably extends offshore (fig. 2); and fluvial sediment discharged from coastal rivers and tributaries. Economically significant concentrations of PGM have not been reported in offshore or beach deposits between Goodnews Bay and Chagvan Bay. However, selected pan concentrates and grab samples collected by Berryhill (5, p. 13) contained heavy mineral accumulations with up to 12.1 pct chromite and trace amounts of platinum, gold, and silver. During the Bureau's 1986 beach sampling program one sample obtained exceeded 10.5 g/m$^3$ PGM and 4.1 g/m$^3$ gold (14).

Beach deposits occurring in the foreshore and backshore are composed of unconsolidated, poorly sorted deposits predominantly of glacial origin (7, 42). The beach is characterized as a thin wedge of coarse-grained sediments overlying "false bedrock", and range in thickness from several centimeters near the base of the bluff to approximately 1 m in the mid-beach zone (7, p. 20). The beaches average 30 m wide and extend to an unknown depth along the shoreface zone. Heavy mineral concentrations occur in the swash zone (foreshore), behind berms in the backshore, and along the "false" bedrock horizon below the beach sands. The "false" bedrock consists of glacially derived clay and sediments (morainal) which are ferricreted in some areas. Black sands are concentrated on the "false" bedrock surface up to 30 m from the bluffs (15). Erosion of the bluff face of approximately 50 cm or more a year provides a continual source of PGM-bearing glacial debris to the beach and nearshore heavy mineral concentrating corridor (42).

Glacial sediments extending 5 km (or more?) offshore were deposited during marine regressive events correlated to ice sheet advances during the Pleistocene and Holocene Epochs. Porter (30) cites evidence which suggests that the sea level may have been 80 m lower than the present elevation. Upon the retreat of the glaciers, the sea level rose towards its present elevation during which time low to high energy waves and littoral currents reworked morainal and glaciofluvial debris deposited on the sea floor. There have been at least four transgressive-regressive cycles associated with Quaternary glacial events.

Fluvial channels were developed during regressive marine events and may be present as buried channels extending offshore. Evidence for such channels is suggested from contours of bathymetric and acoustic "basement" data obtained during an offshore sampling program by the

USGS (4). Sediments overlying the paleochannels range in thickness from 25 to 50 m.

## GEOMORPHOLOGY

The past glacial history and present periglacial climate have strongly influenced the geomorphology of the Goodnews Bay region. It is the geomorphology which ultimately determines the transportation and depositional potential of placer-bearing sediments.

Red Mountain is an elongate ultramafic body 11.3 km long, approximately 1.5 km wide, and 574 m in elevation. The northwestern flank is steeper than the southeastern side, with the asymmetry apparently resulting from the effects of glacial erosion and/or variable insolation (42). The northwestern side of Red Mountain is covered with colluvium and morainal material at lower elevations. The unsorted material ranges from clay sized particles to boulders many meters in diameter. Red Mountain is flanked by soliflual lobes which result from the gravity sliding of water-saturated sediments. Vegetation around Red Mountain is sparse, lichens are found at higher elevations, with moss and other tundral growth becoming denser near the base of the mountain.

The relative rates of chemical versus physical weathering processes occurring on Red Mountain have not been investigated. Ulrich (42) noted that although chemical processes are subdued at higher latitudes, field observations suggest that chemical weathering has contributed significantly to the disaggregation of Red Mountain. She noted that fractures in ultramafic rocks have a thin coating of serpentine and all exposed surfaces were buff-colored and powdery.

The Bering Sea coastline is characterized by a broad low-angle gravel beach backed by bluffs of exposed glacial outwash and morainal debris, except where Red Mountain encroaches on the Bering Sea, locally referred to as Walrus Point (7, p. 9). The bluffs range in height from approximately 1 m, where drainage erosion has occurred, to 15 m at Walrus Point.

The seasonal beach morphology has been observed to change significantly from a storm profile to a swell profile during late May or early June (42). Glacial bluffs were observed by Ulrich (42) to retreat approximately 25 cm during a 5 week field season. Assuming an erosional rate of 50 cm/yr, the shoreline has retreated at least 4,450 m since the last glaciation 8,900 years ago. This estimation is considerably larger than Porter's (30) estimate of 1,609 m which he calculated by extrapolating the slope of the Unaluk till sheet offshore.

Major stream drainages in the Goodnews Bay Mining District include the Salmon River which flows southward between Red and Suzie Mountains and eventually drains into Bristol Bay. The Smalls River, which drains into Goodnews Bay, and Seattle Creek originate from basins on the north flank of Red Mountain. Goodnews Bay receives most of its fluvial material from the Goodnews River which drains from the Ahklun Mountains northeast of the Goodnews Bay District. The Kinegnak River is the major tributary feeding sediments to Chagvan Bay. The four glacial episodes have significantly modified drainage basins in the Goodnews Bay region. Most notably, the Salmon River flowed southeasterly into Chagvan Bay until the Kansan Glaciation modified the drainage system (25).

Goodnews Bay and Chagvan Bay are intertidal lagoons with sandy spits protecting the entrances. The formation of the spits suggests the presence of northerly and southerly littoral currents transporting material from the receding coastal bluffs and stream drainages including the Salmon River (28, 37).

Seasonally flowing tributaries originate in cirques and cirque-like basins around Red Mountain (42). The streams have deeply incised straight, narrow valleys in the glacial morainal material. The streams change gradient at the base of the mountain allowing sediments to settle out and form small alluvial fans in some drainages. Eventually, the streams empty into the Bering Sea where the remaining sediment load comes under the influence of marine processes.

## SEDIMENT TRANSPORT MECHANISMS

Understanding heavy mineral-bearing sediment transport mechanisms is critical in developing depositional environment models. Longshore transport from littoral currents is probably the most important agent concentrating heavy minerals offshore. The rate of transport has not been determined in the Goodnews Bay region, although the directions of sediment movement were cited by Bond (7). Data provided by the U.S. Air Force installation at Cape Newenham indicate that the dominant weather pattern, particularly the storm approach angle, is from the south to southwest during ice-free months (7). Evidence for this northward movement of sediments is observed in the accretion of the recurving spits forming the entrance to Goodnews Bay. Additionally, refraction of the wave train at the Flat Cape - Walrus Point headland produces longshore currents in a southward direction toward Chagvan Bay (7). Formation of the spit along the north side of the entrance of Chagvan Bay demonstrates the southern transport of sediments along the coast from Walrus Point (7). Direct input of sediments to coastal environments is derived from: 1) transport from the Salmon River; 2) erosion of glacial morainal and outwash material; and 3) erosion of the Red Mountain ultramafic body where it encroaches the coast and apparently extends offshore.

Sediment transport from far offshore (2-15 km) probably requires high energy, storm generated waves. Water depths do not exceed 20 m in this region of Kuskokwim Bay, hence high energy waves are probably capable of reworking offshore sediments. Sediment transport along the nearshore conduit, including beaches, is provided by storm events, and to a lesser degree, by wave and tidal activity.

Shoaling waves occur in the mouths of Goodnews and Chagvan Bays. Shoaling waves decrease in energy and dump their sediment load upon entering the bays. Tidal changes of 1 to 3 m in the Kuskokwim Bay region increase in energy towards the mouths of the bays scouring bottom sediments and winnowing out lighter sediments.

## PRIMARY PGM SOURCES

Mertie (23-25) described the ultramafic rocks comprising Red and Suzie Mountains and went on to demonstrate that the PGM are derived from the Red Mountain ultramafic complex. Based on Mertie's (25, p. 41) calculations, the Red Mountain dunite contains 0.016 to 0.023 g/m$^3$ PGM. He concluded that large low-grade PGM deposits of commercial value were not likely to be discovered.

Southworth (35) recently completed a comprehensive petrologic investigation of the Goodnews Bay ultramafic complex and concluded that the intrusive is an Alaskan-type zoned ultramafic complex, similar to those found in southeastern Alaska, British Columbia, and the Ural Mountains in the U.S.S.R. Platinum within the Goodnews Bay ultramafic complex (Red Mountain) is associated with chromite concentrated in the dunite core. Anomalous values of iridium and palladium are apparently associated with sulfides, and/or magnetite in the outer zone of the complex. The central core of dunite is rimmed successively by wehrlite, magnetite clinopyroxenite, hornblende clinopyroxenite, and hornblendite.

All economic PGM placers in the Goodnews Bay Mining District are derived from erosion of the Red Mountain ultramafic complex. Furthermore, Southworth (35) and Fechner (15) have demonstrated that at least some of the gold associated with the PGM placers was derived from Red Mountain. Most of the chromium is weathered from Red Mountain, with minor quantities contributed from Suzie Mountain (35). Although Suzie Mountain consists of a dunite-wehrlite core rimmed by clinopyroxenite (35), it is not a major source of PGM in the valley of the Salmon River (25). The apparent extension of the Goodnews Bay ultramafic complex offshore along a southwestern trend is suggested by bathymetric (4) and limited aeromagnetic data (16).

There is strong evidence which suggests PGM are preferentially associated with chromite at Goodnews Bay (23-24, 35, 42). Additionally, Southworth (35) has noted a strong PGM-magnetite association which is consistent with observations from Mertie (24), and Rosenblum and others (34). Geochemical observations such as the PGM-chromium association should be cautiously extended to secondary placer environments, since the hydraulic behavior of the minerals differ. This was noted by Ulrich (42) who failed to find a correlation between PGM and Fe, presumably the result of ultrafine PGM being lost from the hydraulically concentrated samples.

## SECONDARY PGM SOURCES

As stated, PGM placers of fluvial origin are the only deposits which have been economically developed by industry at Goodnews Bay. The high average density of PGM (sp gr 14 to 19) together with other heavy minerals allows hydraulically concentrated deposits to form in environments with energies high enough to separate the heavy minerals from other sediments. Glacial transport of alluvium generally disperses rather than concentrates heavy minerals. Thus morainal deposits in the Goodnews Bay district, although PGM-bearing and geochemically interesting, do not contain economically important PGM, gold, or chromium accumulations. Glaciofluvial deposits, such as those in the lower Salmon River drainage may have been locally reworked sufficiently to develop significant placer accumulations.

Marine deposits, of interest in this study, occur in offshore, nearshore, and beach environments. Descriptions of possible depositional sites for heavy mineral accumulations have been published by Berryhill (5), Owen (28), Welkie (40), Coonrad and Others (11), Bond (7), and Ulrich (42). The Bureau has been conducting investigations on the beach and marine placer potential at Goodnews Bay since 1981.

## POTENTIAL OFFSHORE, NEAR-SHORE, AND BEACH PLACER DEPOSITS

Available quantitative and qualitative geochemical data, Quaternary geologic history, studies of active marine processes, and inferences concerning depositional environments, suggest favorable environments for offshore and coastal deposits of platinum-group and other heavy minerals. Six deposit classes containing potential heavy mineral accumulations of economic significance are hypothesized: buried paleofluvial channels, recent paleofluvial channels, beach deposits, paleostrand lines, tidal ridges, and shoal deposits. The approximate hypothetical areal distribution and classification of each deposit is shown on figure 4.

### Buried Paleofluvial Channels

Buried paleofluvial channels were identified using limited "acoustic basement" data collected by Barnes in 1969 for the USGS and provided to the author (4). Figure 4 identifies the locations of three possible buried channels recognized as depressions in the "acoustic basement" from seismic data.

The buried channels are presumed to originate from the coastal area between the Salmon River and the northern spit of Chagvan Bay and may represent extensions of the Salmon River drainage which were cut during one or more marine regressive events. These channel locations are very approximate and high resolution data is required to verify and define their locations. Buried channels do not correlate to submarine topographic relief, and are not recognizable from bathymetric data.

The buried channels are apparently covered with 30 to 50 m of alluvium, presumably of glacial and fluvial origin. Since the channels are defined by negative relief in bedrock or possibly ferricreted-gravel "false" bedrock, it is believed that the channels originated during the Kemuk or Clara Creek Glaciation and were later covered with glaciofluvial debris from the Unaluk or Chagvan Glaciation and other marine (e.g. littoral) processes. Heavy mineral accumulations, including PGM may be present in these paleochannels at the "false bedrock" contact. This hypothesis is supported by limited magnetic data collected along the buried channels (4). PGM concentrations may approximate those found in lower Salmon River if the sediments were derived from Red Mountain.

### Recent Paleofluvial Channels

Recent paleofluvial channels, shown in figure 4, are suggested from detailed bathymetric data (1.52 m contours) provided by Barnes (4). These channels also represent fluvial offshore extensions formed during marine regressive events. The channels are younger than the buried channels and are presumably correlated to the Unaluk and/or Chagvan glaciation. The channels are southwest trending but are not all extensions of the Salmon River Valley (fig. 4). The channels are presently covered with an unknown thickness of recent sediments, and 5 to 20 m of water. The channels do not rest on acoustic "bedrock", therefore it is not clear where heavy mineral concentrations, if any, may have accumulated. The channels are identified as gentle

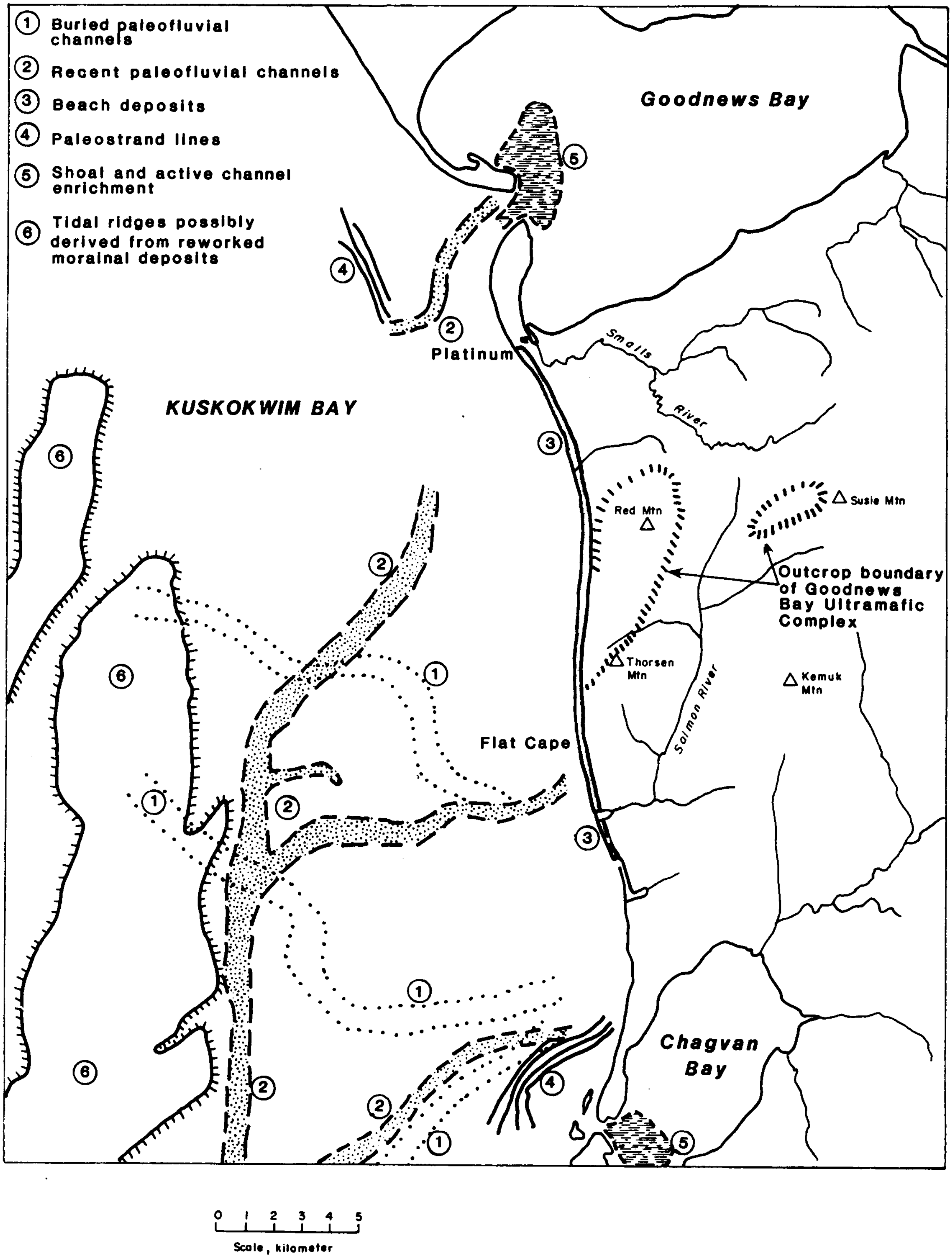



FIGURE 4. Favorable offshore and coastal platinum-bearing depositional environments.

bathymetric depressions up to 1.5 km wide with 5 m or less negative relief, and are traceable from approximately 3 km to 10 km offshore. Channels in the near shore environment extending from the Salmon River Valley are most favorable for PGM mineralization. Welkie (40) originally proposed the offshore channel model based on U.S. Coastal & Geodetic Service bathymetry map 9103. Her evaluation of 88 offshore samples, however, did not suggest selective platinum enrichment in the channels. Barker (1) also has suggested the presence of southwest-trending paleofluvial channels west of Red Mountain. His field investigations identified channels in the sea bluffs at Flat Cape.

## Beach Deposits

Berryhill (5) collected 47 auger and shovel samples of beach sands between the north shore of Goodnews Bay and Chagvan Bay. Although he found trace to minor quantities of PGM and gold in the sands, potentially economic concentrations were not recognized. Selective sampling of specific beach environments was not accomplished.

Welkie (40) found platinum, chromium, and gold concentrations in beach samples which have been enriched up to an order of magnitude above concentrations obtained in offshore samples. Beach deposits containing the greatest PGM and heavy mineral values occurred over a 2 km distance immediately south of the Salmon River (fig. 4).

Bond (7) continued beach placer investigations in the area and found the most significant PGM concentrations between Walrus Point and Platinum (figs. 2, 4). He concluded that the PGM was being derived from two principal sources: (1) direct weathering of Red Mountain where it crops out along the coast at Walrus Point and (2) reworking of morainal material deposited on the western flanks of Red Mountain which is rapidly eroding from coastal processes. Importantly, Bond (7) recognized specific shoreface environments where PGM, chromite, and gold are being selectively concentrated. The highest PGM concentrations are contained in thin layers of heavy mineral accumulations on the back beach near the base of the morainal bluffs, and in storm washover deposits at the mouths of creeks that erode the bluff. Additionally, Bond noted that beach and nearshore wave energy concentrates only fine platinum (less that 250 um). Heavy mineral concentration by wave sorting along the upper swash zone and far back-beach apparently results from swash wave action, storm, and high tide events. Ulrich (42) also concluded that PGM was being concentrated between the upper swash zone and back-beach as a result of daily high-tide spillover events, and in the far back-beach as a result of storm processes. The greatest concentration of PGM was found in the less-than 125 um range.

New data collected by the Bureau in 1986 (15) suggests a hypothetical reserve base of 1,420,000 $m^3$ for beach sands between the bluff at Red Mountain and the south spit at Goodnews Bay with the average tenor of PGM and gold to be 0.0325 $g/m^3$ and 0.0039 $g/m^3$ respectively.

Between Walrus Point and the Salmon River, the areal extent of the beach is limited, with a hypothetical reserve base of 251,800 $m^3$. PGM grades average around 0.2968 $g/m^3$, and gold values average 0.1342 $g/m^3$. Average grades are based on sixty-four 0.0765 $m^3$

(0.1 $yd^3$) samples collected from representative beach facies. PGM and gold grades were determined by weighting the average value of sample site assays against the cross-sectional area of the beach profile between sample sites as described by Wells (41, pp. 55, 58-59). Total available hypothetical resources are limited to approximately 121 kg of PGM. Volume estimates of beaches are hypothetical and assume a 23 m wide beach south of the Red Mountain bluff, and 46 m wide beach north to the South Spit of Goodnews Bay. The thickness of the beach deposits to bedrock was extrapolated from limited test pit sampling data (15). Hypothetical reserves may be significantly increased if nearshore sediments, below the average low tide, are included with the beach deposits.

## Paleostrand Lines

Potential for heavy mineral concentration exists in submerged strand lines (terraces) offshore and subparallel to the present coast line. Submerged paleostrand lines may have formed along ancient coastal areas during marine regressions/transgressions associated with glacial events. This type of deposit is an important offshore concentrator of gold in the Nome district (12). Available bathymetric data suggest the possibility of paleostrand lines 1 km to 6 km west of Goodnews and Chagvan Bays (fig. 4). The strand lines are defined by approximately 5 m of vertical relief over regions as narrow as 1,000 m. PGM and gold may have accumulated as lag deposits along the strands while lighter sediments were winnowed out by wave and current energy during transgressive and regressive marine cycles.

## Shoal Deposits

Littoral sediments originating from eroded morainal bluffs, fluvial discharge, and sediments eroded from seaward extensions of the Red Mountain ultramafic complex at Flat Cape could be deposited as shoals at the mouths of Goodnews Bay and Chagvan Bay due to decreasing wave transport energy (fig. 4). Owen (28) presented evidence that bluff derived sediments including heavy minerals were being concentrated at the mouth of Chagvan Bay. Heavy minerals and coarse-grained sediment accumulations are concentrated in Chagvan Bay as lag deposits by winnowing out lighter sediments. Concentrations exceeding 100 ppm chromium were identified just past the spit in the mouth of Chagvan Bay, however, analyses for PGM were not obtained (28).
Bond (7) suggests the possibility of the Goodnews Bay shoal acting as the final "sink" for ultra-fine (-125 um) PGM. Ultrafine-grained PGM probably would be transported by northerly littoral currents along a low energy near shore corridor (7). The higher energy beach corridor apparently transports slightly coarser platinum towards the Goodnews Bay spits.

The Bureau (1) confirmed the presence of large scale winnowing features offshore. Reconnaissance samples confirmed PGM accumulations in the Goodnews Bay channelway. These observations are consistent with Wakeland's (37) sediment distribution observations which indicate that up to 80 pct of the sediments in the mouth of Goodnews Bay are gravels. PGM tend to associate with coarser sands and gravels (lag deposits) in coastal environments near Goodnews Bay (40, 42).

Sampling by Fechner (14) along the Goodnews Bay spits, however, suggests that PGM concentrations are less than 0.0012 g/m$^3$ and of little economic importance.

### Tidal Ridges

Offshore topographic features which possibly act as corridors for selective heavy mineral concentrating are elongate, topographically high, north-south trending tidal ridges. If the ridges are comprised of reworked offshore morainal deposits, disseminated heavy minerals might be available for selective concentrating. The origin of the ridges is probably due to strong tidal action (6, 38). They are characterized by 3 m to 20 m of relief and are separated by narrow channels (fig. 4). Littoral currents and storm wave energy would be the major forces acting to concentrate PGM and other heavy minerals as lag deposits. Because the floor of Kuskokwim Bay in this region is shallow, most bottom features are within the zone of wave disturbance, and thus capable of producing heavy mineral enriched lag gravels.

### Concentration Along "False" Bedrock Horizon

Placer production from fluvial channels onshore encountered the highest PGM grades directly above bedrock, and within the upper meter of weathered or "false" bedrock (24-25). Clay-rich glacial till and ferricreted gravel horizons were discovered underlying the beach front during Bureau sampling efforts in 1986 (15). Continuous clay-rich or ferricreted gravel stratum over large offshore areas may represent favorable "false" bedrock contacts for platinum-bearing heavy mineral accumulations in some of the other deposit classes.

## RESULTS OF MARINE SEDIMENT ANALYSES NEAR GOODNEWS BAY

Results from geochemical and textural analyses have been reported for marine sediments from the Goodnews Bay Mining District. Unfortunately, significant differences in sampling and chemical analytical techniques prevent comparative evaluation of samples collected by different researchers. Further, low sampling densities and inadequate methods of sample collection and preparation have prevented determination of offshore resources.

PGM placers from high energy beach deposits are very-fine-grained. Ulrich (42) found that most of the PGM occurs in the less-than 125 um range. The PGM mineralization is associated with fine-to medium-grained sand (1.5-2.5 phi range). Bond (7) observed that all of the PGM recovered from beach deposits was less-than 250 um in length. Textural analyses of nearshore and far offshore placer PGM concentrates have not been determined. The presence of very fine grained PGM in high energy beach deposits leaves questions about the distribution of coarser-grained PGM. PGM coarser-than 250 um would be substantially easier to recover using currently available technologies. The location of coarser-grained PGM is unclear. It is possible that coarse PGM grains remain dispersed or have been selectively concentrated offshore in reworked glaciofluvial sediments. Storm wave energy and littoral currents may not be strong enough transport agents to remobilize coarser-than 250 um platinum grains to the nearshore or beach environment. Therefore, depositional environments for fine-grained or coarser PGM may be dependent upon winnowing out of the other hydraulically lighter sediments.

## GEOCHEMICAL ASSOCIATION

The association of PGM with elements exhibiting geochemically and hydraulically similar behavior is useful for delineating regions with potential platinum mineralization based on the abundance of the other elements. Further, since platinum is a noble metal and occurs in trace to very minor concentrations, assays usually have a high degree of analytical uncertainty.

Ideally, detection limits of 50 ppb platinum are obtainable by preconcentrating the prepared sample using a fire assay followed by an atomic absorption analysis (3). However, results obtained using this technique may only represent an order-of-magnitude approximation of the actual PGM abundance if sample collection and concentration were not carefully performed. If the ratio between the elements associated with PGM are determined, coevaluation of those elements will provide a higher degree of certainty regarding the actual concentration of PGM. Anomalous or unexpected PGM assays will be recognized and the sample analysis can be reevaluated if desired.

Unfortunately, fire assay and atomic absorption analysis will not provide information indicating how much PGM is available for placer recovery; the analysis will be positively biased. A more useful analytical technique which determines the abundance of recoverable PGM and gold is obtained by bulk sampling a known volume of sediment, concentrating heavy minerals with a jig or sluice plant, and physically separating PGM and gold from other heavy minerals recovered. A 0.0765 $m^3$ (0.1 $yd^3$) sample should be sufficient to reduce the nugget effect of PGM which are generally very fine grained. Partitioning of PGM and gold from other heavy minerals is accomplished with magnetic separation, gold amalgamation, and most likely a binocular microscope and tweezers. PGM and gold may then be weighed and the grade back calculated knowing the original volume of the sample. This procedure allows the determination of concentrations below 1 ppb, providing data which may be directly applied to economic evaluation of the placer deposit . Analytical certainty is limited only by the efficiency of the concentrating plant and precision of the scale used to weigh out recovered values. Fire assay of residual heavy mineral concentrates will indicate the abundance of commercially nonrecoverable PGM and gold.

Because the compositional analysis of other geochemically similar elements (e.g. Cr, Fe) is not as sensitive to analytical and sampling errors, geochemical data available from previous researchers might be useful in determining the extent of PGM concentration and distribution. High concentrations of PGM were found to be associated with analyses containing greater than 10 pct iron, 5,500 ppm chromite, and 35 ppm cobalt according to Ulrich (42). Bond (7) found platinum concentrations relate to the relative abundance of chromite, nickel, and cobalt. Although the USGS AMRAP program has provided abundant geochemical data onshore in the Goodnews Bay Mining District, there is relatively little semiquantitative offshore and beach data available (11, 17-18).

Wakeland (37) and Owen (28) published reports concerning geochemical investigations of Goodnews and Chagvan Bays, respectively. Concentrations exceeding 18 ppm cobalt and 22 ppm nickel are distributed just inside the mouth of Goodnews Bay (37). Additionally, the mouth of Goodnews Bay is characterized by sediments containing 30 to 80 pct gravel, suggesting a high energy environment favorable for concentration of PGM and other heavy minerals.

The inlet to Chagvan Bay contains 6 to 10 pct heavy minerals with individual samples containing over 400 ppm cobalt, 250 ppm chromite, 45 ppm nickel, 500 ppm manganese, and 5 to 6 pct iron (28). This information suggests the shoal and channels just inside the mouth of Chagvan Bay may contain geochemically significant, and perhaps economically viable concentrations of PGM. Offshore geochemical surveys include 78 semiquantitative sample analyses provided by Barnes for the AMRAP program (4).

Hessin and Others (18) list semiquantitative data for chromium, and Coonrad and Others (11) compiled offshore data for platinum and gold. These data however, are inadequate for identifying regions with favorable PGM concentrations.

The only other offshore geochemical data available was obtained by Welkie (40). Evaluation of her contoured data from 88 sample sites is incomplete, but suggests that anomalously high concentrations of cobalt, chromium, gold, and platinum are found in offshore regions corresponding to paleofluvial channels. Offshore grab samples contained up to 0.8 ppm platinum, 0.06 ppm gold, 30 ppm cobalt, and 180 ppm chromium. All determinations were made using atomic absorption spectrometry, leaving some uncertainty regarding analytical accuracy and actual values of recoverable PGM and gold.

## CONCLUSIONS AND RECOMMENDATIONS

The primary source for platiniferous coastal and offshore sediments in the Goodnews Bay Mining District is the Red Mountain ultramafic complex . Principal secondary sources supplying PGM-bearing sediments to beach and offshore deposits include glacial morainal and outwash deposits and discharge from the Salmon River. Six potential placer deposit classes are recognized: (1) buried paleofluvial channels, (2) recent paleofluvial channels, (3) beach deposits, particularly along the upper swash zone, (4) paleostrand lines, (5) shoal deposits at the mouths of Goodnews and Chagvan Bays, and (6) lag deposits comprised of reworked glacial morainal material along the base of tidal ridges.

Limited assay data prevents direct calculation of the distribution and concentration of PGM and gold in potential offshore placers. The USGS has estimated hypothetical resources of subeconomic grade to be 155,500 kg from offshore placers (29). Limited beach and offshore sampling results suggest this value to be very optimistic. Fechner, in 1986, completed bulk sampling of the beach front between the north spit of Goodnews Bay and the north spit of Chagvan Bay (14). Based on 64 bulk samples, data suggests that 121 kg of PGM is recoverable from a hypothetical resource base of 1,672,000 $m^3$ along the beach between the southern end of the south spit at Goodnews Bay and the Salmon River. The highest average grade of PGM was found between the bluff at Red Mountain and the Salmon River which ranged around 0.2968 $g/m^3$.

The first step required to delineate minable offshore and coastal placer deposits around the Goodnews Bay Mining District involves sufficient reconnaissance sampling to suggest potential economic PGM concentrations. This step is being accomplished and specific depositional environments with potentially economic PGM and heavy mineral accumulations have been recognized. Additional Bureau reports which are currently in preparation will specifically address PGM and gold distributions offshore and along the coast.

The second stage of offshore and beach placer evaluation requires a high sample site density around favorable targets. Reliable evaluations are dependent upon correct bulk sampling techniques and reproducible compositional analysis. Given the approximate size of the various potential deposits around Goodnews Bay, 100 to 150 m sample spacing is probably sufficient to determine if economically minable grades and volumes are present (26). Since some of the PGM placer deposits are stratified and buried to unknown depths (e.g. under marine or reworked glacial debris), stratigraphic control of sampling is critical for representative deposit evaluation.

Mining costs estimated for offshore dredging establishes a subeconomic cut off grade of approximately $1.3/m$^3$ ($1/yd$^3$) contained PGM and gold for economically recoverable placers (12). As assays from sampling programs are evaluated, deposits with potentially economic PGM placer mineralization will be located and minable volumes, if any, estimated using geometrics or proper geostatistical techniques (22).

Bottom grab or suction dredge sampling for offshore placers provides useful information identifying favorable PGM mineralization for some deposit classes. However, since these techniques only sample the upper sediment horizons they are inadequate for determining the volume or grade of potentially minable offshore deposits in the third dimension. An offshore drilling program capable of yielding large uncontaminated samples is necessary to gain stratigraphic control of PGM and gold distributions which will allow the calculation of minable reserves or subeconomic resources.

PGM grains in the Goodnews Bay Mining District, and presumably offshore, are very fine-grained. Therefore, the efficiency of gravity concentrating systems should be considered when evaluating the recoverable value of the reserve base. Historically, micron sized PGM grains have been lost during on-shore dredging operations (12).

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